https://dx.doi.org/10.1016/j.trd.2024.104126

Navigating the green shipping: Stochastic hydrogen hub deployment in inland waterways

Yidan Shangguan [a], Xuecheng Tian [a,1], Anthony Pang [a], Qingfang Ruan [b], Yong Jin [c], Shuaian Wang [a]

[a] Department of Logistics and Maritime Studies, The Hong Kong Polytechnic University, Hung Hom, Hong Kong

[b] Shenzhen Guangming District Institute of Administration, Shenzhen, China

[c] School of Accounting and Finance, Faculty of Business, The Hong Kong Polytechnic University, Hong Kong

Abstract

The maritime industry is shifting toward sustainability to help combat climate change, given the sector's significant contribution to global greenhouse gas emissions. This study focuses on the strategic integration of hydrogen fuel—a zero-emission alternative—into inland waterway transport systems. We recognize the operational characteristics of inland shipping networks and the complexities of two-stage financial planning. Consequently, we propose a two-stage stochastic framework for the deployment of hydrogen refueling hubs, taking into account financial uncertainties in the future. This approach contrasts with a myopic strategy and a two-stage deterministic framework, addressing both immediate financial constraints and future uncertainties. We focus on the Yangtze River's shipping network as a case study, and our analysis validates the superior performance of our proposed two-stage stochastic strategy. This suggests its potential to accommodate volatile future financial uncertainties while ensuring the economic and operational viability of hydrogen integration.

Keywords: green shipping; hydrogen energy; hub deployment problem; two-stage stochastic programming

[1] Corresponding author. Emails: yidan.shangguan@connect.polyu.hk (Y. Shangguan), xuecheng-simon.tian@connect.polyu.hk (X. Tian), anthony.pang@polyu.edu.hk (A. Pang), ruanqf3@163.com (Q. Ruan), jimmy.jin@polyu.edu.hk (Y. Jin), hans.wang@polyu.edu.hk (S. Wang).

1. Introduction

Fossil-fueled shipping significantly contributes to global warming by emitting substantial quantities of greenhouse gases (GHG) such as carbon dioxide (CO_2) and methane (Faber et al., 2021). In 2018, shipping emissions amounted to an alarming 1,056 million tons of CO_2, making the shipping sector a larger global emitter than all but the top five countries (Tay et al., 2023). Although these CO_2 emissions are concerning, the shipping sector also emits methane, which is a GHG many times more potent than CO_2 (Boucher et al., 2009). Roughly a quarter of global warming since the pre-industrial era can be attributed to methane, and thus its mitigation should be prioritized in global efforts to combat climate change.

The International Maritime Organization (IMO) developed an initial strategy to reduce GHG emissions from conventional shipping in April 2018 (Joung et al., 2020). This suggests the adoption of alternative, low-emission fuels in the long run. Four potential clean energy replacements for fossil fuels in shipping have been identified: hydrogen, ammonia, methanol, and liquefied natural gas (Gore et al., 2022; Seddiek et al., 2023). Of these, hydrogen and ammonia stand out due to their carbon-free properties (Zhou et al., 2020; Anderson et al., 2015; Laval et al., 2020; Lewis, 2021; Fridell et al., 2021; Cullinane et al., 2023).

Hydrogen, when combusted in an internal engine, produces only water as a byproduct. In contrast, the harmful emissions from burning ammonia include nitrous oxide (N_2O), nitrogen dioxide (NO_2), and unburned ammonia (Duynslaegher, 2011;

Wang et al., 2015; Shen et al., 2016). In addition to the direct environmental benefits, hydrogen fuel poses fewer environmental risks than ammonia if spilled and directly eliminates the need to produce complex intermediaries like ammonia, methanol, and methane, thus reducing energy loss. Hydrogen is therefore the most sustainable and favorable future zero-emission alternative (Bach et al., 2020).

However, hydrogen fuel's lower energy density coupled with the limited capacity of ships' fuel tanks demands more frequent refueling over long distances. Consequently, our research focuses on inland waterways, which have shorter sailing legs compared to international shipping routes and are better suited for hydrogen use. To encourage wider adoption of hydrogen in maritime operations, our study concentrates on the most frequently used shipping routes, aiming to integrate hydrogen energy in a manner that aligns with these existing operational patterns.

Moreover, the development of hydrogen refueling infrastructure brings substantial financial considerations. Constructing refueling hubs requires significant capital investment, and the planning of these projects is often complicated by the uncertainties regarding future funding. Therefore, governments might consider a phased implementation strategy, taking into account these financial constraints and uncertainties, as suggested by Brown et al. (2006).

In response to these challenges, we propose a two-stage approach to deploying hydrogen refueling hubs. This can address the immediate economic pressures and optimize resource utilization while considering the unpredictability of future funding.

To navigate this two-stage issue, we compare three strategic approaches: a myopic strategy, a two-stage deterministic strategy, and a two-stage stochastic strategy. Our analysis reveals that the two-stage stochastic strategy outperforms the others, thus offering viable solutions for the current stage while effectively accounting for future uncertainties.

2. Literature Review

Green shipping research, emphasizing technological solutions to air pollution, has been popular for over a decade (Kosmas et al., 2017; Shi et al., 2018; Yu et al., 2021; Chua et al., 2023). While the majority of these studies concentrate on international shipping, there is a scarcity of research addressing inland shipping (Raucci, 2017; Thepsithar et al., 2020; McKinlay et al., 2021). Within the realm of green shipping, hydrogen has been recognized as a promising alternative energy source, offering environmental benefits and efficient energy utilization, thereby presenting viable solution for mitigating GHG emissions from the shipping industry (Atilhan et al., 2021). The development of hydrogen refueling stations has received considerable attention, mainly focus on their application in fuel cell electric vehicles and the strategic planning of hydrogen refueling station networks within urban areas (Apostolou et al., 2019; Rose et al., 2020; Kuvvetli 2020; Hernández et al., 2021). However, a handful of research papers (Baykara, 2018; Leonida, 2020; Cetinkaya et al., 2012; Parkinson et al., 2019) have delved into the application of hydrogen in the maritime sector. These studies cover a range of aspects including production methods, techno-economic analysis, safety considerations, and storage solutions, collectively affirming the feasibility of using hydrogen energy in the shipping industry. Nonetheless, there remains a noticeable gap in the literature, particularly concerning practical guidance for governments and investment enterprises. This study aims to bridge this gap by focusing on the strategic implementation of hydrogen hubs, optimizing their use, and minimizing associated costs in the context of inland shipping. This approach not only provides practical insights for policy makers but also enriches the research on inland shipping within the scope of green shipping, thereby facilitating the effective integration of hydrogen energy into the shipping industry.

This research addresses the logistical challenges of deploying hydrogen refueling hubs within inland water transportation, and particularly about hub location problems (HLP). Goldman (1969) first examined HLPs, and they remain an active research area (Alumur et al., 2008; Campbell et al., 2012; Farahani et al., 2013; Zheng et al., 2018; Fadda et al., 2020; Zheng et al., 2022). Correspondingly, the shipping industry mainly solves network design issues. Sun and Zheng (2016) developed a probabilistic model to identify potential hub locations in global shipping networks, while Zheng et al. (2018) explored the global HLP for liner shipping, taking into account cluster structures. Zheng and Yang (2016) addressed the design of a liner wheel-spoke network for inland navigation, which is also an HLP. These traditional HLPs typically concentrate on identifying hub locations before formulating shipping networks and schedules. However, the deployment of hydrogen hubs for inland water systems presents a different scenario. Unlike global shipping routes, subject to geopolitical complexities and requiring multinational consensus, inland waterways offer a more controlled setting for prompt implementation. Moreover, the deployment strategy for hydrogen hubs in this sector must consider routes with high-frequency usage to encourage widespread adoption of hydrogen energy by ships. This requires a nuanced approach, in which the location of hydrogen hubs should align with the operational patterns of the ships. This aspect sets it apart from the conventional HLP, where infrastructure design is primarily shipping-network-based. To date, this issue has not been extensively explored, posing a significant challenge to our study.

We address the financial and practical challenges of constructing hydrogen refueling hubs in maritime transport and highlight the current impracticality of equipping all ports with such facilities due to the significant capital costs and potential funding uncertainties. Ports along shipping routes cannot be simultaneously outfitted with hydrogen refueling infrastructure, especially given the constrained financial resources and the uncertain forecast of future investment. These factors are central to strategies for the rollout of hydrogen infrastructure. The notion of provider-side uncertainty, as categorized by Shen et al. (2011), is particularly relevant to our research. This encompasses the unpredictability of future financial support along with other factors that contribute to the complexity of infrastructure planning. Nickel et al. (2012) developed a multi-stage programming model to manage uncertain demand and returns in facility layout. Albareda-Sambola et al. (2013) introduced a fix-and-relax coordination approximation procedure to tackle multi-period facility location problems involving uncertainties in costs and customer service requests. Escudero et al. (2018) extended this research by specifically designing two mathematical heuristics specifically designed for such problems. Our study aims to address provider-side uncertainty in deploying hydrogen refueling hubs, considering their integration within shipping networks. The models we propose are robust and nuanced and are engineered to navigate and mitigate future uncertainties. By doing so, we render solutions that are not only effective in the current financial landscape but also resilient and flexible in their responses to future fiscal conditions.

2.1 Contributions

This study makes three main contributions to the literature:

(1) We combine the strategic intent for hydrogen energy use with its practical implementation in the maritime sector through a pioneering reference model. By offering a comprehensive approach to embedding hydrogen energy at the strategic level, this study not only identifies the implementation pathway but also sets a precedent in terms of energy integration, which can be extended across the industry.

(2) We introduce a novel model for deploying hydrogen refueling hubs, specifically designed for the inland water transportation networks. This model is meticulously designed to synchronize with the regular service patterns prevalent in these networks. By doing so, it ensures that the deployment of hydrogen hubs integrates smoothly with existing shipping operations, maintaining uninterrupted service. A key feature of our

approach is the use of an arc-based deployment method. This method strategically positions hydrogen hubs by considering the interactions between network flows and refueling activities. Additionally, our model can be modified to consider other renewable resources beyond hydrogen by considering their different characteristics, potentially enabling ports to adopt various energies. This positions ports as comprehensive energy nodes, supporting the shipping industry's shift towards sustainability. It is also noteworthy that the majority of research in green shipping has primarily focused on international shipping, often neglecting the nuances of inland waterway transportation. Hence, our study makes a contribution to the literature by focusing on the application of green energy and technology transition within the realm of inland waterway transportation.

(3) In addressing the planning issues for hydrogen refueling infrastructure, we propose three distinct strategies: a myopic framework, a two-stage deterministic framework, and a two-stage stochastic planning framework. The myopic framework overlooks the impact of current decisions on future decisions. Although the two-stage deterministic framework accounts for the influence of current decisions, it fails to acknowledge the uncertainties in future decision making. On the other hand, the two-stage stochastic planning framework encompasses all the aspects, offering a deployment process that is resilient against potential financial instabilities. This framework presents a thorough, forward-thinking planning approach that alleviates immediate financial burdens, equipping the maritime industry to efficiently confront

future financial challenges. Consequently, this framework aids in establishing and managing energy hubs within the maritime sector, fostering a gradual transition towards renewable energy sources.

The remaining sections of this paper are structured as follows. Section 3 presents a detailed description of the problem under consideration. In Section 4, we formulate three strategies to tackle the hydrogen hub deployment problem with uncertain future funding. In Section 5, we report the results obtained from the strategies and present a comparative analysis. Section 6 concludes the paper.

3. Problem Description

3.1. Characteristics of Hydrogen Hub Deployment in Inland Waterways

In the realm of inland water transportation, the development of hydrogen refueling hubs entails unique challenges. These are underscored by the low energy density of hydrogen fuel and the limited bunker capacity of vessels, necessitating more frequent refueling over long distances. The strategic deployment of these hubs in international shipping networks involves decision makers from various nations. Before investigating the hydrogen hub location problem for international ports which should consider competition and cooperation among multi-national investors, our research concentrates on inland waterways which only has a single decision maker. Given this context, while hydrogen fuel emerges as a feasible option for inland navigation, its practical application should consider following aspects:

(1) Significant financial outlay: The establishment of hydrogen refueling hubs involves considerable capital investment (Baronas et al., 2018). Given this high cost, it becomes impractical to outfit all existing ports with hydrogen refueling hubs simultaneously. This constraint necessitates a more strategic approach to deployment, balancing financial resources with the pressing need for infrastructure development.

(2) Inherent uncertainties: The phased deployment strategy, while necessary, introduces uncertainties. Each phase faces different financial limitations and varying costs of installation. Moreover, the deployment of future hubs is influenced by the locations of existing ones, creating a complex network of dependencies. This necessitates a flexible and adaptive planning process, capable of responding to evolving financial and logistical realities.

(3) Strategic planning: Facilitating the increased utilization of hydrogen energy in maritime operations necessitates a strategic approach to planning hydrogen refueling infrastructure. Our initial planning is conducted based on existing high-frequency shipping routes. By strategically aligning the refueling hubs with established shipping patterns, this approach ensures not only the effective fulfilment of current demands but also encourages the wider adoption of hydrogen as an alternative fuel source.

3.2. Arc-based Shipping Network

This study investigates strategies to establish hydrogen refueling hubs at ports, with the aim of maximizing the number of hydrogen-powered ships along the inland water system, given the limited construction resources.

Inland waterways primarily consist of ports located alongside rivers, known as "physical ports". We denote these ports by $p \in \mathbf{P}$, where $\mathbf{P}$ is the set of such physical ports. When a ship transports cargoes between two or more physical ports, a shipping route is defined. We assume that each port on a shipping route facilitates cargo loading and unloading. Each route is denoted by r, and the complete set of routes is represented as $\mathbf{R}$ (i.e., $r \in \mathbf{R}$).

For hydrogen refueling hubs to be implemented effectively, it is imperative that they be closely integrated with the existing physical ports. This integration is crucial for aligning with established shipping patterns, thereby enabling a greater number of ships on busy routes to utilize hydrogen energy. Consequently, "hydrogen-energy-capable routes" are defined as those where ships can complete their entire journey using hydrogen energy. Routes that necessitate a mix of hydrogen and traditional fuels do not fall under this definition, as the technical complexities, environmental regulations, and economic factors involved in switching fuel types of mid-voyage are significant barriers (Sürer et al., 2022).

During a voyage, ships may dock at a given physical port more than once. Every docking of a voyage is referred to as a "port of call", which we denote by i. The set of these ports of call for a given route r is expressed as $\mathbf{I}_r$, such that $i \in \mathbf{I}_r$. To elucidate the relationship between $r\ (r \in \mathbf{R})$, $i\ (i \in \mathbf{I}_r)$, and $p\ (p \in \mathbf{P})$, we introduce the following example.

Example 1. As illustrated in Figure 1, four distinct physical ports are situated along the river: A, B, C, and D. The distances between these physical ports along the river are given in nautical miles (nm). Three shipping routes emerge from these ports: Routes 1, 2, and 3. Route 1 connects the ports in the sequence A, C, D, B, and then back to A. Route 2 follows the sequence B, C, D, returns to C, and concludes at B. Route 3 follows the sequence C, D, and then concludes at C. Each port on every route is visited weekly except port C on Route 2, which has two weekly visits. Consequently, Route 1 comprises four ports of call (stops), labeled as 1 (A); 2 (C); 3 (D); and 4 (B). Route 2 has the same number of ports of call: 1 (B); 2 (C); 3 (D); and 4 (C). Route 3 comprises two ports of call: 1 (C) and 2 (D).

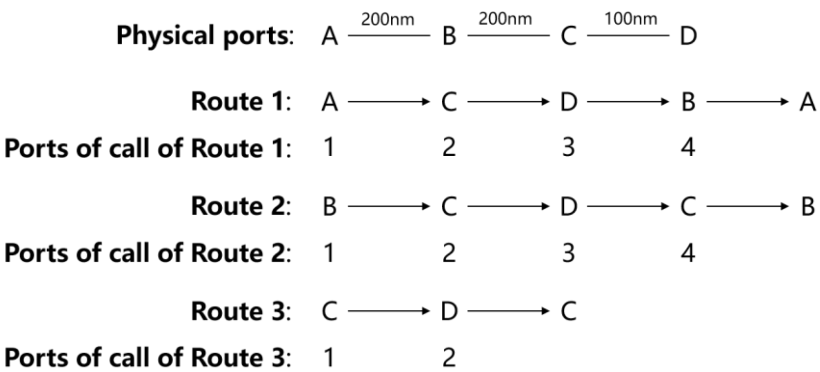

Figure 1. Illustration of physical ports and ports of call.

The segment of a shipping route between two consecutive ports of call is referred to as a leg. We denote the maximum distance a ship can travel on a full hydrogen charge as L. For routes navigable exclusively using hydrogen energy, each route $r \in \mathbf{R}$, must satisfy a specific criterion: the distance of every individual shipping leg of route r should be less than L.

Given the circular nature of the route, the shipping distance between any two ports of call in the shipping direction necessitates the consideration that it should consider two consecutive round shipping voyages. For instance, in Example 1 on Route 1, the shipping distance from the 3rd to the 2nd port of call in the shipping direction should be the sum of distances of shipping legs D–B, B–A, and A–C. To accommodate this feature, we introduce the function $f_r(i'')$ (where $i'' \in \{i, i+1, \ldots, i'-1\}$), which will be used to facilitate the representation of shipping legs from a port of call i to another port of call i' (where $i' \neq i$ and $i' \in \mathbf{I}_r$) within the direction of route r. $f_r(i'')$ is defined as follows:

$$f_r(i'') = (i'' - 1)\text{mod}|\mathbf{I}_r| + 1.$$

Given this expression, the shipping legs involved from port of call i to another port of call i' on route r can be represented as

$$\{f_r(i), f_r(i+1), \ldots, f_r(i'-1)\}.$$

Concurrently, the distance from the port of call i to the next port of call $f_r(i+1)$, i.e., the length of shipping leg i, is denoted as l_{ri}. Thus, the distance from port of call i to another port of call i' can be represented as the cumulative distance of the intermediate shipping legs: $l_{rf_r(i)} + l_{rf_r(i+1)} + \ldots + l_{rf_r(i'-1)}$.

Example 2 (continued). Consider Route 1 in Figure 1 where $|\mathbf{I}_r| = 4$. For $i = 3$, we have $i' = 4, 1, 2$. Applying the function $f_r(i')$ yields the following traveling distances between two ports of call:

- From port of call $i = 3$ to $i' = 4$: $l_{rf_r(3)} = 300$ nm;
- From port of call $i = 3$ to $i' = 1$: $l_{rf_r(3)} + l_{rf_r(4)} = 500$ nm;
- From port of call $i = 3$ to $i' = 2$: $l_{rf_r(3)} + l_{rf_r(4)} + l_{rf_r(1)} = 900$ nm.

Recall that $\mathbf{R}$ is the set of "hydrogen-energy-capable routes" and L indicates the maximum distance a ship can sail on a full hydrogen charge. We can thus separate $\mathbf{R}$ into two mutually exclusive and complementary subsets $\mathbf{R}_1$ and $\mathbf{R}_2$ depending on whether the total distance of a round voyage for a route is less than or equal to L. $\mathbf{R}_1$ comprises routes with total distances no greater than L:

$$\mathbf{R}_1 = \left\{r \in \mathbf{R} \middle| \sum_{i=1}^{I_r} l_{ri} \leq L\right\}.$$

For any route in $\mathbf{R}_1$, a single hydrogen hub positioned anywhere along the route can ensure that the entire trip is hydrogen-powered. In contrast, $\mathbf{R}_2$ contains the remaining routes: $\mathbf{R}_2 = \mathbf{R} - \mathbf{R}_1$, and the approach for establishing hubs on these routes is distinct.

Since the deployment of hydrogen hubs hinges on the integration with existing physical ports and established shipping routes, we introduce the concept of an "arc" to assess the feasibility of designating routes as "hydrogen-energy-capable routes" post the installation of hydrogen hubs. For any given route $r \in \mathbf{R}_2$, we define arc $a_{rii'}$ as the transportation path from port of call i to i' ($i' \neq i \in \mathbf{I}_r$). The set of arcs for route

$r \in \mathbf{R}_2$, originating from port of call i, in the direction of shipping, to port of call i' (where $i' \neq i$ and $i' \in \mathbf{I}_r$), with a total distance less than L, is given by

$$\mathbf{A}_{ri} = \left\{ a_{rii'} \middle| i' \neq i, i' \in \mathbf{I}_r, \sum_{i''=i}^{f_r(i'-1)} l_{ri''} \leq L \right\}, i \in \mathbf{I}_r, r \in \mathbf{R}_2.$$

Here, $\mathbf{A}_{ri}$ is the set of viable arcs on route r ($r \in \mathbf{R}_2$) that a ship, if refueling at the port of call i with hydrogen, can travel. Therefore, if a hydrogen refueling hub is deployed at port of call i, $\mathbf{A}_{ri}$ defines the arcs that are accessible, i.e., feasible arcs, after hydrogen refueling from that port. Consequently, the collective set of all feasible arcs on route r is represented as

$$\mathbf{A}_r = \cup_{i=1,2,\ldots,I_r} \mathbf{A}_{ri}.$$

Therefore, in order to make a route $r \in \mathbf{R}_2$ entirely viable for hydrogen propulsion, the selection of ports for the establishment of refueling hubs must be strategic: the combined arcs in $\mathbf{A}_r$ originating from the chosen hubs should encompass the entire route r. This ensures that ships traversing route r have access to hydrogen refueling at strategic ports, allowing for an uninterrupted hydrogen-powered voyage.

Example 3 (continued). Referring to Figure 1, consider $L = 400$ nm. The traveling distance of the round voyage for Route 3 is 100 nm, which is less than L. Therefore, Route 3 belongs to $\mathbf{R}_1$. In contrast, for Routes 1 and 2, their respective total distances exceed L, and thus they are classified as $\mathbf{R}_2$. Take Route 1 an example, the set of feasible arcs for Route 1 is denoted as $\mathbf{A}_1 = \mathbf{A}_{11} \cup \mathbf{A}_{12} \cup \mathbf{A}_{13} \cup \mathbf{A}_{14}$, where $\mathbf{A}_{11} = \{a_{112}\}$, $\mathbf{A}_{12} = \{a_{123}, a_{124}\}$, $\mathbf{A}_{13} = \{a_{134}\}$, and $\mathbf{A}_{14} = \{a_{141}\}$ represent specific sets of viable arcs starting from each port of call on Route 1, as shown in Figure 2 (a). Arcs

a_{112}, a_{124}, a_{141} in Route 1 are able to cover the entire route as shown in Figure 2 (b), and we can establish hydrogen fueling hubs at ports of call 1 (A), 2 (C), and 4 (B) to ensure that Route 1 is entirely viable for hydrogen propulsion. Furthermore, arcs a_{112}, a_{123}, a_{134}, a_{141} in Route 1 can also cover the entire route as shown in Figure 2 (c), and we can alternatively establish hydrogen fueling hubs at ports of call 1 (A), 2 (B), 3 (C), and 4 (D), further ensuring that Route 1 is entirely viable for hydrogen propulsion.

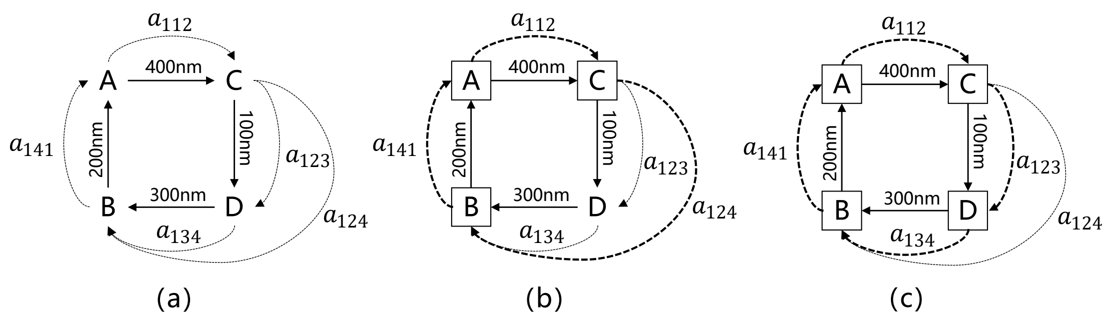

Figure 2. Illustration of viable arcs in Route 1.

3.3. Two-Stage Hydrogen Hub Deployment Problem with Uncertainty

Our arc-based formulation provides insight into the hydrogen-oriented inland shipping network. However, the uncertainty of funding for the deployment of hydrogen hubs in ports is a significant challenge in our research. Establishing a hydrogen hub demands substantial investment, and governments are unlikely to commit large lump sums up front. A phased investment approach is therefore often favored, but this brings the challenge of predicting future funding, which can be particularly difficult given the ever-changing financial landscape and rapid technological advances. Thus, the unpredictability of future funding is a major concern. Failing to account for such uncertainties during the initial planning can lead to inefficient resource allocation in the subsequent stages of hydrogen energy deployment, risking potential resource wastage. We further investigate this challenge with another example.

Example 4 (continued). Following on from the introduction, Figure 1 indicates that:

- For Route 1 to be deemed "hydrogen-energy-capable", we must select arcs $a_{112}, a_{124},$ and a_{141} to cover the entire route. Consequently, hydrogen refueling hubs must be established at ports of call 1, 2, and 4, corresponding to physical ports A, C, and B.
- For Route 2, two potential arc sets, $\{a_{212}, a_{224}, a_{241}\}$ and $\{a_{223}, a_{232}\}$, are viable for covering the entire journey. Hydrogen fueling hubs must be established either at ports of call 1, 2, and 4 or solely at ports of call 2 and 3. These translate to physical ports B and C (since ports of call 2 and 4 corresponds identically to the physical port C), or C and D.
- As Route 3 belongs to $\mathbf{R}_1$, it offers the flexibility to establish a hub at either port C or D.

We can then assume three ships operate on Route 1, while Routes 2 and 3 are traversed by two ships each. The government currently has resources to deploy two hydrogen refueling hubs, with provisions to deploy an additional hub in a second stage. Without accounting for potential future funding, the immediate construction plan could include hubs at either ports B and C or ports C and D. This decision would enable

Routes 2 and 3 to operate on hydrogen, accommodating four ships in total. However, if the present deployment focuses on ports B and C, and future funding materializes, a hub at port A becomes feasible. This addition will render Route 1 “hydrogen-energy-capable,” thus facilitating all seven ships to utilize hydrogen. Conversely, with the current commitment to ports C and D, Route 1 remains incompatible with hydrogen energy, irrespective of future port developments. When we consider the anticipated future funding, it becomes evident that a comprehensive strategy is required. Neglecting potential resource availability during the two-stage plan can be regarded as myopic, leading to sub-optimal resource allocation.

Example 4 emphasizes the ripple effects of current deployment decisions on future hydrogen hub projects. Given the unpredictability of future funding across various scenarios, our research focuses on identifying the most suitable ports for hydrogen hub establishment, with the goal of optimizing the transition of ships to hydrogen fuel. This is a complex task. The decisions made not only set the stage for further operations but are also clouded by the uncertainty of future funding. This volatility adds depth to our decision-making process: our immediate choices will influence both the short-term results and long-term strategies. Our decisions may either facilitate or block paths for future opportunities, and potential future developments can influence the decisions made. This combination of present choices, future uncertainties, and forthcoming decisions necessitates a comprehensive exploration of decision-making models, to ensure they can address this multifaceted scenario.

The uncertainty surrounding future developments in hydrogen refueling infrastructure primarily hinges on two key components: the cost of deploying hydrogen refueling hubs and the availability of funds for their deployment. The deployment cost is largely influenced by advancements in technology; as technological level improves, we can anticipate a gradual reduction in these costs. The availability of funds for the deployment of these hubs is contingent upon governmental budgeting and funding strategies. The interplay between these two factors, specifically the ratio of available funds to the deployment cost, critically determines the feasible number of hydrogens refueling hubs that can be deployed in the future. It is our assertion that the maximum number of hydrogens refueling hubs deployable in the future follows a discrete distribution, reflecting the combined impact of these two variables.

Before formulating the mathematical models, we further make the following assumptions:

(1) The shipping network, including routes and ports, is already determined.

(2) Ships on each route are homogeneous, with a fixed hydrogen refill capacity and a maximum distance achievable post-refueling.

(3) A ship maintains a constant speed. From the governmental perspective, the ship sailing speed can be represented by average speed across the shipping network. The time and costs of refueling with hydrogen are negligible, and refueling often coincides with cargo handling. When compared to the substantial investment in hydrogen hub construction, such minor expenses can be overlooked.

(4) The maximum number of hydrogen hub construction at present is known and derived from evaluating the current financial resources and construction cost.

(5) The maximum number of hydrogen hub construction funding under various scenarios and the probabilities of these scenarios are known. The estimations are based on factors such as government strategies, industry funding, grants, partnerships, and the technology.

4. Mathematical Models of Three Strategies

The focal problem can be approached as a two-stage planning problem. In the first stage, the available resources are deterministic, while in the second they are uncertain, as represented by various scenarios. The main objective is to optimize the deployment of hydrogen refueling hubs to maximize the number of ships using hydrogen energy in the long term by considering both present and future decisions. The government can take different approaches to solving this problem, as shown in Figure 3. The most basic is a myopic strategy, in which the government makes separate deployment decisions for each stage without considering their interactions or mutual influence. Beyond this basic strategy, the government can address the impact of future uncertainty on present decisions through various approaches. The mean value can be regarded as deterministic and thus a representation of future uncertainty. This method is termed the two-stage deterministic strategy. Another approach is to use various scenarios to characterize future uncertainties, known as the two-stage stochastic strategy. We examine these strategies in detail in the following subsections. The notations used are described in Table 1.

Table 1. Notations

Indices and Sets	
$\mathbf{P}$	Set of all ports on shipping routes, indexed by p.
$\mathbf{R}$	Set of shipping routes, indexed by r.
$\mathbf{I}_r$	Set of the ports of call (or legs) on ship route r, indexed by i.
$\mathbf{R}_1$	Set of routes that can be traveled entirely by refilling hydrogen once at any port of call on the route.
$\mathbf{R}_2$	Set of routes that cannot be traveled entirely by refilling hydrogen once at any port of call on the route, $\mathbf{R}_2 = \mathbf{R}/\mathbf{R}_1$.
$\mathbf{A}_r$	Set of feasible arcs of route r.
$\mathbf{A}_{ri}$	Set of feasible arcs in route r starting from the port of call i, $\mathbf{A}_{ri} \in \mathbf{A}_r$.
$\mathbf{S}$	Set of future resource scenarios for hydrogen refueling hubs deployment, indexed by s.
Deterministic parameters	
M	Number of hydrogen hubs that can be constructed within the currently available funding.
L	Maximum distance a ship can travel after hydrogenation.
D_r	Number of ships deployed on the route r.
l_p	Distance from the physical port p to the physical port $p+1$.
p_{ri}	The physical port of the port of call i on route r, $p_{ri} \in \mathbf{P}$.
l_{ri}	Distance from the port of call i to the port of call $i+1$ on route r.
$a_{rii'}$	The route from the port of call i, in the direction of shipping, to the port of call i', $a_{rii'} \in \mathbf{A}_{ri}$, $i \in \mathbf{I}_r$, $i' \in \mathbf{I}_r$, $i \neq i'$.
Stochastic parameters	
N_s	Number of hydrogen refueling hubs that could be constructed within the future available funding under scenario s.
α_s	Probability of occurrence of scenario s in the future.
Binary decision variables	
β_r	$\beta_r = 1$ represents that route r can be a "hydrogen-energy-capable route" in the current stage; $\beta_r = 0$, otherwise.
γ_p	$\gamma_p = 1$ represents that the port p is deployed as a hydrogen refueling hub in the current stage; $\gamma_p = 0$, otherwise.
y_{ri}	$y_{ri} = 1$ represents that the port of call i on route r is deployed as a hydrogen refueling hub in the current stage; $y_{ri} = 0$, otherwise.
$u_{rii'}$	$u_{rii'} = 1$ represents that in the current stage, the feasible arc from the port of call i to the port of call i' on route r, in the direction of shipping, is selected, $i \in \mathbf{I}_r$, $i' \in \mathbf{I}_r$, $i \neq i'$; $u_{rii'} = 0$, otherwise.
$\beta'_{r,s}$	$\beta'_{r,s} = 1$ represents that route r is deployed as a "hydrogen-energy-capable route" under scenario s for the second stage; $\beta'_{r,s} = 0$, otherwise.
$\gamma'_{p,s}$	$\gamma'_{p,s} = 1$ represents that physical port p is deployed as a hydrogen refueling hub under scenario s for the second stage in the future; $\gamma'_{p,s} = 0$, otherwise.
$y'_{ri,s}$	$y'_{ri,s} = 1$ represents that port of call i on route r is deployed as a hydrogen refueling hub under scenario s for the second stage in the future; $y'_{ri,s} = 0$, otherwise.
$u'_{rii',s}$	$u'_{rii',s} = 1$ represents that the feasible arc from the port of call i to the port of call i' on route r, in the direction of shipping, is selected under scenario s for the second stage in the future, $i \in \mathbf{I}_r$, $i' \in \mathbf{I}_r, i \neq i'$, $s \in S$; $u'_{rii',s} = 0$, otherwise.

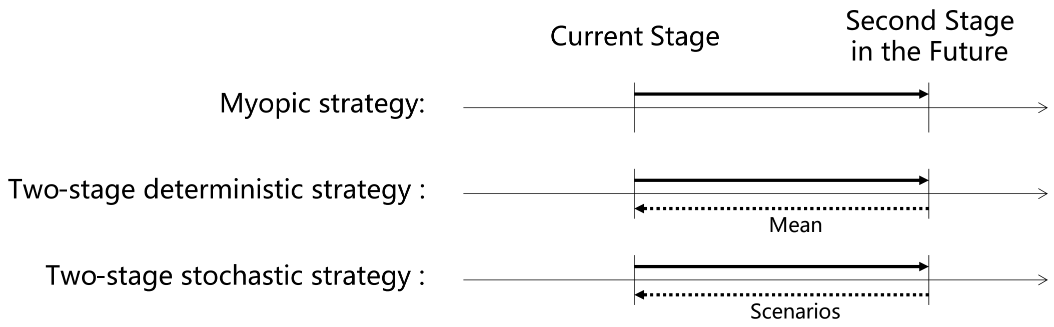

Figure 3. Illustration of three strategies.

4.1. Myopic Strategy and its Model

Decisions in the myopic strategy are made according to two separate stages, each with its own objectives and constraints. In the first, the model allocates the funding available at the time to determine the optimal deployment of hydrogen refueling hubs, with the goal of maximizing the number of ships powered by hydrogen. In this current stage, note that the decisions do not account for potential future financial shifts. As the model transitions to the second stage, although decisions are still made according to the available funding, those for the future are influenced by the deployments made in the current stage and only consider ports that have not yet deployed hydrogen hubs, as the current deployments will have already been accounted for.

The model for the current stage is as follows:

$$\max \sum_{r\in \mathbf{R}} D_r \beta_r \tag{1}$$

subject to

$$\sum_{p\in \mathbf{P}} \gamma_p \le M \tag{2}$$

$$y_{ri} = \gamma_{p_{ri}},\ r \in \mathbf{R},\ i \in \mathbf{I}_r,\ p \in \mathbf{P} \tag{3}$$

$$\beta_r \le \sum_{i=1}^{|\mathbf{I}_r|} y_{ri}, r \in \mathbf{R}_1 \tag{4}$$

$$u_{rii'} \leq y_{ri},\ r \in \mathbf{R}_2,\ i \in \mathbf{I}_r,\ i' \in \mathbf{I}_r,\ i \neq i',\ a_{rii'} \in \mathbf{A}_r \tag{5}$$

$$\sum_{a_{rii'} \in \mathbf{A}_{ri}} u_{rii'} \leq 1, i \in \mathbf{I}_r, r \in \mathbf{R}_2 \tag{6}$$

$$\sum_{a_{rii'} \in \mathbf{A}_{ri}} u_{rii'} = \sum_{a_{ri'i} \in \mathbf{A}_r} u_{ri'i}, i \in \mathbf{I}_r, r \in \mathbf{R}_2 \tag{7}$$

$$\left\lceil \frac{\sum_{i \in \mathbf{I}_r} l_{ri}}{L} \right\rceil \beta_r \leq \sum_{a_{rii'} \in \mathbf{A}_r} u_{rii'}, r \in \mathbf{R}_2 \tag{8}$$

$$u_{rii'} \in \{0,1\},\ r \in \mathbf{R}_2,\ i \in \mathbf{I}_r,\ i' \in \mathbf{I}_r,\ i \neq i',\ a_{rii'} \in \mathbf{A}_r \tag{9}$$

$$y_{ri} \in \{0,1\}, r \in \mathbf{R}, i \in \mathbf{I}_r \tag{10}$$

$$\gamma_p \in \{0,1\}, p \in \mathbf{P} \tag{11}$$

$$\beta_r \in \{0,1\}, r \in \mathbf{R}. \tag{12}$$

Objective function (1) maximizes the number of ships using hydrogen energy at the current stage. Constraint (2) requires that the number of hydrogen refueling hubs deployed at the current stage cannot exceed available resources. Constraints (3) ensure that the construction of a hydrogen refueling hub at the port of call i on route r aligns with the construction of a hydrogen refueling hub at the corresponding physical port p_{ri}. Constraints (4) require that for set $\mathbf{R}_1$, the route can be a "hydrogen-energy-capable route" as long as one of the ports of call on the route is chosen to be deployed a hydrogen refueling hub. Constraints (5)–(8) restrict the relationships between a route, a port of call, and a viable arc. For any route in set $\mathbf{R}_2$, if it is selected as a "hydrogen-energy-capable route", the chosen ports of call to deploy hydrogen refueling hubs should satisfy: we can at least choose viable arcs staring from these ports of call to span the whole shipping route. Specifically, Constraints (5) require that if a viable arc is selected, the port of call corresponding to the head of the arc should be deployed a hydrogen refueling hub. Constraints (6) require that the number of selected arcs starting from each port of call is not larger than one. Constraints (7) require that if a viable arc starting from port of call i is chosen, there must exist another chosen viable arc that ends at i, so as to span the whole shipping route. Constraints (8) require that, if route r is chosen as a "hydrogen-energy-capable route," the number of ports of calls to be deployed hydrogen refueling hubs, i.e., the number of chosen viable arcs, should be no less than the number of refueling stops that a ship needs to sail the entire route. Constraints (9)–(12) define the domains of binary decision variables.

Let $\boldsymbol{\beta}^* = \{\beta_1^*, \ldots, \beta_r^*, \ldots, \beta_{|\mathbf{R}|}^*\}$ and $\boldsymbol{\gamma}^* = \{\gamma_1^*, \ldots, \gamma_p^*, \ldots, \gamma_{|\mathbf{P}|}^*\}$ be the optimal decisions in the current stage. Given them, we can then define the optimal objective function value under scenarios s in the second stage as $h^*(\boldsymbol{\beta}^*, \boldsymbol{\gamma}^*, s)$. The model for the second stage under scenario s is as follows:

$$h^*(\boldsymbol{\beta}^*, \boldsymbol{\gamma}^*, s) = \max \textstyle\sum_{r\epsilon\mathbf{R}} D_r\, \beta'_{r,s} \tag{13}$$

subject to

$$\beta'_{r,s} \leq 1 - \beta_r^*, r \in \mathbf{R} \tag{14}$$

$$\textstyle\sum_{p\in\mathbf{P}} \gamma'_{p,s} \leq N_s \tag{15}$$

$$\gamma_p^* + \gamma'_{p,s} \leq 1, p \in \mathbf{P} \tag{16}$$

$$y'_{ri,s} = \gamma_{p_{ri}}^* + \gamma'_{p_{ri},s}, r \in \mathbf{R}, i \in \mathbf{I}_r, p \in \mathbf{P} \tag{17}$$

$$\beta'_{r,s} \leq \textstyle\sum_{i=1}^{|\mathbf{I}_r|} y'_{ri,s}\,, r \in \mathbf{R}_1 \tag{18}$$

$$u'_{rii',s} \leq y'_{ri,s}, r \in \mathbf{R}_2, i \in \mathbf{I}_r, i' \in \mathbf{I}_r, i \neq i', a_{rii'} \in \mathbf{A}_r \tag{19}$$

$$\textstyle\sum_{a_{rii'}\in\mathbf{A}_{ri}} u'_{rii',s} \leq 1, i \in \mathbf{I}_r, r \in \mathbf{R}_2 \tag{20}$$

$$\sum_{a_{rii'}\in\mathbf{A}_{ri}} u'_{rii',s} = \sum_{a_{ri'i}\in\mathbf{A}_r} u'_{ri'i,s}\,, i \in \mathbf{I}_r, r \in \mathbf{R}_2 \tag{21}$$

$$\left\lceil \frac{\sum_{i\in\mathbf{I}_r} l_{ri}}{L} \right\rceil \beta'_{r,s} \le \sum_{a_{rii'}\in\mathbf{A}_r} u'_{rii',s}\,, r \in \mathbf{R}_2 \tag{22}$$

$$u'_{rii',s} \in \{0,1\}, a_{rii'} \in \mathbf{A}_r, r \in \mathbf{R}_2, i \in \mathbf{I}_r, i' \in \mathbf{I}_r, i \neq i' \tag{23}$$

$$y'_{ri,s} \in \{0,1\}, r \in \mathbf{R}, i \in \mathbf{I}_r \tag{24}$$

$$\gamma'_{p,s} \in \{0,1\}, p \in \mathbf{P} \tag{25}$$

$$\beta'_{r,s} \in \{0,1\}, r \in \mathbf{R}. \tag{26}$$

Constraints (14) require that route r can be considered for future deployment only if it is not a hydrogen-energy-capable route in the current stage. Constraint (15) requires that the number of hydrogen refueling hubs deployed in the future in scenario s in the second stage in the future cannot exceed the available resources. Constraints (16) require that hydrogen refueling hub can be considered for future deployment only if it has not been deployed in port of call p in the current stage. The remaining constraints in scenario s for the second stage in the future are the counterparts of those in the current stage.

We can then determine the optimal solutions for the second stage if scenario s is realized, denoted by $\boldsymbol{\beta}'^{*}_{s} = \{\beta'^{*}_{1,s}, \ldots, \beta'^{*}_{r,s}, \ldots, \beta'^{*}_{|\mathbf{R}|,s}\}$ and $\boldsymbol{\gamma}'^{*}_{s} = \{\gamma'^{*}_{1,s}, \ldots, \gamma'^{*}_{p,s}, \ldots, \gamma'^{*}_{|\mathbf{P}|,s}\}$. To obtain the overall effect of the myopic strategy, we calculate the weighted sum of the optimal objective function values for the second stage across all scenarios, along with that of the current stage. The combined value represents the overall effect for the myopic strategy, denoted by $\sum_{r\in\mathbf{R}} D_r \beta^{*}_{r} + \sum_{s\in\mathbf{S}} \alpha_s \sum_{r\in\mathbf{R}} D_r \beta^{*}_{r,s}$.

Although the myopic mode facilitates rapid decision making and optimizes decisions at respective stages, it often overlooks the impact of future decisions on the current stage are overlooked. Decision-makers then achieve solutions that are optimal for a single stage but sub-optimal for the entire process. We explore the two-stage deterministic strategy, which emphasizes the significance of forecasting future uncertainties and seamlessly incorporates them into current decision making. Rather than only focusing on the present stage, this model uses the mean value to depict possible future uncertainty, offering a more long-term view.

4.2. Two-Stage Deterministic Strategy and its Model

In the two-stage deterministic strategy, decisions for the current stage are made by considering both current funding and a projected mean future funding value. It incorporates the mean value of anticipated future funding to maximize the number of ships utilizing hydrogen in the long term.

The average value of available resources in the future is denoted as N. β'_r, γ'_p, y'_{ri}, and $u'_{rii'}$ are newly introduced decision variables corresponding to the future decisions made under the projected mean value of future funding. The model solves not only for the optimal solutions $\boldsymbol{\beta}^* = \{\beta_1^*, \ldots, \beta_r^*, \ldots, \beta_{|\mathbf{R}|}^*\}$ and $\boldsymbol{\gamma}^* = \{\gamma_1^*, \ldots, \gamma_p^*, \ldots, \gamma_{|\mathbf{P}|}^*\}$ for the current stage but also for the optimal solutions $\boldsymbol{\beta}'^* = \{\beta_1'^*, \ldots, \beta_r'^*, \ldots, \beta_{|\mathbf{R}|}'^*\}$ and $\boldsymbol{\gamma}^* = \{\gamma_1'^*, \ldots, \gamma_p'^*, \ldots, \gamma_{|\mathbf{P}|}'^*\}$ for the second stage given a mean value prediction. The model for the current stage is as follows:

$$\max \textstyle\sum_{r \in \mathbf{R}} D_r \beta_r + h(\boldsymbol{\beta}, \boldsymbol{\gamma}) \tag{27}$$

subject to

$$\sum_{p\in\mathbf{P}}\gamma_p \leq M \tag{28}$$

$$y_{ri}=\gamma_{p_{ri}}, r\in\mathbf{R}, i\in\mathbf{I}_r, p\in\mathbf{P} \tag{29}$$

$$\beta_r \leq \sum_{i=1}^{|\mathbf{I}_r|} y_{ri}, r\in\mathbf{R}_1 \tag{30}$$

$$u_{rii'} \leq y_{ri},\ r\in\mathbf{R}_2,\ i\in\mathbf{I}_r,\ i'\in\mathbf{I}_r,\ i\neq i',\ a_{rii'}\in\mathbf{A}_r \tag{31}$$

$$\sum_{a_{rii'}\in\mathbf{A}_{ri}} u_{rii'} \leq 1, i\in\mathbf{I}_r, r\in\mathbf{R}_2 \tag{32}$$

$$\sum_{a_{rii'}\in\mathbf{A}_{ri}} u_{rii'} = \sum_{a_{ri'i}\in\mathbf{A}_r} u_{ri'i}, i\in\mathbf{I}_r, r\in\mathbf{R}_2 \tag{33}$$

$$\left\lceil\frac{\sum_{i\in\mathbf{I}_r} l_{ri}}{L}\right\rceil \beta_r \leq \sum_{a_{rii'}\in\mathbf{A}_r} u_{rii'}, r\in\mathbf{R}_2 \tag{34}$$

$$u_{rii'}\in\{0,1\},\ r\in\mathbf{R}_2,\ i\in\mathbf{I}_r,\ i'\in\mathbf{I}_r,\ i\neq i',\ a_{rii'}\in\mathbf{A}_r \tag{35}$$

$$y_{ri}\in\{0,1\}, r\in\mathbf{R}, i\in\mathbf{I}_r \tag{36}$$

$$\gamma_p\in\{0,1\}, p\in\mathbf{P} \tag{37}$$

$$\beta_r\in\{0,1\}, r\in\mathbf{R} \tag{38}$$

Under the projected mean value of future funding, the maximum number of ships with available hydrogen energy can be calculated as follows:

$$h(\boldsymbol{\beta},\boldsymbol{\gamma}) = \max \sum_{r\epsilon\mathbf{R}} D_r\,\beta_r' \tag{39}$$

subject to

$$\beta_r' \leq 1-\beta_r, r\in\mathbf{R} \tag{40}$$

$$\sum_{p\in\mathbf{P}}\gamma_p' \leq N \tag{41}$$

$$\gamma_p+\gamma_p' \leq 1, p\in\mathbf{P} \tag{42}$$

$$y_{ri}'=\gamma_{p_{ri}}+\gamma_{p_{ri}}',\ r\in\mathbf{R},\ i\in\mathbf{I}_r,\ p\in\mathbf{P} \tag{43}$$

$$\beta_r' \leq \sum_{i=1}^{|\mathbf{I}_r|} y_{ri}', r\in\mathbf{R}_1 \tag{44}$$

$$u'_{rii'} \leq y'_{ri}, r \in \mathbf{R}_2, i \in \mathbf{I}_r, i' \in \mathbf{I}_r, i \neq i', a_{rii'} \in \mathbf{A}_r \tag{45}$$

$$\sum_{a_{rii'} \in \mathbf{A}_{ri}} u'_{rii'} \leq 1, r \in \mathbf{R}_2, i \in \mathbf{I}_r \tag{46}$$

$$\sum_{a_{rii'} \in \mathbf{A}_{ri}} u'_{rii'} = \sum_{a_{ri'i} \in \mathbf{A}_r} u'_{ri'i}, r \in \mathbf{R}_2, i \in \mathbf{I}_r \tag{47}$$

$$\left\lceil \frac{\sum_{i \in \mathbf{I}_r} l_{ri}}{L} \right\rceil \beta'_r \leq \sum_{a_{rii'} \in \mathbf{A}_r} u'_{rii'}, r \in \mathbf{R}_2 \tag{48}$$

$$u'_{rii'} \in \{0,1\}, r \in \mathbf{R}_2, i \in \mathbf{I}_r, i' \in \mathbf{I}_r, i \neq i', a_{rii'} \in \mathbf{A}_r \tag{49}$$

$$y'_{ri} \in \{0,1\}, r \in \mathbf{R}, i \in \mathbf{I}_r \tag{50}$$

$$\gamma'_p \in \{0,1\}, p \in \mathbf{P} \tag{51}$$

$$\beta'_r \in \{0,1\}, r \in \mathbf{R}. \tag{52}$$

Based on the optimal solution $\boldsymbol{\beta}^*$ and $\boldsymbol{\gamma}^*$ from the current stage, we can further solve for the optimal solution value $h^*(\boldsymbol{\beta}^*, \boldsymbol{\gamma}^*, s)$ if scenarios s is finally realized in the second stage in the future, shown as in model (13)–(26). The final objective function value for this two-stage deterministic programming model is $\sum_{r \in \mathbf{R}} D_r \beta_r^* + \sum_{s \in \mathbf{S}} \alpha_s \sum_{r \in \mathbf{R}} D_r \beta_{r,s}^*$.

While the two-stage deterministic strategy accounts for future uncertainties and guides decision-makers toward prudent long-term choices, it can overlook substantial future fluctuations, and extreme conditions or marked variations across scenarios can be challenging. Thus, a more adaptive and comprehensive method is required. We therefore introduce the two-stage stochastic strategy. This recognizes the unpredictability of future scenarios and enables decision-makers to formulate strategies that are resilient to various possible outcomes.

4.3. Two-Stage Stochastic Strategy and its Model

The two-stage stochastic strategy not only takes into account the current stage and the second stage in the future and their interrelated impacts, but also incorporates various future scenarios. This approach enables decision-makers to navigate future uncertainties more effectively while holistically considering all stages.

The current-stage model is as follows:

$$\max \sum_{r\in\mathbf{R}} D_r\beta_r + \sum_{s\in\mathbf{S}} \alpha_s \cdot h(\boldsymbol{\beta},\boldsymbol{\gamma},s) \tag{53}$$

subject to

$$\sum_{p\in\mathbf{P}} \gamma_p \leq M \tag{54}$$

$$y_{ri} = \gamma_{p_{ri}},\ r\in\mathbf{R},\ i\in\mathbf{I}_r,\ p\in\mathbf{P} \tag{55}$$

$$\beta_r \leq \sum_{i=1}^{|\mathbf{I}_r|} y_{ri}, r\in\mathbf{R}_1 \tag{56}$$

$$u_{rii'} \leq y_{ri},\ r\in\mathbf{R}_2,\ i\in\mathbf{I}_r,\ i'\in\mathbf{I}_r,\ i\neq i',\ a_{rii'}\in\mathbf{A}_r \tag{57}$$

$$\sum_{a_{rii'}\in\mathbf{A}_{ri}} u_{rii'} \leq 1, i\in\mathbf{I}_r, r\in\mathbf{R}_2 \tag{58}$$

$$\sum_{a_{rii'}\in\mathbf{A}_{ri}} u_{rii'} = \sum_{a_{ri'i}\in\mathbf{A}_r} u_{ri'i}, i\in\mathbf{I}_r, r\in\mathbf{R}_2 \tag{59}$$

$$\left\lceil\frac{\sum_{i\in\mathbf{I}_r} l_{ri}}{L}\right\rceil \beta_r \leq \sum_{a_{rii'}\in\mathbf{A}_r} u_{rii'}, r\in\mathbf{R}_2 \tag{60}$$

$$u_{rii'}\in\{0,1\},\ r\in\mathbf{R}_2,\ i\in\mathbf{I}_r,\ i'\in\mathbf{I}_r,\ i\neq i',\ a_{rii'}\in\mathbf{A}_r \tag{61}$$

$$y_{ri}\in\{0,1\}, r\in\mathbf{R}, i\in\mathbf{I}_r \tag{62}$$

$$\gamma_p\in\{0,1\}, p\in\mathbf{P} \tag{63}$$

$$\beta_r\in\{0,1\}, r\in\mathbf{R}. \tag{64}$$

We define decision variable solutions at the current stage as $\boldsymbol{\beta} = (\beta_1,\ldots,\beta_r,\ldots,\beta_{|\mathbf{R}|})$ and $\boldsymbol{\gamma} = (\gamma_1,\ldots,\gamma_p,\ldots,\gamma_{|\mathbf{P}|})$. The objective function (53) consists of two parts:

$\sum_{r\in\mathbf{R}} D_r\beta_r$ denotes the number of ships using hydrogen energy when the maximum number M of hydrogen refueling hubs can be deployed in the current stage; $\alpha_s \cdot h(\boldsymbol{\beta},\boldsymbol{\gamma},s)$ denotes the number of ships using hydrogen energy when the occurrence probability of the scenario s ($s \in \mathbf{S}$) is α_s, and $h(\boldsymbol{\beta},\boldsymbol{\gamma},s)$ is the optimal objective function value under scenarios s for the second stage in the future.

In the second-stage model, for scenario s ($s \in \mathbf{S}$), the maximum number of ships with available hydrogen energy can be calculated as follows:

$$h(\boldsymbol{\beta},\boldsymbol{\gamma},s) = \max \sum_{r\in\mathbf{R}} D_r\, \beta'_{r,s} \tag{65}$$

subject to

$$\beta'_{r,s} \le 1-\beta_r, r \in \mathbf{R} \tag{66}$$

$$\sum_{p\in\mathbf{P}} \gamma'_{p,s} \le N_s \tag{67}$$

$$\gamma_p + \gamma'_{p,s} \le 1, p \in \mathbf{P} \tag{68}$$

$$y'_{ri,s} = \gamma_{p_{ri}} + \gamma'_{p_{ri},s}, r \in \mathbf{R}, i \in \mathbf{I}_r, p \in \mathbf{P} \tag{69}$$

$$\beta'_{r,s} \le \sum_{i=1}^{|\mathbf{I}_r|} y'_{ri,s}\,, r \in \mathbf{R}_1 \tag{70}$$

$$u'_{rii',s} \le y'_{ri,s}, r \in \mathbf{R}_2, i \in \mathbf{I}_r, i' \in \mathbf{I}_r, i \ne i', a_{rii'} \in \mathbf{A}_r \tag{71}$$

$$\sum_{a_{rii'}\in\mathbf{A}_{ri}} u'_{rii',s} \le 1, i \in \mathbf{I}_r, r \in \mathbf{R}_2 \tag{72}$$

$$\sum_{a_{rii'}\in\mathbf{A}_{ri}} u'_{rii',s} = \sum_{a_{ri'i}\in\mathbf{A}_r} u'_{ri'i,s}\,, i \in \mathbf{I}_r, r \in \mathbf{R}_2 \tag{73}$$

$$\left\lceil \frac{\sum_{i\in I_r} l_{ri}}{L} \right\rceil \beta'_{r,s} \le \sum_{a_{rii'}\in\mathbf{A}_r} u'_{rii',s}\,, r \in \mathbf{R}_2 \tag{74}$$

$$u'_{rii',s} \in \{0,1\}, a_{rii'} \in \mathbf{A}_r, r \in \mathbf{R}_2, i \in \mathbf{I}_r, i' \in \mathbf{I}_r, i \ne i' \tag{75}$$

$$y'_{ri,s} \in \{0,1\}, r \in \mathbf{R}, i \in \mathbf{I}_r \tag{76}$$

$$\gamma'_{p,s} \in \{0,1\}, p \in \mathbf{P} \tag{77}$$

$$\beta'_{r,s} \in \{0,1\}, r \in \mathbf{R}. \quad (78)$$

The objective function (65) represents the maximum number of ships that can use hydrogen energy under scenario s. Constraints (66)– (78) ensure adherence to resource limitations and the stipulation that whether routes are compatible with hydrogen energy. These constraints mandate that the deployment of hydrogen refueling hubs aligns with the establishment of “hydrogen-energy-capable routes”.

The two-stage stochastic strategy has the advantage of providing a framework that considers resource constraints not only in the current stage but across a range of possible future scenarios. This comprehensive approach guarantees that planning decisions are adaptive and resilient and can manage various changes in future. Thus, it effectively reconciles immediate needs with long-term goals, and by achieving a balance, it can often outperform traditional models.

5. Case Study

In this section, we consider a real-world case study and conduct computational experiments to evaluate the efficacy of the three strategies. Our comparative analysis yields essential managerial insights, providing actionable guidance for real-world operations. Our models were constructed and executed in the Python programming environment, and the optimization models were solved by Gurobi 9.1.0.

5.1. Parameter Setting

We focus on the shipping network along the Yangtze River, which comprises 13 ports (their full names and abbreviations are given in Table A.1 of Appendix A), as shown in Figure 4. The waterway consists of 14 shipping routes that connect these ports, as indicated in Table 2 (Wang et al., 2022). The traveling distances between any two ports along the river are provided in Table 3.

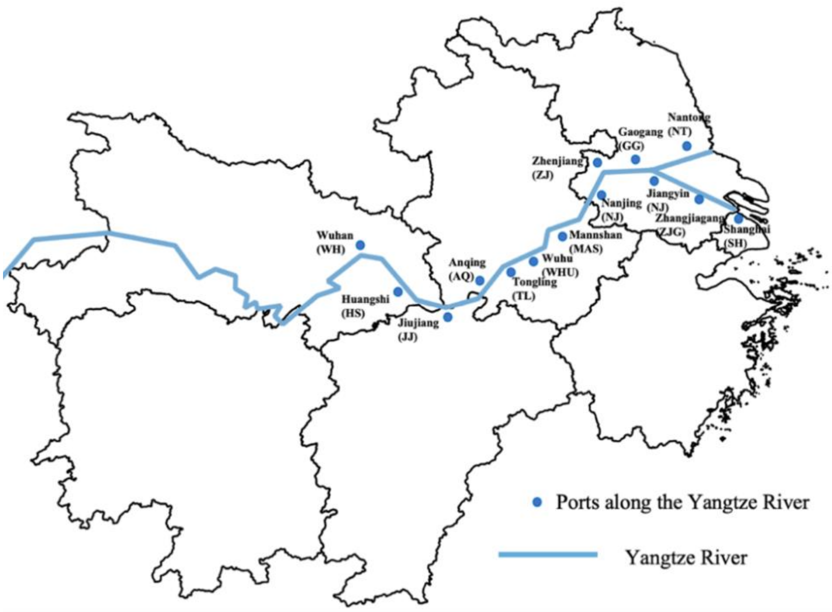

Figure 4. Physical ports along the Yangtze River.

Following the literature, we assume that ships deployed on the same shipping route arrive at each port of call at the same time each week (Meng et al., 2014), and the traveling speed of each ship is 10.5 knots (Wang et al., 2022; Elmi et al., 2023). The ships also have specific handling requirements in the ports, and the handling hours vary according to the ports. The handling time at each port, denoted by O_p $(p \in P)$, is shown in Table A.2 of Appendix A. Thus, the number of ships deployed on each shipping route is influenced by the length of the shipping route and the handling hours of involved the ports of call, and is calculated as $\left\lceil \frac{\sum_{i \in I_r} l_{ri} \div 10.5 + \sum_{i \in I_r} O_{p_{ri}}}{7 \times 24} \right\rceil, i \in I_r, r \in$ R, which is shown in Table A.3 of Appendix A.

Table 2. Shipping routes along the Yangtze River.

No.	Route
1	WH→HS→JJ→NJ→TC→SH→TC→NJ→JJ→HS→WH
2	WH→HS→AQ→NJ→AQ→HS→WH
3	WH→AQ→WH
4	HS→JJ→WHU→SH→WHU→JJ→HS
5	AQ→TL→TC→SH→TC→TL→AQ
6	WHU→NJ→SH→NJ→WHU
7	NJ→SH→NJ
8	ZJ→ZJG→TC→ZJG→ZJ
9	ZJ→TC→SH→TC→ZJ
10	JY→ZJG→TC→SH→TC→ZJG→JY
11	JY→TC→SH→TC→JY
12	ZJG→NT→TC→SH→TC→NT→ZJG
13	ZJG→NT→SH→NT→ZJG
14	TC→SH→TC

Table 3. Traveling distances between ports (nautical miles) (Wang et al., 2022).

Ports	WH	HS	JJ	AQ	TL	WHU	NJ	ZJ	JY	ZJG	NT	TC	SH
WH	0	77.2	145.2	233.8	285.6	344.0	395.8	442.8	505.9	515.7	538.3	579.8	607.5
HS	77.2	0	68.0	156.6	208.4	266.7	318.6	365.6	428.7	438.5	461.1	502.6	530.2
JJ	145.2	68.0	0	88.6	140.4	198.7	250.6	297.5	360.7	370.4	393.1	434.6	462.2
AQ	233.8	156.6	88.6	0	51.8	110.2	162.0	209.0	272.2	281.9	304.6	346.0	373.7
TL	285.6	208.4	140.4	51.8	0	58.3	110.2	157.1	220.3	230.0	252.7	294.2	321.8
WHU	344.0	266.7	198.7	110.2	58.3	0	51.8	98.8	162.0	171.7	194.4	235.9	263.5
NJ	395.8	318.6	250.6	162.0	110.2	51.8	0	47.0	110.2	119.9	142.6	184.0	211.7
ZJ	442.8	365.6	297.5	209.0	157.1	98.8	47.0	0	63.2	72.9	95.6	137.0	164.7
JY	505.9	428.7	360.7	272.2	220.3	162.0	110.2	63.2	0	9.7	32.4	73.9	101.5
ZJG	515.7	438.5	370.4	281.9	230.0	171.7	119.9	72.9	9.7	0	22.7	64.2	133.3
NT	538.3	461.1	393.1	304.6	252.7	194.4	142.6	95.6	32.4	22.7	0	41.5	69.1
TC	579.8	502.6	434.6	346.0	294.2	235.9	184.0	137.0	73.9	64.2	41.5	0	27.6
SH	607.5	530.2	462.2	373.7	321.8	263.5	211.7	164.7	101.5	133.3	69.1	27.6	0

Following Bicer et al. (2018), we set the maximum distance a ship can travel after a full hydrogen fill-up as 260 nm. We evaluated various hydrogen refueling hubs and found that the most cost-effective in terms of construction cost was the externally supplied high-pressure hydrogen refueling hub (Baronas et al., 2018). We therefore regard the construction cost of this specific hub as the deployment cost, which is estimated at the current stage as approximately $2,000,000.

5.2. Solutions of the Three Strategies

Currently, a fund of $6,000,000 is available for the deployment of hydrogen refueling hubs. Given this budget, the maximum number of hubs that can be deployed at this stage is three. We assume that the maximum numbers of hydrogen refueling hubs deployable under various future scenarios, along with the associated probabilities, are detailed in Table 4.

Table 4. Maximum number of hubs and related probability in the future.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Maximum number of hubs (N_s)	0	1	2	3
Probability (α_s)	0.1	0.3	0.4	0.2

In this case study, Table 5 presents both the number of ships associated with each route and the specific sets of physical ports needed to deploy each route as a "hydrogen-energy-capable route", as identified by the arc-based model. Importantly, there may be multiple sets of physical ports that enable a route to achieve the status of a "hydrogen-energy-capable route".

Table 5. The set of physical ports and the number of ships for each route.

Route	Set of ports	Number of ships	Route	Set of ports	Number of ships
1	{2,3,7,12}	3	8	{8,10}, {10,12}	1
2	{1,4,7}, {2,4,7}	2	9	{8,12}	2
3	{1,4}, {4}	1	10	{12}	2
4	{3,6}	2	11	{12}	1
5	{12}, {5}	2	12	{10}, {11}, {12}, {13}	2
6	{7,13}	1	13	{10}, {11}, {13}	1
7	{7,13}	1	14	{12}	1

Figure 5 presents the results of the three strategies. The y-axis displays the number of ships using hydrogen energy across the strategies, reflecting both current and future scenarios. The x-axis denotes the various decision stages linked with the three strategies, including the current stage, potential future scenarios, and overall long-term effect. By analyzing the weighted-sum objective function values for the overall long-term effect, we find that the two-stage stochastic strategy is superior. However, its performance in the current stage is inferior to that of the other strategies. This highlights the significant influence of future uncertainties on present-day planning.

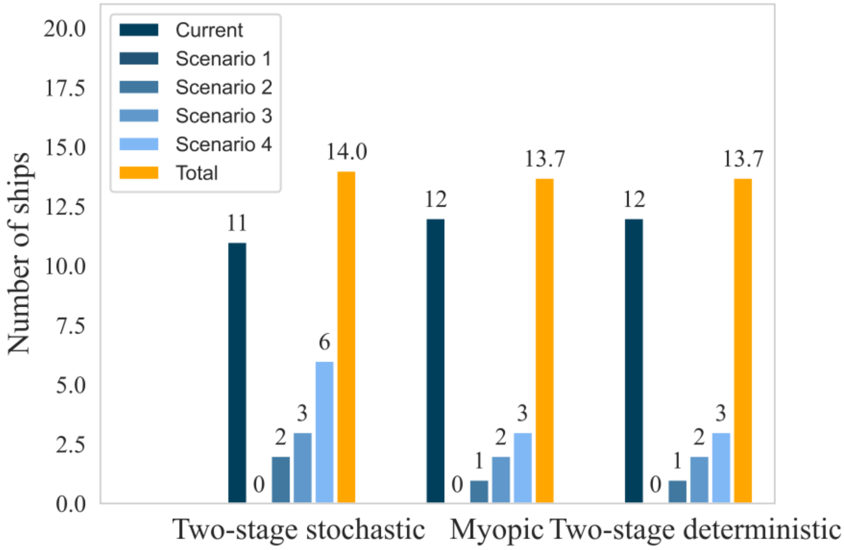

Figure 5. The results of three strategies.

The optimal solutions for the three strategies are detailed in Table A.4 and A.5 of Appendix A, including both ports in which the hydrogen hubs should be deployed and the routes that enable ships to use hydrogen. In Table A.4 and A.5 of Appendix, a value of 1 indicates a decision to deploy a hydrogen refueling hub or to designate a route as hydrogen-energy-capable. These solutions offer the best choices for the deployment of hydrogen refueling hubs and the designation of hydrogen-energy-capable routes for the current stage and for potential future scenarios under the three strategies. Notably, the myopic strategy and the two-stage deterministic strategy yield identical results.

The difference observed in the two-stage stochastic strategy, as opposed to the other two, stems from unique decisions taken in the current phase. Specifically, the two-stage stochastic strategy opts for hydrogen refueling stations at physical ports 7, 12, and 13, enabling routes 5, 6, 7, 11, 12, 13, and 14 as hydrogen-energy-capable. In contrast, the myopic and two-stage deterministic strategies select physical ports 8, 10, and 12, making routes 5, 8, 9, 10, 11, 12, 13, and 14 hydrogen-energy-capable. Hence, at this stage, the divergences in outcomes across the scenarios primarily arise from routes 6 and 7 versus routes 8 and 9. These initial decisions will significantly influence future choices. In the two-stage stochastic strategy, the current stage's choices are intentionally made more flexible, paving the way for more adaptive and effective decision making in subsequent stages.

5.3. Robustness Tests

The two-stage stochastic strategy detailed in Section 5.2 outperforms the other strategies. To further test the robustness of our results concerning its superior performance, we conduct various groups of experiments by adjusting parameters such as the shipping networks, future uncertainty, and the probabilities of future scenarios.

(1) Comparison under different shipping networks.

We present a shipping network consisting of 14 routes in Section 5.1. We investigate other networks by selecting different numbers of routes from the original 14 while keeping the other parameters consistent. The settings for the various groups of routes are shown in Table A.6 of Appendix A. The solutions obtained from the three strategies are illustrated in Figure 6.

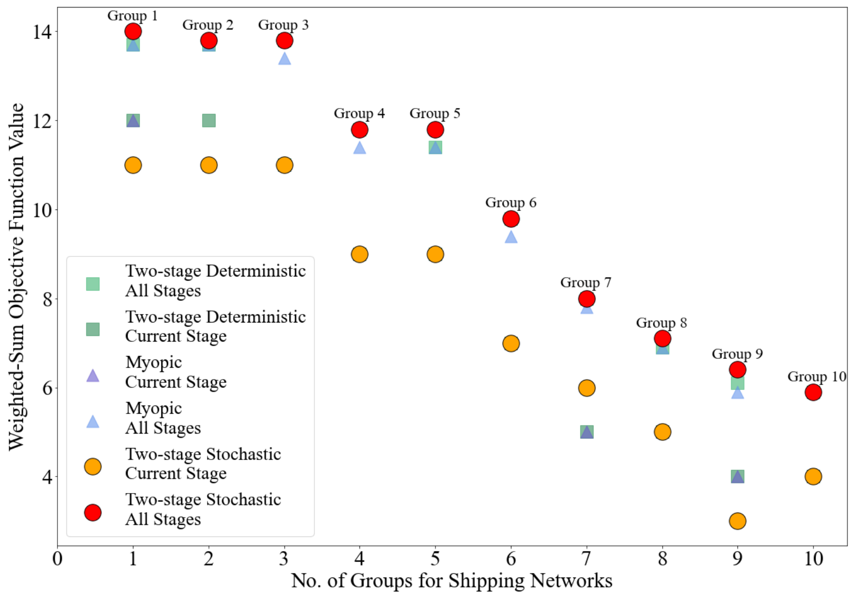

Figure 6. Comparison of three strategies under different shipping networks.

Across all groups, the two-stage stochastic strategy reliably surpasses the other two strategies in long-term performance. This advantage is sometimes achieved at the expense of immediate returns, as evidenced in Groups 1, 2, and 9. Conversely, there are groups where the two-stage stochastic strategy not only achieves short-term outcomes as good as those of the alternative strategies but also delivers significantly enhanced long-term benefits, as seen in Groups 3, 4, 5, and 6. Furthermore, in Group 7, the two-stage stochastic strategy not only matches the long-term benefits of the other strategies but also provides significantly superior short-term advantages. Consequently, the two-stage stochastic strategy maintains a distinct edge across varying route combinations, underscoring the model's robustness and stability.

(2) Comparison under different situations without uncertainty

We have organized the maximum number of hydrogen hubs (N_S) that can be deployed in the future into seven distinct groups. Each group specifically enables the deployment of 1, 2, 3, 4, 5, 6, and 7 hydrogen hubs, respectively. For all groups, we assume a definite likelihood of reaching these maximum numbers, with a probability of 1. Actually, this represents that the two-stage stochastic strategy resembles the two-stage deterministic strategy in these groups. Our focus is thus to compare the performance of myopic and two-stage strategies. The outcomes of the three strategies are illustrated in Figure 7.

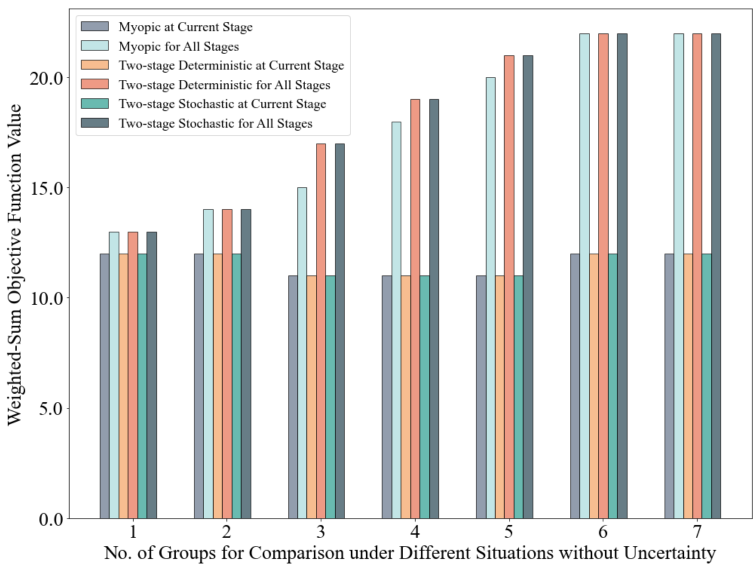

Figure 7. Comparison of three strategies different situations without uncertainty.

The performance of the three strategies remains consistent in situations where the funding for establishing hydrogen refueling hubs is either severely limited or exceptionally abundant, as seen in Groups 1, 2, 6, and 7. This uniformity stems from the lack of room for improvement under extreme resource constraints or overabundance. In resource-scarce conditions, the limited funds do not allow for significant strategic variation, while in resource-abundant situations, the saturation of “hydrogen-energy-capable routes” eliminates the need for distinct strategies.

However, in other situations, like Groups 3, 4, and 5, the two-stage deterministic and stochastic strategies exhibit significant benefits. Despite similar results in the present stage across all strategies, these two strategies stand out in their long-term effects. This is because they integrate current stage considerations into future strategy, leading to identical results in scenarios with no future uncertainty (i.e., where only one future scenario is considered). This finding highlights the necessity of considering future-stage impacts in deploying hydrogen hubs. It emphasizes that strategic planning should extend beyond immediate effects to include potential future scenarios, underscoring the need for a comprehensive approach that encompasses both present circumstances and future possibilities.

(3) Comparison under different situations with uncertainty

We maintained the same parameter settings as those in case (2) of Section 5.3 but established two scenarios for the number of hydrogen hubs in future deployment. Each scenario is characterized by a probability of 0.5, as detailed in Table A.7 of Appendix A. Following these adjustments, we readdressed the problem. The results obtained from employing the three strategies under these new settings are illustrated in Figure 8.

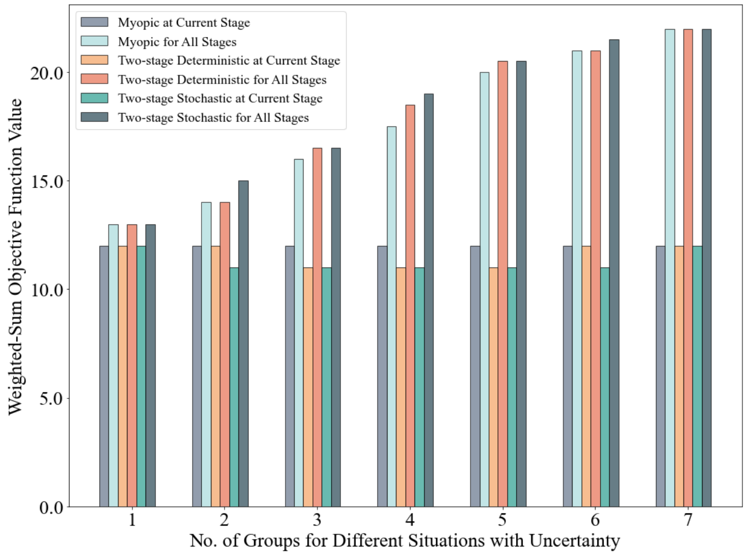

Figure 8. Comparison of three strategies under different situations with uncertainty.

When the impact of uncertainty is not considered, the two-stage deterministic and stochastic strategies display identical performance, both outperforming the myopic strategy. However, when simple probabilities are introduced, a divergence in the performance of the two-stage deterministic and stochastic strategies becomes evident. For instance, in Groups 2, 4 and 6 in Figure 8, the two-stage stochastic strategy demonstrates superior long-term performance (across all stages), despite potential minor sacrifices in the current stage. This observation indicates that when future uncertainty exists, a phased deterministic model (like the two-stage deterministic strategy) may not be able to produce efficient outcomes. It highlights the need for further considering uncertainty to enhance decision making in two-stage problems.

(4) Comparison under different probabilities

We preserved the parameter settings of Groups 2, 3, and 4 as specified in case (3) of Section 5.3 but varied the probability of the cost for hydrogen hubs' deployment to further examine its impact on the three strategies. This adjustment is detailed in Table A.8 of Appendix A. The results derived from these revised conditions are depicted in Figure 9.

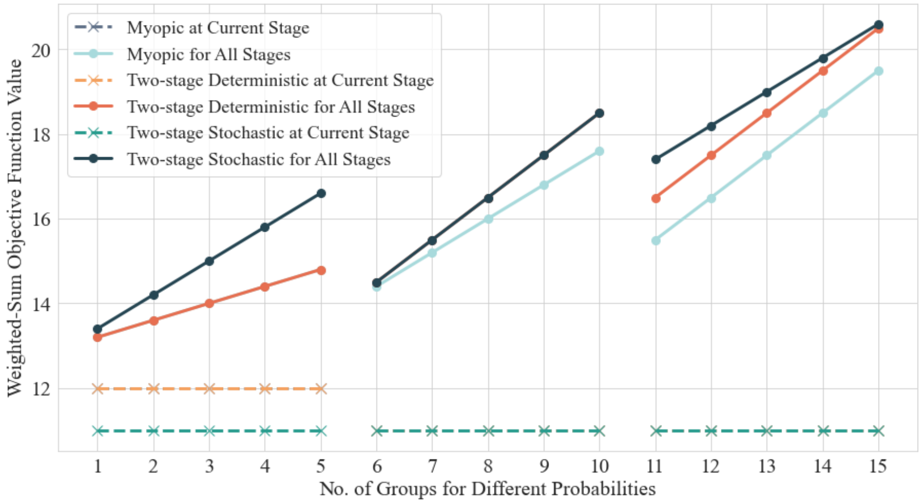

Figure 9. Comparison of three strategies under different probabilities.

In case (3) of Section 5.3, the two-stage stochastic strategy demonstrates superior performance over the other two strategies in Groups 2 and 4. However, in Group 3, the two-stage stochastic and deterministic strategies exhibit identical performance. This pattern of similarity is maintained under the revised conditions, as depicted in Figure 9. This consistency suggests that variations in the probabilities do not significantly impact the relative effectiveness of the strategies. Furthermore, while these probability changes do not significantly alter the strategies' relative effectiveness, they do result in fluctuations in the optimal value of the objective function across all groups.

5.4. Policy Implications

5.4.1 Strategic Framework for Financial Planning

1. Adaptive financial strategy in uncertain investment climates.

The maritime industry's transition towards green shipping, specifically through the integration of hydrogen fuel in inland waterways, presents both operational and financial challenges. Our study's two-stage stochastic strategy emphasizes the need for flexible and robust financial planning in this context. This approach outperforms the myopic and deterministic strategies by accommodating uncertain investment climates and ensuring the economic viability of hydrogen integration.

- Policy Recommendation: Governments and maritime authorities should adopt this two-stage stochastic framework for financial planning in hydrogen hub deployment. This method considers the unpredictability of future funding and allows for adjustments according to changing financial landscapes. By doing so, it mitigates the risk of suboptimal investments and maximizes the utilization of available funds.

2. Phased implementation strategy.

Given the operational constraints and financial limitations, a phased approach to deploying hydrogen refueling hubs is prudent. This strategy allows for the gradual rollout of infrastructure, in alignment with available funding and operational readiness.

- Policy Recommendation: Implementing a phased strategy for hydrogen hub deployment would enable maritime sectors to progressively adapt to green shipping initiatives. This approach should be guided by a detailed anticipatory planning process that accounts for both current financial constraints and potential future funding scenarios, as demonstrated in our case study with the Yangtze River shipping network.

5.4.2 Aligning with Environmental Goals

1. Sustainable transition to renewable energy sources.

This study proposes a viable method for integrating renewable energy sources, such as hydrogen, into the maritime sector. In the early phases, these renewable energy sources are particularly apt for inland waterway transport, considering the complex interplay of interests among different nations for international shipping. To facilitate the adoption of hydrogen as a fuel source in more ships, this study has developed an arc-based model that is anchored in a network of frequently used shipping routes. Moreover, the adoption of renewable energies often confronts substantial financial challenges and investment uncertainties. The phased stochastic approach outlined in this study offers a strategy to alleviate financial burdens while concurrently enhancing the utilization of renewable fuels in the maritime sector.

- Policy Recommendation: Policymakers are advised to develop a framework that facilitates the maritime industry's shift to renewable energy sources, such as hydrogen. This framework should encompass not only financial incentives but also regulatory policies that motivate the implementation of eco-friendly technologies and practices. These initiatives will ensure a sustainable transition, while also guaranteeing the economic and operational feasibility of adopting renewable fuel.

6. Conclusions and Future Research Directions

In this study, we propose a viable approach for integrating hydrogen energy into maritime transport within inland waterway systems. The critical aspect of our approach is the seamless integration of hydrogen refueling hubs within existing port infrastructures, aligning them with the prevailing shipping networks and timetables to ensure a continuous demand fulfillment. Our research proposes an arc-based model designed to sustain uninterrupted operations within the existing maritime network.

To address the challenges posed by the variability and uncertainty in future, our study introduces and compares three strategic approaches: a myopic strategy, a two-stage deterministic strategy, and a two-stage stochastic strategy. We utilize data from the Yangtze River shipping network for an in-depth comparative analysis of these strategies. The results indicate that the two-stage stochastic strategy is superior, offering a robust and comprehensive framework for long-term planning in the sector. This strategy adeptly navigates future uncertainties, effectively reducing the financial load on governmental bodies and curtailing resource wastage. Our approach not only amplifies the environmental benefits but also presents a scalable and adaptable solution for incorporating various other renewable energy sources into the maritime industry.

We provide three future research areas below. Firstly, an in-depth examination of the multifaceted nature of uncertainty in funding is essential. The potential variations in investment scenarios, driven by shifts in the environmental landscape, present a significant challenge in accurately predicting the outcomes. Furthermore, the implementation of hydrogen refueling hubs across multiple ports will likely necessitate a phased planning approach, adding layers to the financial complexity. Future studies should aim to develop a model that more accurately reflects the challenges and uncertainties of such large-scale infrastructure projects in the maritime sector, potentially including predictive analytics and scenario planning to better prepare for various future states.

Secondly, the study’s scope could broaden from inland waterway transportation to encompass international shipping, necessitating a strategic exploration of the complex negotiations among nations with diverging interests. An in-depth analysis within this expanded context is crucial for developing feasible and adaptable strategies that support the international maritime industry’s transition to clean energy.

Furthermore, our present study concentrates on strategic considerations from the government’s viewpoint, deliberately without optimizing the ship type, fleet size, and ship speed from the perspective of shipping companies. Future research could explore the design of shipping networks and the scheduling of shipping operations for shipping companies. This could be done in a two-level model that simultaneously consider government initiatives and shipping company responses. Such a shift in perspective will allow for a more detailed and company-specific approach to maritime operations within the evolving framework of hydrogen fuel infrastructure.

References

Alumur, S., & Kara, B. Y. (2008). Network hub location problems: The state of the art. European Journal of Operational Research, 190(1), 1–21.

Anderson, B., Den Boer, E., Ng, S., Dunlap, L., Hon, G., Nelissen, D., & Ray, J. (2015). Study of emission control and energy efficiency measures for ships in the port area. Retrieved from International Maritime Organization (IMO), London, UK, 24, 52.

Apostolou, D., & Xydis, G. (2019). A literature review on hydrogen refueling stations and infrastructure: Current status and future prospects. Renewable and Sustainable Energy Reviews, 113, 109292.

Atilhan, S., Park, S., El-Halwagi, M. M., Atilhan, M., Moore, M., & Nielsen, R. B. (2021). Green hydrogen as an alternative fuel for the shipping industry. Current Opinion in Chemical Engineering, 31, 100668.

Baykara, S. Z. (2018). Hydrogen: A brief overview on its sources, production, and environmental impact. International Journal of Hydrogen Energy, 43(23), 10605–10614.

Bach, H., Bergek, A., Bjørgum, Ø., Hansen, T., Kenzhegaliyeva, A., & Steen, M. (2020). Implementing maritime battery-electric and hydrogen solutions: A technological innovation systems analysis. Transportation Research Part D: Transport and Environment, 87, 102492.

Bicer, Y., & Dincer, I. (2018). Environmental impact categories of hydrogen and ammonia driven transoceanic maritime vehicles: A comparative evaluation. International Journal of Hydrogen Energy, 43(9), 4583–4596.

Baronas, J., & Achtelik, G. (2018). Joint agency staff report on assembly bill 8: 2018 annual assessment of time and cost needed to attain 100 hydrogen refueling stations in California. California Energy Commission.

Boucher, O., Friedlingstein, P., Collins, B., & Shine, K. P. (2009). The indirect global warming potential and global temperature change potential due to methane oxidation. Environmental Research Letters, 4(4), 044007.

Brown, G., Carlyle, M., Salmerón, J., & Wood, K. (2006). Defending critical infrastructure. Interfaces, 36(6), 530-544.

Campbell, J. F., & O’Kelly, M. E. (2012). Twenty-five years of hub location research. Transportation Science, 46(2), 153–169.

Cetinkaya, E., Dincer, I., & Naterer, G. F. (2012). Life cycle assessment of various hydrogen production methods. International Journal of Hydrogen Energy, 37(3), 2071–2080.

Christiansen, M., Hellsten, E., Pisinger, D., Sacramento, D., & Vilhelmsen, C. (2020). Liner shipping network design. European Journal of Operational Research, 286(1), 1–20.

Chua, Y. J., Soudagar, I., Ng, S. H., & Meng, Q. (2023). Impact analysis of environmental policies on shipping fleet planning under demand uncertainty. Transportation Research Part D: Transport and Environment, 120, 103744.

Cullinane, K., & Chang, Y. T. (2023). Editorial–Alternative fuels and energy sources for shipping. Transportation Research Part D: Transport and Environment, 103885.

Duynslaegher, C. (2011). Experimental and numerical study of ammonia combustion. Doctoral dissertation, University of Leuven.

Elmi, Z., Li, B., Fathollahi-Fard, A. M., Tian, G., Borowska-Stefańska, M., Wiśniewski, S., & Dulebenets, M. A. (2023). Ship schedule recovery with voluntary speed reduction zones and emission control areas. Transportation Research Part D: Transport and Environment, 125, 103957.

Fadda, P., Fancello, G., Mancini, S., Pani, C., & Serra, P. (2020). Design and optimization of an innovative two-hub-and-spoke network for the Mediterranean short-sea-shipping market. Computers & Industrial Engineering, 149, 106847.

Farahani, R. Z., Hekmatfar, M., Arabani, A. B., & Nikbakhsh, E. (2013). Hub location problems: A review of models, classification, solution techniques, and applications. Computers & Industrial Engineering, 64(4), 1096–1109.

Fridell, E., Salberg, H., & Salo, K. (2021). Measurements of emissions to air from a marine engine fueled by methanol. Journal of Marine Science and Application, 20, 138–143.

Goldman, A. J. (1969). Optimal locations for centers in a network. Transportation Science, 3(4), 352–360.

Gore, K., Rigot-Müller, P., & Coughlan, J. (2022). Cost assessment of alternative fuels for maritime transportation in Ireland. Transportation Research Part D: Transport and Environment, 110, 103416.

Hernández, B., Alkayas, A., Azar, E., & Mayyas, A. T. (2021). Mathematical model for the placement of hydrogen refueling stations to support future fuel cell trucks. IEEE Access, 9, 148118–148131.

Kosmas, V., & Acciaro, M. (2017). Bunker levy schemes for greenhouse gas (GHG) emission reduction in international shipping. Transportation Research Part D: Transport and Environment, 57, 195-206.

Kuvvetli, Y. (2020). Multi-objective and multi-period hydrogen refueling station location problem. International Journal of Hydrogen Energy, 45(55), 30845–30858.

Joung, T. H., Kang, S. G., Lee, J. K., & Ahn, J. (2020). The IMO initial strategy for reducing Greenhouse Gas (GHG) emissions, and its follow-up actions towards 2050. Journal of International Maritime Safety, Environmental Affairs, and Shipping, 4(1), 1–7.

Laval, A., Hafnia, H. T., & Vestas, S. G. (2020). Ammonfuel—an industrial view of ammonia as a marine fuel. Hafnia, 7, 32–59.

Leonida, C. (2020). Power play. Engineering and Mining Journal, 221(6), 62–67.

Lewis, A. C. (2021). Optimizing air quality co-benefits in a hydrogen economy: A case for hydrogen-specific standards for NO_x emissions. Environmental Science: Atmospheres, 1(5), 201–207.

McKinlay, C. J., Turnock, S. R., & Hudson, D. A. (2021). Route to zero emission shipping: Hydrogen, ammonia or methanol? International Journal of hydrogen energy, 46(55), 28282–28297.

Meng, Q., Wang, S., Andersson, H., & Thun, K. (2014). Containership routing and scheduling in liner shipping: Overview and future research directions. Transportation Science, 48(2), 265-280.

Parkinson, B., Balcombe, P., Speirs, J. F., Hawkes, A. D., & Hellgardt, K. (2019). Levelized cost of CO 2 mitigation from hydrogen production routes. Energy & Environmental Science, 12(1), 19–40.

Raucci, C. (2017). The Potential of Hydrogen to Fuel International Shipping (Doctoral dissertation, UCL (University College London)).

Rose, P. K., & Neumann, F. (2020). Hydrogen refueling station networks for heavy-duty vehicles in future power systems. Transportation Research Part D: Transport and Environment, 83, 102358.

Seddiek, I. S., & Ammar, N. R. (2023). Technical and eco-environmental analysis of blue/green ammonia-fueled RO/RO ships. Transportation Research Part D: Transport and Environment, 114, 103547.

Shen, J., Chen, D., Bai, M., Sun, J., Coates, T., Lam, S. K., & Li, Y. (2016). Ammonia deposition in the neighbourhood of an intensive cattle feedlot in Victoria, Australia. Scientific Reports, 6(1), 32793.

Shen, Z. J. M., Zhan, R. L., & Zhang, J. (2011). The reliable facility location problem: Formulations, heuristics, and approximation algorithms. INFORMS Journal on Computing, 23(3), 470–482.

Shi, W., Xiao, Y., Chen, Z., McLaughlin, H., & Li, K. X. (2018). Evolution of green shipping research: Themes and methods. Maritime Policy & Management, 45(7), 863–876.

Sürer, M. G., & Arat, H. T. (2022). Advancements and current technologies on hydrogen fuel cell applications for marine vehicles. International Journal of Hydrogen Energy, 47(45), 19865–19875.

Sun, Z., & Zheng, J. (2016). Finding potential hub locations for liner shipping. Transportation Research Part B: Methodological, 93, 750–761.

Tay, Z. Y., & Konovessis, D. (2023). Sustainable energy propulsion system for sea transport to achieve United Nations sustainable development goals: A review. Discover Sustainability, 4(1), 20.

Thepsithar, P., Kiong, M. K. E., Piga, M. B., Zengqi, M. X., Yin, S. J., Ming, L., ... & Rosario, M. M. K. P. (2020). Alternative fuels for international shipping. Maritime Energy & Sustainable Development (MESD) Centre of Excellence, Nanyang Technological University.

Wang, S., Nan, J., Shi, C. Fu, Q., Gao, S., Wang, D., & Zhou, B. (2015). Atmospheric ammonia and its impacts on regional air quality over the megacity of Shanghai, China. Scientific Reports, 5(1), 15842.
Wang, W., Liu, Y., Zhen, L., & Wang, H. (2022). How to deploy electric ships for green shipping. Journal of Marine Science and Engineering, 10(11), 1611.
Wiegmans, B., & Konings, R. (2016). Inland Waterway Transport: Challenges and Prospects. Routledge.
Yu, H., Fang, Z., Fu, X., Liu, J., & Chen, J. (2021). Literature review on emission control-based ship voyage optimization. Transportation Research Part D: Transport and Environment, 93, 102768.
Zheng, J., Qi, J., Sun, Z., & Li, F. (2018). Community structure based global hub location problem in liner shipping. Transportation Research Part E: Logistics and Transportation Review, 118, 1–19.
Zheng, J., & Yang, D. (2016). Hub-and-spoke network design for container shipping along the Yangtze River. Journal of Transport Geography, 55, 51–57.
Zheng, J., Yang, L., Ni, L., Fagerholt, K., & Zhang, Y. (2022). Efficient models for the liner shipping hub location problem with spatial structure. Computers & Industrial Engineering, 173, 108725.
Zhou, Y., Pavlenko, N., Rutherford, D., Osipova, L., & Comer, B. (2020). The potential of liquid biofuels in reducing ship emissions. International Council on Clean Transportation, 1, 31.

Appendix A. Auxiliary Information of Case Study

Table A.1. Ports along the downstream of Yangtze River (Wang et al., 2022).

Index	Port
1	Wuhan (WH)
2	Huangshi (HS)
3	Jiujiang (JJ)
4	Anqing (AQ)
5	Tongling (TL)
6	Wuhu (WHU)
7	Nanjing (NJ)
8	Zhejiang (ZJ)
9	Jiangyin (JY)
10	Zhangjiagang (ZJG)
11	Nantong (NT)
12	Taicang (TC)
13	Shanghai (SH)

Table A.2. Port handling time.

Index	Port	Handling Time (Hours)
1	WH	24.54
2	HS	31.38
3	JJ	29.70
4	AQ	16.44
5	TL	13.20
6	WHU	31.26
7	NJ	16.08
8	ZJ	19.20
9	JY	15.06
10	ZJG	7.68
11	NT	22.20
12	TC	43.92
13	SH	44.10

Table A.3. Length of routes and number of ships.

No.	Length (nm)	Number of ships
1	1214.90	3
2	791.58	2
3	467.58	1
4	1060.48	2
5	747.32	2
6	527.00	1
7	423.32	1
8	274.08	1
9	329.36	2
10	203.02	2
11	203.02	1
12	183.58	2
13	183.58	1
14	55.28	1

Table A.4. The optimal hydrogen refueling hub deployment for three strategies.

		1	2	3	4	5	6	7	8	9	10	11	12	13
Two-stage stochastic strategy	Current stage	0	0	0	0	0	0	**1**	0	0	0	0	**1**	**1**
	Scenario 1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Scenario 2	0	0	0	0	0	0	0	**1**	0	0	0	0	0
	Scenario 3	0	**1**	**1**	0	0	0	0	0	0	0	0	0	0
	Scenario 4	0	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0
Myopic strategy	Current stage	0	0	0	0	0	0	0	**1**	0	**1**	0	**1**	0
	Scenario 1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Scenario 2	0	0	0	**1**	0	0	0	0	0	0	0	0	0
	Scenario 3	0	0	0	0	0	0	**1**	0	0	0	0	0	**1**
	Scenario 4	0	0	0	**1**	0	0	**1**	0	0	0	0	0	**1**
Two-stage deterministic strategy	Current stage	0	0	0	0	0	0	0	**1**	0	**1**	0	**1**	0
	Scenario 1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Scenario 2	0	0	0	**1**	0	0	0	0	0	0	0	0	0
	Scenario 3	0	0	0	0	0	0	**1**	0	0	0	0	0	**1**
	Scenario 4	0	0	0	**1**	0	0	**1**	0	0	0	0	0	**1**

Table A.5. The optimal Hydrogen-energy-capable route for three strategies.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Two-stage stochastic strategy	Current stage	0	0	0	0	**1**	**1**	**1**	0	0	**1**	**1**	**1**	**1**	**1**
	Scenario 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Scenario 2	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0
	Scenario 3	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0
	Scenario 4	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0
Myopic strategy	Current stage	0	0	0	0	**1**	0	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**
	Scenario 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Scenario 2	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0
	Scenario 3	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0
	Scenario 4	0	0	**1**	0	0	**1**	**1**	0	0	0	0	0	0	0
Two-stage deterministic strategy	Current stage	0	0	0	0	**1**	0	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**
	Scenario 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Scenario 2	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0
	Scenario 3	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0
	Scenario 4	0	0	**1**	0	0	**1**	**1**	0	0	0	0	0	0	0

Table A.6. No. of groups for different shipping networks.

No.	Shipping Network
1	1,2,3,4,5,6,7,8,9,10,11,12,13,14
2	1,3,4,5,6,7,8,9,10,11,12,13,14
3	1,4,5,6,7,8,9,10,11,12,13,14
4	1,6,7,8,9,10,11,12,13,14
5	1,2,4,6,7,9,10,11,12,13,14
6	1,2,4,6,7,9,11,12,13,14
7	1,2,3,4,6,7,9,11,13,14
8	1,2,3,4,7,9,11,13,14
9	1,2,3,4,7,9,11,13
10	1,2,4,7,9,11,13

Table A.7. No. of groups for different situations with uncertainty.

No.	Scenario (s)	Maximum number of hubs (N_s)	Probability (α_s)
1	1	0	0.5
	2	2	0.5
2	1	1	0.5
	2	3	0.5
3	1	2	0.5
	2	4	0.5
4	1	3	0.5
	2	5	0.5
5	1	4	0.5
	2	6	0.5
6	1	5	0.5
	2	7	0.5
7	1	6	0.5
	2	8	0.5

Table A.8. No. of groups for different probabilities.

No.	Scenario (s)	Maximum number of hubs (N_s)	Probability (α_s)
1	1	1	0.9
	2	3	0.1
2	1	1	0.7
	2	3	0.3
3	1	1	0.5
	2	3	0.5
4	1	1	0.3
	2	3	0.7
5	1	1	0.1
	2	3	0.9
6	1	2	0.9
	2	4	0.1
7	1	2	0.7
	2	4	0.3
8	1	2	0.5
	2	4	0.5
9	1	2	0.3
	2	4	0.7
10	1	2	0.1
	2	4	0.9
11	1	3	0.9
	2	5	0.1
12	1	3	0.7
	2	5	0.3
13	1	3	0.5
	2	5	0.5
14	1	3	0.3
	2	5	0.7
15	1	3	0.1
	2	5	0.9