**Marine fuel refining technology improvement trade-offs: A game theoretic approach**

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**Abstract**

The implementation of International Maritime Organization (IMO) 2020 sulfur cap requires ship operators to decrease fuels’ sulfur content and this may increase their demand for low-sulfur fuel (LSF). In anticipation, bunker companies can choose to upgrade their refining technology to produce better quality distillate and lighter oil. In this study, we consider a bunker supply chain consisting of bunker companies and a population of ship operators with two main marine fuel products, low-sulfur fuel (LSF) and high-sulfur fuel (HSF). We use Cournot game to model the competition between LSF and HSF under two different market channels (i.e., dual and single channels). The results show that bunker companies’ refining technology upgrading choice is affected by many operational parameters, such as the basic market demand, cost difference between LSF and HSF, market competition, variable and fixed cost for upgrading, the increase of market demand due to upgrading, and so on. Compared with a dual channel bunker company, a single channel bunker company is less likely to implement new refining technology. We further consider the scenario where bunker companies can make decisions after the realization of ship operators’ demand uncertainty. The findings are beneficial for both LSF and HSF bunker companies and may reach a win-win solution for bunker companies.

**Key words:** Technology upgrading; Cournot game; market channel; market uncertainty

## 1. Introduction

About 90% of international trade is carried out by shipping and shipping acts as a prime facilitator of global trade and economic growth (IMO, 2011). The demand for seaborne trade is expected to recover in 2021 and expands by 4.8% (UNCTAD, 2020). For most running vessels, burning heavy fuel oil (HFO) is a natural choice (Fagerholt and Psaraftis, 2015). HFO is a mixture of oil that contains residues and distillates, which are created from complex processes during refining, and is mainly used by ship operators due to economic reasons (Mueller et al., 2015) because bunker consumption can make up for more than 50% of the total operating cost (Lindstad et al., 2013). However, serious problems can be caused by burning HFO. HFO has a fairly poor atomization characteristic and combustion quality (Sun et al., 2019), and ships fueled with HFO would release sizable amounts of pollutants to the environment (Mueller et al., 2015).

During the fuel combustion process, particle-associated pollutants and gas are emitted(Mueller et al., 2015). Shipping emissions are one of the most significant factors affecting global air quality, especially in coastal areas (Viana et al., 2014). Among all the shipping emissions, sulfur oxide (SOx) emissions are one by-product that require further consideration (Li et al., 2020). Serious health and environment problems are created if excessive SOx emissions are emitted to the air (IMO, 2019), and this motivates tighter regulation for ship exhaust emissions. The International Maritime Organization (IMO), a specialized branch of United Nations first adopted the Marine Pollution Convention (MARPOL) Annex VI in 1997 aims to reducing ships’ main air pollutants, including nitrous oxides (NOx) and SOx, and prohibits deliberate emissions of ozone depleting substances (IMO, 2011). Under MARPOL Annex VI, global sulfur cap for fuel oil should first reduced to 3.5% m/m and then progressively to 0.5% on 1 January 2020. This policy is also known as IMO 2020 sulfur cap (Li et al., 2020). To comply with sulfur regulations, ship operators should substitute high sulfur fuel (HSF) consumption with low sulfur fuel (LSF) consumption or adopt other measures to reduce SOx emissions when burning fuel.

In general, ship operators can choose among three options to comply with the sulfur regulation (Yang et al., 2012). The first option is to continue using HSF but install exhaust gas cleaning systems (scrubbers). Sulfur content in the exhaust gas can be removed by scrubbers with the use of seawater (Lindstad et al., 2017). However, installing scrubbers would incur a large investment cost (Patricksson et al., 2015), force vessels to layup at shipyards during retrofitting (Bergqvist et al., 2015), and decrease their loading capacity (Panasiuk and Turkina, 2015). Directly switching to LSF consumption is another option available for ship operators (Register, 2018). Ship operators can choose this option by making minor adjustments and enjoy minimal capital cost (Lindstad et al., 2017). However, they would face large operational costs in the long run (Patricksson et al., 2015) since the price difference between HSF and LSF is widening and has reached to $50 per barrel in 2020 (Li et al., 2020). Running on liquefied natural gas (LNG) is another option for ship operators but adopted by fewer ship operators because high initial investment costs and specialized bunkering facilities are needed (Panasiuk and Turkina (2015); Fagerholt et al. (2015); Kim and Seo (2019)). These three options have pros and cons and have been implemented by different ship operators to suit their circumstances (Lindstad et al., 2015). Nevertheless, we can anticipate that the marine oil refining process and marine fuel market will adjust accordingly with the enaction of the environmental regulations.

From the bunker companies’ perspective, refineries may face increasing demand for LSF with more stringent environment regulations (Chu Van et al., 2019). CONCAWE (2016) predicted that the annual demand for distillate oil would increase 500,000 bbl/d, whereas annual demand for residual oil would decrease 150,000 bbl/d. Hence, bunker companies may choose to upgrade their refining technology to increase the capacity of residue transition processes to LSF (IEA, 2016). Bunker fuel refining technology upgrade means to upgrade the current desulphurization process to decrease the sulfur content of the refined oil so that the refined oil can satisfy ship operators demand for LSF consumption directly. In the following, without special mention, technology upgrade or improvement stands for bunker fuel refining technology upgrade for short. On the one hand, the increased demand for LSF can be fulfilled if the bunker companies choose to upgrade their technology. In general, 50% of crude oil would be used for HSF production; however, more complex refining processes can be applied to produce more LSF (Chu Van et al., 2019). On the other hand, large capital investment costs are needed for potential refining modification processes. Abdel-Halim et al. (2018) states that the capital investment cost for 350,000 bbl/d refinery is $2-5 billion and payout periods can last for 4.2-5 years. A number of technologies can be applied to decrease fuel sulfur content to lower levels but all these refining processes require additional energy and hydrogen consumption which will increase refineries’ cost (Chu Van et al., 2019). For instance, the main factor used in hydrodesulphurization treatment process to reduce sulfur in the distillates of gasoline and kerosene is to use hydrogen. Besides, ship operators’ demand for LSF is uncertain. CONCAWE (2016) also mentioned that their prediction on the fuel market depends on total demand projection and scrubber/LNG penetration. This means that if many ship operators choose to install scrubbers and run-on LNG, then demand for distillate oil may not necessarily increase and demand for residual oil may not necessarily decrease. This gives rise a fundamental question: should the bunker companies upgrade their refining technology or not?

This question has not been answered by the current research though firms’ technology upgrading decision has been widely examined in the supply chain field. The enaction of IMO 2020 sulfur cap poses new challenges for the whole shipping industry and not just the bunker supply chain. On the one hand, desulphurization of the refined oil will become a persistent trend for the whole bunker supply chain and thus, bunker companies must make suitable changes in response to this trend. Bunker companies may lose their competitiveness if a huge amount of ship operators turn to consume LSF or when the bunker companies’ production capacity cannot satisfy ship operators’ demand. On the other hand, given the pros and cons of the three options available for ship operators to comply with the IMO 2020 sulfur cap, ship operators’ compliance decision may vary among the three options that pose great uncertainty for ship operators’ demand for fuel products. These new challenges for the bunker supply chain motivate this research.

The main goal of this research is to examine bunker companies’ technology upgrading choice while considering ship operators’ demand uncertainty. We consider a bunker supply chain consisting of bunker companies and a population of ship operators. There are two main fuel products, LSF and HSF, offered to the market. The two products compete with each other under Cournot competition and ship operators’ demand can be satisfied by purchasing any of the products. With the implementation of stringent regulations, reducing sulfur content from the running fuel becomes an unavoidable trend for both refiners and ship operators. Bunker companies can choose to upgrade their refining technology in anticipation of ship operators’ growing demand for LSF. In fact, the increase of demand for LSF faces uncertainty and depends on the scrubber or LNG penetration. Moreover, bunker companies’ cost structure including both variable and fixed cost will be affected if new refining technologies are adopted as large investment costs and more complex refining processes are needed. We also consider the impact of market channel on bunker companies’ technology upgrading choice. In the dual channel setting, LSF and HSF are respectively sold by two different bunker companies and the LSF bunker company will decide whether or not to upgrade its LSF’s refining technology. In the single channel setting, LSF and HSF are sold by the same bunker company and it needs to consider the technology upgrading choice. To reiterate, the following research questions are examined:

1. What are the bunker companies’ optimal results before and after upgrading their technology under two different market channels (i.e., dual channel and single channel)?
2. How does operational parameters (i.e., cost structure, basic market demand, market competition, fixed and variable cost incurred, and two different market channels) affect bunker companies’ technology upgrading choice?
3. If bunker companies can make decision after realizing ship operators’ demand uncertainty, will such realization be beneficial for both LSF and HSF bunker companies?

Our key results are summarized as follows. First, we found that bunker companies would increase their production quantity of LSF and decrease the production quantity of HSF with the implementation of new technology. However, the increased (decreased) production quantity of LSF (HSF) will not cause the bunker companies to decrease (increase) their sales price. Instead, the sales price of LSF (HSF) would increase (decrease) with increased (decreased) production quantity. Second, we investigated the impact of several operational parameters on bunker companies’ technology upgrading choice and found that the bunker companies would less likely upgrade their technology when basic market demand is low, or when the cost difference between LSF and HSF products, and the fixed and variable cost incurred for upgrading are high. While for the market competition parameter, it is surprising to note that bunker companies are more likely to implementing new technology when the competition intensity of the market is low. Third, when considering two different market channels, we found that bunker companies in the single channel setting are less likely to implementing new refining technology than that of in the dual channel setting as the single channel bunker companies not only need to incur upgrading cost but also offset profit loss from HSF. Finally, we found that bunker companies whether in single channel or dual channel setting can make more accurate decisions and are more likely to upgrade to new technology when they can make decision after the realization of ship operators’ demand uncertainty. Besides, the information value would be spilled over to HSF bunker company and a win-win solution may exist for both LSF and HSF bunker companies.

The rest of this paper is organized as follows. In Section 2, we briefly review the previous work relates to our topic. Model descriptions and assumptions are presented at Section 3. Bunker companies’ technology upgrading choice in dual channel and single channel settings are examined at Sections 4 and 5, respectively. The impact of ship operators’ demand uncertainty on bunker companies’ technology upgrading choice is investigated at Section 6. Section 7 concludes the paper, and all proofs are provided at the Appendix.

## 2. Literature review

This study is built on four streams of research: (a) environment regulations on marine supply chain; (b) ship operators’ compliance choices; (c) technology upgrading; and (d) market structures on supply chain. This study’s relationship with the four streams of research and the contributions of our study will be elaborated below.

Environment regulations with respect to marine fuel products have changed marine supply chain greatly and this stream of research is closely related to the study. First of all, fuel refining process changes with the implementation of environment regulations. Jang and Choi (2016) used chemical laboratory tests to examine the effects of fuel additives on fuel oil stability and emission components. Chu Van et al. (2019) argued that various technologies would be used to remove fuel sulfur content with the enaction of more stringent environment requirements. However, these removal processes require additional energy and hydrogen, and would cause environmental problems. Sun et al. (2019) considered to develop new surrogate fuels to run on marine engine to replace HFO. Selecting optimized maritime routine and speed are also available for ship operators but such methods are not useful when environmental regulations are implemented globally. Qi and Song (2012) optimized liner shipping’s vessel schedule aiming at minimized total fuel consumption and emissions. Fagerholt and Psaraftis (2015) studied two speed optimization problems for vessels who can run HFO outside emission control area (ECA) and then switch to LSF inside ECA. With similar settings, Fagerholt et al. (2015) further considered ship operators’ sailing paths selection problem with speed optimization. Mueller et al. (2015) examined the particulate emission patterns when ship engines are able to switch between HFO and LSF. Lindstad et al. (2015) found that allowing running vessels to burn very dirty fuels at high sea is economically profitable for ship operators by using a three-layered, damage-based approach. Zavitsas et al. (2018) examined the impact of ECAs on maritime operations at sea considering many operational factors. Zhen et al. (2020) proposed a bi-objective integer linear programming model to optimize liner shipping companies’ sailing routes and speeds when environmental regulations are implemented. Yan et al. (2020) used a two-stage ship fuel consumption model to reduce dry bulk ship’s fuel consumption and emissions. Our relation to this stream of research is that we consider the impact of environmental regulations on marine supply chains, but we do not focus on any specific sulfur removal process. Instead, we consider whether bunker companies should upgrade their fuel refining technology after IMO 2020 sulfur cap is implemented globally.

Ship operators have many choices to comply with environmental regulations, but their specific choice may vary according to different conditions. Yang et al. (2012) established an evaluation tools for ship operators to select their preferred emission reduction techniques. Acciaro (2014) used a real option model to discuss the optimal time for ship operators to invest in LNG retrofit and found that ship operators invest in LNG decision depends on LNG’s future price, reduction in capital costs and retrofitting costs. Bergqvist et al. (2015) even examined the case when companies transfer from ship to land transport. Gu and Wallace (2017) argued that an incorrect investment decision would be caused by an inaccurate estimation of certain technologies’ value. Subsequently, they integrated a ship’s sailing pattern into emission control technology’s lifespan cost assessment to help ship operators make right emission control technology investment. Ship operators’ choice between LSF and installing scrubbers is one of the streams of research that has been studied by many researchers. Panasiuk and Turkina (2015) compared the economic issues of LSF and scrubber and found that additional costs are needed no matter which technology is selected. Patricksson et al. (2015) modeled ship operators’ choice between LSF and scrubber with a stochastic programming and proposed various means to cope with emission control regulations. Abadie et al. (2017) presented an economic assessment of LSF and scrubber choice that considers fuel prices, scrubber installation costs, remaining useful lifetime of the vessel and vessel running time on ECA. Lindstad et al. (2017) compared ship operators’ compliance options and considered ship type and operational patterns. They found that distillate is an attractive choice for smaller vessels, while installing scrubbers is more profitable for larger vessels. Zis and Psaraftis (2017) examined European Ro-Ro operators’ compliance choice when current and future market price are considered. Fan et al. (2020) examined ship operators’ compliance options between fuel switching and scrubber installing by using a cost-benefit analysis. Zhu et al. (2020) found that using scrubbers is more economical beneficial because of its high net present value and low annual unit cost. It is more attractive in most cases. Li et al. (2020) presented an overview of ship operators’ three abatement options and identified the determinants of ship operators’ choice among the three options. Based on the research mentioned above, it can conclude that different ship operators will make different abatement decisions, considering different operational factors. In this study, we do not consider ship operators’ compliance choice to comply with the stricter environmental regulations. However, ship operators’ compliance choice will significantly affect bunker companies’ fuel market and hence, we model the aforementioned ship operators’ behavior as market uncertainty.

It is widely accepted that environmental regulations can provide motivation for technological innovation. Some of the research are built on specific industry, such as the marine industry. Al-Belushi et al. (2015) asserted that the key factor for organizational competitiveness is the ability to innovate. Makkonen and Inkinen (2018) addressed the linkage between environmental regulation and innovation policy and provided an overall framework for future innovation. Chen and Qian (2020) investigated the manufacturing industry’s industrial structure amendment with the implementation of stringent environmental regulation. Researcher have also studied some scenarios based on common industry practices and conclusions in these studies can be applied to any industry when facing similar conditions. Krass et al. (2013) examined a monopolistic firm’s emission control technology, production quantity and price selection when regulator interferes with the market with tax, subsidy, and rebate. Kraft et al. (2013) studied a firm’s replacement decision when its product contains potential hazardous substances and found that a firm should always dedicate toward developing a replacement substance as long as there exists a regulation threat. Kraft and Raz (2017) further extended Kraft et al. (2013) to two manufacturers competing case and examined the impact of market competition on firms’ replacement decision. Yang et al. (2021) studied two symmetric competing firms’ green technology upgrading choice and the role of government subsidy. Based on a specific background in which is the marine industry (i.e., IMO 2020 sulfur cap), this study considers bunker companies’ refinery technology upgrading choice while considering LSF and HSF competing with each other in Cournot competition and ship operators’ demand for LSF is uncertain.

The research on supply chain market structures is another stream of research that relates to our study. Shao et al. (2017) studied the government’s role on mass adoption of electric vehicles while considering two different market structures. They found that the government’s subsidy program and optimal subsidy level are different under different market structures and electric market in the monopoly setting is more environmentally friendly than that of in the duopoly setting. Zhou and Yuen (2021) built a two-stage game model to examine the impact of government subsidy on LSF consumption process when its goal is to maximize the total social welfare. They found that market structure plays a vital role on firms’ and government’s optimal policy, and different results would be reached under different market structure. In this study, we also integrate market structure with bunker companies’ technology upgrading choice and examine the impact of market structure on bunker companies’ refinery technology upgrading process.

## 3. Model Setting

This study considers a bunker supply chain offering two main marine fuel products, LSF and HSF. The bunker supply chain contains a population of ship operators who needs to purchase either LSF or HSF for their daily operations. However, in accordance with IMO 2020 sulfur cap, scrubbers must be installed if they choose to purchase HSF. Installing scrubbers will put the ships on layup at the shipyard and such practice cannot be implemented in the short run. Hence, ship operators’ demand for LSF may increase substantially in the short run. However, the bunker companies cannot fulfill ship operators’ LSF demand without upgrading their technology. Such a bunker supply chain structure is quite common in the industry with the implication of IMO 2020 sulfur cap.

We are interested in the bunker companies’ technology upgrading choice in such a model setting. More specifically, an important question for the bunker companies is whether the bunker companies should upgrade their LSF refining technology to satisfy the increased demand that is associated with an increase of fixed and variable cost. In addition, LSF and HSF compete in the same market but may not exist in the same market channel. When a bunker company offers both LSF and HSF, the two products exist in the same channel. However, LSF and HSF will not exist in the same channel when they are respectively offered by two different bunker companies. The former case refers to single channel, whereas the latter refers to dual channel. The aim of considering the two market channels is to investigate the impact of the product offerings on bunker companies’ technology upgrading choice.

A two-stage game in the bunker supply chain is considered in this study. In the first stage of the game, the bunker companies that offer LSF decide on their technology upgrading choice. In particular, the bunker company may choose to either not upgrade or upgrade their technology. The former scenario is referred as “not upgrading,” or N for short, while the latter scenario is called “upgrading,” or U for short. After the technology choice has been determined, the bunker companies decide their production quantity of LSF and HSF in the second stage of the game. We assume that LSF and HSF compete in the market with Cournot competition where the two products compete with production quantities. Hence, we assume the inverse demand functions for the fuel product are:

 

where  is the fuel product  price,  is its production quantity, and  is a parameter that measures the competition intensity in the market. This form of inverse demand function is a standard assumption in economic and marketing literature (Niu et al., 2019; Yang et al., 2021). Note that , where  corresponds to the case when the two products are independent, and  corresponds the case when the two products are perfect substitutes. With the enaction of the IMO 2020 sulfur cap, ship operators can consume LSF directly, but they cannot consume HSF without installing scrubbers. Hence, LSF is assumed to be perfect substitutes for HSF, but the reverse is not true. Therefore, we assume that  and . This assumption is to simplify the analysis but without losing generality, and such perfect substitution assumption between products is also widely used in the literature, such as Wang et al. (2013).  is the basic market demand for LSF and HSF product before upgrading technology, and is assumed to be sufficiently large so that no production case will not occur. The basic market demand for LSF will be expanded to  if the bunker companies choose to upgrade their LSF refinery technology. Hence, the inverse demand functions for LSF and HSF after technology upgrading are:





where  is a random variable with a mean of  and variance of , which measures the market uncertainty of ship operators’ demand. The impact of the market uncertainty of ship operators’ demand on bunker companies’ technology upgrading choice will be examined in Section 6.

The bunker companies need to incur both variable and fixed costs to produce LSF and HSF, and the variable and fixed costs of manufacturing LSF are always larger than that of producing an HSF. Without losing generality, we assume that the variable and fixed costs of producing LSF and HSF are . This assumption allows us to focus on the technology improvement process. Let  denote the cost difference between producing a LSF and an HSF product. An additional variable cost of  and fixed investment cost  are incurred if the bunker companies choose to upgrade their LSF refining process. In the analysis, we assume that , which represents the technology upgrading process will increase the bunker companies’ variable cost. In fact, the bunker companies’ motivation to upgrade the technology will increase if upgrading can decrease their variable cost and this would influence their upgrading choice. Hence, we do not consider the scenario (i.e., ) in this research.

Let ,  and  denote LSF, HSF and the total profit of the two products in scenario , where refer to not upgrading and upgrading technology scenario, respectively. Hence, the bunker companies’ profits are:







where  is an indicator function. If bunker companies choose to upgrade their technology, then the value of  is equal to  and  otherwise. In this research, we assume that all events transpire in one period and there is no production lead time. All products can bring to the market at the same time even when the bunker companies have made technology improvement decision. The single period assumption can be considered as the average status of the supply chain when similar products are introduced to the market repeatedly (Ma et al., 2017; Savaskan et al., 2004).

In the following, we first investigate the bunker companies’ technology upgrading choice in the dual channel setting. The bunker companies’ technology upgrading choice in the single channel setting is examined in Section 5.

## 4. Technology upgrading choice in the dual channel setting

In this setting, the LSF and HSF are sold by two different bunker companies. We solve the problem by backward induction as a two-stage game is considered in this study. We first investigate the two bunker companies’ optimal results before and after the LSF bunker company upgrade its refining technology (i.e., scenarios N and U). The LSF bunker company’s technology upgrading choice is examined in the following. The equilibrium results in scenarios N and U when the LSF bunker company does not upgrade and upgrades its LSF refinery technology are summarized in Table 1.

**Table 1.** Bunker companies’ optimal results in scenarios N and U in the dual channel setting.

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| Optimal Solutions | Scenario N | Scenario U |
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The sales quantity of LSF and HSF shall be nonnegative to make the analysis feasible. Hence, the increase of the market demand  should satisfy: , where  and .

**Lemma 1.** The equilibrium results in the dual channel setting satisfy:

1. The equilibrium production quantity of LSF in scenario U is larger than that in scenario N, while the production quantity of HSF in scenario U is smaller than that in scenario N, i.e., , and ;
2. The equilibrium sales price of LSF in scenario U is larger than that in scenario N, while the sales price of HSF in scenario U is smaller than that in scenario N, i.e., , and .

Lemma 1 first compares the equilibrium production quantity of LSF and HSF in scenarios N and U. It shows that the production quantity of LSF will increase with the upgrade of the refining technology, whereas the production quantity of HSF will decrease in scenario U. With the implementation of IMO 2020 sulfur cap, ship operators that do not install scrubbers need to consume LSF if they want to operate their vessel. Hence, the LSF bunker company needs to increase the production quantity of LSF product. Besides, more LSF products can be produced by upgrading the technology. However, fewer ship operators will purchase HSF as they switch to LSF. Hence, the HSF bunker company needs to decrease its HSF production. In addition, a large initial investment cost will be incurred if scrubbers are installed in vessels and the installing process can also lead to ship layup. In the short run, ship operators cannot fulfill their transportation demand which can further decrease ship operators’ demand for HSF product.

Lemma 1 also compares equilibrium sales price of LSF and HSF in scenarios N and U. It implies that the LSF bunker company will increase the sales price of LSF when it upgrades its refining technology, whereas the HSF bunker company will decrease the sales price of HSF in scenario U. In the first part of Lemma 1, we show that the LSF bunker company will increase the production quantity of LSF, whereas the HSF bunker company will decrease the production quantity of HSF when the LSF bunker company upgrades its technology. In general, the bunker company has to decrease its sales price when it increases its production quantity. However, we show that the LSF bunker company increases the sales price with the increase of production quantity, whereas the HSF bunker company decreases the sales price with the decrease of production quantity. This is because, a large population of ship operators still need to consume LSF even when the sales price of LSF has increased substantially. Besides, the LSF bunker company needs to incur an additional variable and fixed cost of manufacturing if it upgrades its technology. Hence, the LSF bunker company increases the sales price of LSF to offset the additional cost, and such increase in the sales price does not decrease ship operators’ demand for LSF. For HSF bunker company, it wants to increase ship operators’ demand for HSF product by decreasing the sales price of HSF. However, the decrease of the sales price cannot motivate ship operators to purchase HSF, and the production quantity of HSF in scenarios U is smaller than that of in scenario N.

**Proposition 1.** The LSF and HSF bunker companies’ equilibrium profit in the dual channel setting indicate:

1. The LSF bunker company prefers not to upgrade its refining technology if , i.e., , and the LSF bunker company prefers to upgrade its refining technology if , i.e., , where ;
2. The HSF bunker company always prefers the LSF bunker company to not upgrade the technology, i.e., .

Proposition 1 shows the LSF and HSF bunker company’s equilibrium profits in scenarios U and N. It shows whether and when the LSF bunker company should upgrade its LSF refining technology, and the impact of the LSF bunker company’s technology upgrading choice on the HSF bunker company’s equilibrium profit. For the HSF bunker company, it is worse off if the LSF bunker company upgrade its technology. This is because the HSF bunker company’s production quantity and sales price of HSF will decrease with the implementation of new technology. The HSF bunker company suffers a profit loss because of a lower profit margin and a small market demand.

For the LSF bunker company, its technology upgrading choice highly depends on the increase of the market demand. The LSF bunker company should not upgrade its LSF refining technology when the increase of the market demand is at a low level (i.e., ). While the LSF bunker company should upgrade its technology when the market demand increases. From Lemma 1, we can see that LSF’s production quantity and sales price in scenario U are always larger than that in scenario N. However, this does not mean that the LSF bunker company can always benefit from upgrading. This is because the LSF bunker company has to incur fixed investment cost to upgrade its technology which can increase its cost and limit its profits. The LSF bunker company cannot benefit from upgrading technology if the market is small and hence, the technology upgrading choice only happens when the increase of the market demand is high. The decision to upgrade depends on the threshold . This threshold increases with  and , which implies higher refining costs will decrease LSF bunker companies’ technology upgrading process.

In addition to upgrading cost, the basic market demand (), competition intensity of the market (), and cost difference between LSF and HSF () also affect the LSF bunker company’s technology upgrading choice. However, it is difficult to analyze their monotonicity. Therefore, we use numerical studies to show the impact of ,  and  on the LSF bunker company’s profit in scenarios U and N.

Figure 1 shows the impact of basic market demand (i.e., ) on the LSF bunker company’s profit in scenarios U and N. The LSF bunker company is more likely to upgrade its technology, incurring additional fixed and variable cost when the basic market demand is high, and vice versa. A small increase of market demand (i.e., ) can induce the LSF bunker company to upgrade its LSF refinery technology when the initial market demand is large. However, when the initial market demand is small, the LSF bunker company will only upgrade its technology when the increase of the market (i.e., ) is sufficiently large.

The impact of the market competition intensity (i.e., ) on LSF bunker company’s technology upgrading choice is shown in Figure 2. Figure 2 implies that the LSF bunker company is less likely to upgrade its technology with a small , and vice versa. Parameter  stands for the intensity of market competition, and a large  means a high market competition, and a high substitution effect between LSF and HSF. Ship operators’ demand for LSF cannot be satisfied with the purchase of HSF when the market competition intensity is at a low level and this demonstrates the non-substitutability of LSF and HSF. As such, the LSF bunker company will not upgrade its technology when the increase of market demand (i.e.,) is low. On the contrary, the company will upgrade its technology to meet the large increase of market demand when the market competition becomes fierce.

Figure 3 shows the impact of the cost difference between LSF and HSF (i.e., ) on the LSF bunker company’s profit in scenarios U and N. It shows that LSF bunker company is more likely to upgrade its technology with a low manufacturing cost, and less likely to upgrade the technology with a high manufacturing cost. The impact of  on the LSF bunker company’s profit is similar to that of  and . Parameter  implies a cost disadvantage when producing LSF and hence, a large market increase (i.e., ) is needed for the LSF bunker company to upgrade its technology to compensate for the high manufacturing cost.



Figure 1. Impact of basic market demand on dual channel bunker companies’ technology upgrading.



Figure 2. Impact of market competition on dual channel bunker companies’ technology upgrading.



Figure 3. Impact of cost difference on dual channel bunker companies’ technology upgrading.

## 5. Technology upgrading choice in the single channel setting

In this setting, LSF and HSF are sold by the same bunker company. The bunker company needs to decide whether to upgrade its technology. Similarly, we also solve the problem by backward induction. The bunker company’s optimal results before and after the upgrading are examined first, and then we investigate the bunker company’s technology upgrading choice by comparing the bunker company’s profit before and after upgrading. The equilibrium results in scenarios N and U are summarized in Table 2.

**Table 2.** Bunker companies’ optimal results in scenarios N and U in the single channel setting.

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| Optimal Solutions | Scenario N | Scenario U |
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Similarly, the sales quantity of LSF and HSF shall be nonnegative to make the analysis feasible and hence, the increase of the market demand should satisfy: , where  and . Note that, the feasible condition in this setting is lesser than that of in the dual channel setting as  and .

**Lemma 2.** The equilibrium results in the single channel setting indicate:

1. The equilibrium production quantity of LSF in scenario U is larger than in scenario N, while the production quantity of HSF in scenario U is smaller than that in scenario N, i.e., , and ;
2. The equilibrium sales price of LSF in scenario U is larger than that in scenario N, while the sales price of HSF in scenario U is smaller than that in scenario N, i.e., , and .

Consistent with the previous section where LSF and HSF are respectively sold by two different bunker companies, we show that the single channel bunker company will increase the production quantity of LSF and decrease the production quantity of HSF in scenario U. This implies that whether LSF and HSF exist in the same channel does not affect the bunker companies’ production decision for LSF and HSF when it chooses to upgrade LSF’s refining technology. Similarly, the single channel bunker company increases the sales price of LSF and decreases the sales price of HSF after upgrading. This is because ship operators need to consume more LSF for their daily operations even when the production quantity of LSF has increased substantially. The increase of the sales price does not discourage ship operators from purchasing LSF product. On the contrary, the single channel bunker company wants to decrease sales price for HSF aiming at increase ship operators’ demand for such product. However, ship operators will not purchase HSF even though the sales price is decreased. With the installation of scrubbers, a high investment cost may occur if ship operators choose to use HSF.

**Proposition 2.** The single channel bunker company that sells both LSF and HSF prefers not to upgrade refining technology if , i.e., , and prefers to upgrade refining technology if , i.e., , where .

Proposition 2 shows that the technology upgrading choice of a single channel bunker company that sells both LSF and HSF. Consistent with the previous section, the single channel bunker company prefers not to upgrade its technology when the increase of the market demand is at a low level, and upgrades its technology when the increase of the market demand is at a high level. In contrast, the threshold of the increase of the market demand in the single channel setting is larger than that of in the dual channel setting. This implies that as compared to a dual channel company, the single channel bunker company that sells LSF and HSF to the market is less likely to upgrade its technology. In addition to incur a fixed and variable cost to upgrade refining technology, the single channel bunker company also has to decrease both production quantity and sales price of HSF. Therefore, for the single channel bunker company, the increase of profit from upgrading of LSF refining technology should offset the single channel bunker company’s cost incur and HSF’s profit loss. While on the dual channel setting, LSF bunker company’s technology upgrading choice only depends on the cost incurred, and LSF bunker company will upgrade its technology as long as the increase of profit from upgrading is large than the cost incurred. The upgrading threshold also increases with the variable cost of manufacturing and fixed cost incurred (i.e.,  and ). The single channel bunker company is less likely to upgrade its technology if a high cost is incurred.

From the expression of the threshold, we know that basic market demand (), competition intensity of the market (), and cost difference between LSF and HSF () also affect the single channel bunker company’s technology upgrading choice. We use numerical studies to investigate the impact of , , and  on the single channel bunker company’s technology upgrading choice to isolate the monotonicity of these parameters.

Figure 4 depicts the impact of basic market demand (i.e., ) on the single channel bunker company’s profits in scenarios U and N. It shows that the single channel bunker company is more (less) likely to upgrade its LSF refining technology when the basic market demand is high (low). The single channel bunker company can earn enough profit from ship operators when the basic market demand for fuel products is large and hence, the bunker company will be more motivated to upgrade its technology to satisfy ship operators’ increasing demand.

From Figure 5, we can see that the impact of competition intensity of the market (i.e., ) on the bunker company’s profit. The market competition becomes fierce and the substitution effect between LSF and HSF becomes large when  is large. However, such competition will not motivate the single channel bunker company to upgrade its technology early. By contrast, when market competition is fierce, the single channel bunker is less likely to upgrade its technology and only upgrades its technology when the increase of market demand is high. This result is consistent with that of in the dual channel setting and real practice. For instance, before the implementation of IMO 2020 sulfur cap, ship operators’ immediate demand can be satisfied by either purchasing LSF or HSF (i.e., a high market competition intensity and a large ). As such, single channel bunker company will not incur additional cost to upgrade its refining technology. However, with the enaction of IMO 2020 sulfur cap, LSF and HSF cannot substitute each other as sulfur emission level have to be complied with by ship operators. Hence, the single channel bunker company should upgrade its LSF refining technology to satisfy ship operators’ demand for LSF.

The impact of cost difference between LSF and HSF on the single channel bunker company’s profit before and after upgrading is shown in Figure 6. We can see that the increase of market demand that motivates the single channel bunker company to upgrade its technology is small when then cost difference between LSF and HSF is small. There is no optimal point for the single channel bunker company to upgrade its technology when the cost difference between LSF and HSF is large.



Figure 4. Impact of basic market on single channel bunker companies’ technology upgrading.



Figure 5. Impact of market competition on single channel bunker companies’ technology upgrading.



Figure 6. Impact of cost difference on single channel bunker companies’ technology upgrading.

We also use numerical example to examine the impact of market channel on the bunker companies’ profit in scenarios U and N, and the numerical result is illustrated in Figure 7. From Figure 7, we can see that bunker company in the dual channel setting is more likely to upgrading its technology than that of in the single channel setting where the bunker company sells both LSF and HSF. As explained earlier, the single channel bunker company not only needs to offset the upgrading cost but also needs to offset the profit loss from the HSF business. This implies that the dual channel bunker company is more likely to upgrade technology than that of the single channel bunker company and hence, incentives should be given to dual channel bunker company if technology upgrading is unavoidable.



Figure 7. Impact of market channel on dual channel and single channel bunker companies’ technology upgrading.

## 6. Discussion—impact of market uncertainty

In this section, we discuss how the market uncertainty of ship operators’ demand affect the bunker companies’ technology upgrading choice in the two market channels. To examine the impact of market uncertainty of ship operators’ demand on the bunker companies’ technology upgrading choice in the two market channels, we assume both the dual channel and single channel bunker company make their decisions after they observe the uncertainty of ship operators’ demand. The bunker companies’ optimal results do not change if the bunker companies do not upgrade their technology as the market uncertainty only affects the bunker companies’ demand function when new refining technology is implemented. The bunker companies’ profit functions in the dual channel and single channel settings after the upgrading of technology are the same as those in the basic model, and the optimal results are similar to that of in Tables 1 and 2. Hence, we omit the discussion. We use scenario U’ to denote this case when the bunker companies can make decision after the realization of ship operators’ demand uncertainty. Choosing to upgrade LSF’s refining technology is a strategic decision for a bunker company whether in a dual channel or single channel setting. Hence, we use bunker companies’ expected profits to measure the preferences over technology choice, and the equilibrium expected profits are summarized in Table 3.

**Table 3.** Bunker companies’ equilibrium expected profits after the realization of ship operators’ demand uncertainty.

|  |  |  |
| --- | --- | --- |
| Equilibrium profits | Scenario U’ | |
| Dual channel | Single channel |
|  |  |  |
|  |  |  |
|  |  |  |

We compare the dual channel and single channel bunker companies’ expected profits in Table 3 to investigate bunker companies’ technology upgrading choice, and the results are summarized in Proposition 3.

**Proposition 3.** The bunker companies’ technology upgrading choice in dual channel and single channel settings when ship operators’ demand uncertainty is realized are summarized as follow:

1. In the dual channel setting, the LSF bunker company prefers not to upgrade LSF technology if , i.e., , and the LSF bunker company prefers to upgrade LSF technology if , i.e., , where . The HSF bunker company prefers the LSF bunker company to upgrade its LSF technology if , i.e., , and the HSF bunker company prefers the LSF bunker company not to upgrade its LSF technology if , i.e., , where .
2. In the single channel setting, the bunker company that sells both LSF and HSF prefers not to upgrade LSF refining technology if , i.e., , and prefers to upgrade LSF refining technology if , i.e., , where .

Proposition 3 shows the impact of ship operators’ demand uncertainty on bunker companies’ technology upgrading choice in two different market channels. Consistent with the basic model, LSF bunker company in the dual channel setting or single channel bunker company that sells both LSF and HSF will prefer to upgrade its LSF refinery technology when the increase of the market demand is larger than a certain threshold, and prefers not to upgrade its technology when the increase of the market demand is at a low level. However, the threshold for the bunker companies to upgrade their technology in this scenario is smaller than that of in the basic model. In other words, when bunker companies make decisions after the realization of ship operators’ demand uncertainty, the bunker companies will be more likely to upgrade their technology. That is when the bunker companies have an accurate demand forecast, they can make more accurate decision.

In the previous section where the bunker companies make decisions before the realization of ship operators’ demand uncertainty, we show that HSF bunker company always prefers the LSF bunker company not to upgrade the technology as the HSF bunker company would need to decrease the production quantity and sales price of HSF. One may think that the HSF bunker company’s profit might be affected further because the realization of ship operators’ demand uncertainty will benefit the LSF bunker company which may further decrease the production quantity and sales price of HSF. However, we show a win-win situation for the LSF and HSF bunker companies. Proposition 3 implies that the HSF bunker company can also benefit from the LSF bunker company’s technology upgrading choice when the increase of the market demand is at a low level. The LSF bunker company’s information value will be spilled over to HSF bunker company, benefitting the HSF bunker company.

Note that a win-win situation for the LSF and HSF bunker companies can exist if the LSF bunker company upgrades or does not upgrade its refining technology and the specific condition depends on the value of two thresholds (see Figure 8). For instance, if , then the LSF bunker company upgrading its technology is a win-win solution for LSF and HSF bunker companies for  (see Figure 8a). While if , then the LSF bunker company not upgrading its technology is a win-win solution for LSF and HSF bunker companies for  (see Figure 8b).

The findings of Proposition 3 are illustrated in Figure 9. Figure 9 shows the impact of ship operators’ demand uncertainty on bunker companies’ technology upgrading choice in the two market channels. It shows the possibility that the bunker companies upgrade their technology will increase when these bunker companies can make decision after the realization of ship operators’ demand uncertainty. Bunker companies’ profit difference line, after and before upgrading of the technology also moves toward left when  increases from 1 to 2. This implies that a technology upgrading choice is more likely to be adopted when ship operators’ demand uncertainty is realized with a high value. This result is intuitive because more ship operators will choose LSF when the realization of demand uncertainty is at a high level and hence, bunker companies will be more likely to upgrade their technology. However, note that,  stands for the variance of ship operators’ demand uncertainty. A high value of means a high variance level of ship operators’ demand uncertainty and this may give bunker companies a high operational risk if they cannot identify such uncertainty.



Figure 8. Win-win solution for LSF and HSF bunker companies.



Figure 9. Impact of market uncertainty on dual channel and single channel bunker companies’ technology upgrading.

## 7. Conclusion

With the implementation of IMO 2020 sulfur cap, all ships operators need to reduce the sulfur content in their running fuels. To achieve this, some ship operators choose to switch from HSF to LSF, whereas some ship operators continue to use HSF by installing scrubbers. Installing scrubbers will incur a large initial investment cost and make ships to go on layup at the shipyard. Ship operators’ demand for LSF may increase substantially in a short time as ship operators cannot fulfill shipping demand when ships layup at the shipyard and wait for installing scrubbers. However, bunker companies that sell LSF may not be able to satisfy ship operators demand without upgrading their technology. In this paper, we examine the bunker companies’ technology upgrading choice in two market channels (i.e., dual channel and single channel) with the increase of ship operators’ demand but at the cost of production cost (both variable and fixed cost).

In the dual channel setting, LSF and HSF are respectively sold by two different bunker companies, whereas LSF and HSF are sold by the same bunker company in the single channel setting. We use Cournot model to depict the competition between LSF and HSF. Bunker companies’ optimal results before and after the upgrading of refining technology are investigated. Then, bunker companies’ strategic decision of whether they should upgrade their technology is examined based on the optimal results. We further investigated the impact of ship operators’ demand uncertainty on bunker companies’ technology upgrading choice.

We found that, in the dual channel setting when LSF and HSF are sold by two different bunker companies, LSF bunker company would increase the production quantity of LSF while HSF bunker company would decrease the production quantity of HSF with the upgrading of technology. However, the increase (decrease) of production quantity would not induce the LSF (HSF) bunker company to decrease (increase) the sales price of LSF (HSF). By contrast, the LSF (HSF) bunker company would increase (decrease) the sales price of LSF (HSF) with the increase (decrease) of production quantity as ship operators’ demand for LSF (HSF) would increase (decrease) substantially with the enaction of IMO 2020 sulfur cap even when the sales price has increased (decreased). Moreover, the aim of LSF bunker company to increase the sales price is to offset the cost incurred in the technology upgrading process. As a result, the LSF bunker company would upgrade its refining technology if the increase of the market demand is larger than a threshold. However, the LSF bunker company’s technology upgrading choice is always harmful to the HSF bunker company.

Consistent with the results in the dual channel setting, we found that the single channel bunker company that sells both LSF and HSF would also increase the production quantity of LSF and decrease the production quantity of HSF. The increase of the market demand should also be larger than a threshold to motivate the single channel bunker company to upgrade its technology. However, the single channel bunker company is less likely to upgrading its technology than that of in the dual channel setting. This is because, compared with the LSF bunker company in the dual channel setting, the single channel bunker company’s profit derives from selling both LSF and HSF. The production quantity and sales price of HSF would decrease simultaneously with the implementation of new technologies. If new technologies are adopted, the single channel bunker company not only needs to offset profit loss from HSF but also incurs cost to upgrade. Hence, in the single channel setting, the bunker company is less likely to upgrade its technology.

The bunker companies’ technology upgrading choice is also affected by several parameters, such as those of the basic market demand (), competition intensity of the market (), and the cost difference between LSF and HSF ().Bunker companies’ motivation to upgrade their technology increases with the basic market demand but decreases with the cost difference between LSF and HSF. This is because more ship operators will purchase the product when the basic market demand is high. On the other hand, bunker companies are at a disadvantage position when they have to produce at high cost and hence, a larger motivation is needed if they choose to upgrade the technology. For the market competition, one may think that the fierce competition between LSF and HSF would induce the bunker companies to upgrade their technology. However, it is surprising to note that bunker companies are more likely to implementing new technology when the competition intensity of the market is at a low level. Perhaps because of the uniqueness of the product, influencing the bunker companies to upgrade the technology when market competition is mild.

We further examined the impact of market uncertainty on bunker companies’ technology upgrading choice. We found that bunker companies would make more accurate decisions with the realization of ship operators’ uncertainty. Bunker companies would be more likely to implementing new technology if ship operators’ demand uncertainty is realized with a high value. Moreover, LSF bunker company’s information value would be spilled over to HSF bunker company and creates a win-win solution for LSF and HSF bunker companies. The win-win solution for LSF and HSF bunker companies exists whether the LSF bunker company upgrades or does not upgrade its technology. This result is completely different from that of in the basic model where the bunker companies make upgrading decision before the realization of ship operators’ demand and upgrading is always harmful to the HSF bunker company.

Ship operators must make some changes in response to the implementation of IMO 2020 sulfur cap which will greatly affect the bunkering market. As such, bunker companies also need to take some measures to respond to the changes. The results in this study provide managerial guidance for bunker companies in the marine industry. We investigated the conditions under which bunker companies shall upgrade their technology, considering market competition, upgrading cost, product substitution, ship operators’ demand uncertainty, and two different market channels (i.e., dual channel and single channel). Grounded on marine bunker industry, our results can also be extended to other real practices. Technology upgrading choice is a strategic decision that many firms need to consider in their daily operations, and our research can also provide valuable managerial insights for these firms interested in upgrading technology with similar market conditions.

There are some limitations in this study that need further exploration. First, the environmental impact of LSF and HSF product is not considered in this study. In fact, products’ environmental performance is an important motivation for firms to implement new technology with the increasingly tight environment regulation. Second, we do not consider government policy in this research. Government plays an important goal in technology upgrading process either through subsidy or tax and which will incentive firms to implement a new and environmentally friendly technology. Therefore, it would be very interesting to combine government’s role with firms’ technology upgrading process.

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**Appendix: Proofs**

**Proof of Table 1**

The decision problems faced by LSF and HSF bunker companies before upgrading of technology are given by  and . LSF and HSF bunker companies make their production quantity decisions simultaneously and indepedently. LSF and HSF bunker companies’ optimization problem is concave with respect to  and  as  and . The first-order conditions of  and  are:



.

Solving the two formulas simultaneously, we obtain  and . The LSF and HSF bunker companies’ optimal results in scenario N in Table 1 can be obtained by substituting  and .

Proofs of the rest of the optimal results in Table 1, Tables 2 and 3 are similar to that of scenario N in dual channel setting, so we omit the proving process.

**Proof of Lemma 1**

To prove Lemma 1, we need to compare bunker companies’ optimal results before and after upgrading of technology in the dual channel setting. We have , , , and .

Based on these, it is easy to prove Lemma 1.

**Proof of Proposition 1**

For the HSF bunker company, it is easy to prove that  since  and . While for the LSF bunker company, we need to compare LSF bunker company’s equlibrium profit before and upgrading of technology. Hence, we have. To solve the roots of , we have . The feasible condition for this scenario is  and hence,  is the only feasible solution for . Based on these, it is easy to prove the first part of Propostion 1.

**Proof of Lemma 2**

To prove Lemma 2, we compare the single channel bunker company’s optimal results before and upgrading of technology. We have , , , and . Based on these, it is easy to prove Lemma 2.

**Proof of Proposition 2**

To prove Proposition 2, we compare the single channel bunker company’s equilibrium profits before and after upgrading of technology. We have . To solve the roots of , we have , whereas  is the only feasible solution. Based on these, it is easy to prove Proposition 2.

**Proof of Proposition 3**

To prove Proposition 3, we need to compare bunker companies’ optimal results before and after upgrading of technology in dual channel and single channel setting when bunker companies can make decision after the realization of ship operators’ demand uncertainty. Hence, we have , , and .

We need to obtain the roots of , , and  to prove Proposition 3. To solve the roots of , we have . The roots for  are , and the roots for  are . Note that, all the roots are not necessarily the feasible solutions and hence, we need to consider feasible conditions for each root. Based on these, it is easy to prove Proposition 3.

This completes the proof.

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