Evaluation of Liquefied Natural Gas as a ship fuel for liner shipping using evolutionary game theory

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Abstract: Strict limits on air emissions released by burning fuel of ships have recently been imposed in Emission Control Areas. Retrofitting ships to use Liquefied Natural Gas (LNG) as a ship fuel is one of methods for liner companies to comply with global regulations. Since the LNG retrofitting investment is expensive, it is likely that liner companies need a more scientific methodology to evaluate the LNG for propulsion of ships. Liner companies are particularly interested in their profits determined by the pricing decision. Based on the evolutionary game theory, this paper develops a mathematical model for the pricing problem with the consideration of market competition, LNG investment, and price elasticity. We also consider several realistic factors, such as the demand sensitivity for LNG effort, to make the proposed methodology meet the realistic demands when more and more liner companies need a revolutionary transformation because of the stricter regulations. Numerical experiments, including a simulated-data case, are performed to validate the proposed methodology. Some managerial insights are concluded according to the computational experiments and sensitivity analysis.

Keywords: LNG; Pricing decision; Evolutionary game theory; Green shipping.

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1 Introduction

Shipping industry plays a vital role in the international trade and the global economy. Supported by the global economic recovery, about 11 billion tons of cargo were transported by shipping (UNCTAD, 2019). Although shipping activities have significant contributions, they have harmful effects on the global environment and human health because of tremendous air emissions. Air emissions released by ships are directly relevant to the fuel burning (Cullinane and Bergqvist, 2014). Particularly, marine fuel normally has a very high sulphur content, which means that the shipping industry actually emits more sulphur related air emissions than other means of transportation when consuming the same amount of fuel. Sofiev et al. (2018) estimated that even low-sulphur marine fuels still account for about 6.4 million childhood asthma cases and about 250 thousand deaths annually.

Currently, ships use diesel engines to burn heavy fuel oil (HFO[1]) releasing sulphur oxide (SO_X), carbonic oxide, and nitrogen oxide (NO_X) emissions since HFO is less expensive. Hence, the air pollution from marine transport becomes an emergent problem for the global environment. In order to regulate ships that move between different jurisdictions, the Marine Environment Protection Committee of the International Maritime Organization requires ships operating all over the world to reduce the sulphur emissions to 0.5% from 2020 (IMO, 2016). Compared to HFO, LNG has extremely low contents of SO_X, NO_X and particle matter (Wang and Notteboom, 2014). More specifically, compared to emissions of burning HFO, SO_X and PM emissions of using LNG are reduced by around 100%, NO_X by up to $85-90\%$, and CO_2 by about 15–20% (Brett, 2008; Pitt et al., 2010; Bengtsson, 2011).

The main component of LNG is methane, and natural gas will turn from gas to liquid when it is cooled to about -162℃ under atmospheric pressure (Aymelek et al., 2014). LNG is a kind of high quality, efficient and clean low-carbon energy, which is favored by countries all over the world due to its economic and environmental advantages. Throughout the history of shipping, the LNG technology appeared relatively late, so the research on LNG maritime transportation also appeared relatively late. In the mid and late 20th century, the first LNG ship

[1] HFO is high sulphur fuel oil with a sulphur content of greater than 0.5%.

has been put into maritime shipping makes the LNG seaborne trade begin. Since then, because of the unbalanced distribution of world natural gas energy and the increase in demand for natural gas energy from the rest of the world, the LNG technology gets rapid development.

Hence, this study is motivated by this realistic problem during the development of green shipping. The goal of green shipping is achieving the sustainable economy development by balancing the trade-off between environmental protection and productivity activities (Cheng et al., 2013). With stricter emission regulations, shipping companies may be willing to apply some green technologies to deal with this intractable issue because the operating cost is relatively low compared with fuel switching whose investment cost is very low (Zhen et al., 2020). For instance, in 2015, China COSCO Shipping Group spent 27 million USD to burn marine gas oil than it used HFO before (Zhen et al., 2019). But the investments in LNG retrofitting are usually expensive. For example, for a ship of 3,000 tons, the retrofitting cost of using LNG is nearly 230 thousand USD (LNG, 2019). Therefore, using LNG for propulsion for liner shipping is a strategic decision, which needs serious consideration as well as decision supports.

Since the above mentioned issue is vital, based on the evolutionary game theory, this study proposes a pricing decision model with the consideration of market competition, LNG investment, and price elasticity. We also consider several realistic factors, such as the demand sensitivity for LNG switching effort, to make the proposed methodology meet the realistic demands when more and more liner companies need a revolutionary transformation because of the stricter regulations.

The remainder of the paper is organized as follows. Section 2 introduces an overview of related studies. The proposed model formulation is introduced in Section 3. Section 4 shows the numerical experiments with a simulated-data case and sensitivity analysis. Conclusions are summarized in Section 5.

2 Literature review

This paper proposes a quantitative decision methodology to evaluate LNG for propulsion for liner shipping using evolutionary game theory. The research methods in this paper are mainly related to LNG technology, competition and pricing in liner shipping, and evolutionary game theory. Hence, the following three paragraphs review three streams of related literature on these three fields.

The first stream of studies is concerned with the application of LNG technology. Most of the research on LNG is based on the path problem from the perspective of supply chain. Grønhaug and Marielle (2009) studied the planning of actual transport in the LNG offshore supply chain, which involved the size and volume of the fleet using LNG. Andersson et al. (2010) developed a mathematical model to solve a LNG sea transportation inventory routing problem. Recently, fleet deployment, ship allocation and ship scheduling are considered in the study of LNG. However, these problems are only mentioned and studied as constraints. Halvorsen-Weare and Fagerholt (2013) studied the path planning of the offshore transport of LNG. Based on the signed LNG long and short term transport contracts, Fodstad et al. (2010) considered the impact of the price fluctuation caused by seasonal changes on the LNG transport market, and developed some reasonable plans of routing lines, fleet deployment and inventory management, so as to provide optimal decision-making strategies for LNG offshore transport. From the perspective of LNG suppliers, Stålhane et al. (2012) aimed to maximize the profit of suppliers by minimizing the total cost in long-term contracts. Uggen et al. (2013) firstly proposed an LNG fleet deployment problem in the case of invariant time and variable time by using a time decomposition combined with heuristic algorithm method. Bouman et al. (2017) provided a review of greenhouse gas reduction measures, including LNG, shore power, alternative fuels and so on, and their potential in shipping.

The second topic of related studies explores the competition and pricing problems in maritime industry. Scholars in maritime industry have studied the competition and pricing problems for a long time (Zheng et al., 2017). Numerous models were proposed for this issue (Lee and Song, 2017). Zhou and Lee (2009) developed a mathematical model to investigate the pricing strategy and study the outcome of competition in a shipping network. Yin and Kim (2012) proposed a new methodology for a quantity discount pricing problem to optimize container lines' tariffs to maximize their profits. Wang et al. (2014) studied Nash game, Stackelberg game and deterrence models to investigate the competition between two liner companies in a new market. Chen et al. (2016) proposed two models to investigate the competition and pricing problems in liner shipping consideration of empty container reposition.

Zheng et al. (2017) found the Nash equilibrium solutions when studying pricing strategies for two competitors with risk aversion. Choi et al. (2020) investigated a pricing problem for competitive liner companies to investigate whether the risk seeking behaviors do more good than harm.

The last stream of studies explores the evolutionary game theory. Game theory is a useful mathematical tool for scholars to show the interactions as well as investigate behaviors between players (Lin et al., 2021). Many analyses on maritime policy implications were conducted according to the game theory (Zhou and Yuen, 2021). Smith (1976) proposed an evolutionary game method whose players were boundedly rational and can learn from their rivals in order to fit the market environment. Weibull (1997) introduced the current evolutionary game theory, especially the deterministic models of games in the normal form. Friedman (1998) showed the considerable potential of the evolutionary game theory for solving substantive economic issues. Wang et al. (2015) proposed a static and an evolutionary game models studying mutual effects between vehicle manufacturers and the government. Mahmoudi and Rasti-Barzoki (2018) used a bi-population of supply chains and retailers to study how government policy influences manufacturers' strategies. Johari et al. (2019) proposed a one-population evolutionary game to investigate different strategies of manufacturers.

In summary, many studies on the green shipping problem disregarded the application of the LNG technology. Although some related literatures did consider this, they did not incorporate pricing decision, market competition, and LNG investment. Moreover, some other limits, such as the price elasticity, have also been frequently ignored. But these neglected factors are important to seaborne activities.

3 Model formulation

We consider two operational strategies for liner companies to conduct their shipping business. The first operational strategy is using LNG as a ship fuel, which can help to reduce global air emissions. Another operational strategy is non-LNG strategy which allow ships to use HFO. These two operational strategies have different advantages and drawbacks. For example, when the market population is sensitive toward the environment, liner companies choosing LNG technology may be more popular and gain more market share than their rivals choosing non-LNG technology because using HFO releases tremendous air emissions, although it is cost-effective. However, applying LNG technology is not economically feasible because of the high installation cost for retrofitting ships (Aymelek et al., 2014).

This study formulates a pricing model considering the LNG technology, price elasticity, and the market competition. More specifically, we assume that there are two liner companies (players) in the competition. Three scenarios are considered in this study to investigate different strategies. The first scenario is that both liner companies choose the LNG strategy, denoted by (L, L). The second scenario is that one of liner companies adopts the LNG strategy and the other adopts the non-LNG strategy, denoted by (L, N). The last scenario is that both liner companies choose the non-LNG strategy, denoted by (N, N). Many researchers used the evolutionary game theory to analyze maritime problems, especially emission control measures. Jiang et al. (2018) developed an evolutionary game model to study the evolutionary stability of the unilateral strategy and the mixed strategy of the government and the shipping company. Jiang et al. (2020) proposed an evolutionary game model to analyze the differences in the benefits of the government and shipping companies in the implementation of China's ECA supervision. Moreover, some studies investigated the strategical behavior within one population under the competition market. Johari et al. (2019) proposed a one-population evolutionary game to investigate different strategies of manufacturers. Lin et al. (2021) developed a one-population evolutionary game model to evaluate green strategies in liner shipping. Hence, we propose a one-population evolutionary game model to consider the pricing problem under different scenarios.

Based on the above analysis, this study develops a mathematical model. Some assumptions are summarized as follows:

(I) Liner companies (players) take part in a one-shot game where both companies make decisions without coordination simultaneously.

(II) Each player should choose one strategy between LNG and non-LNG strategies.

(III) The investment in retrofitting ships for using LNG is approximated by a quadratic function of the effort of LNG retrofitting by the liner company, which shows the diminishing returns for LNG efforts (Jamali and Rasti-Barzoki, 2018; Lin et al., 2021).

The notation used in this paper is summarized as follows.

Indices and sets

I — set of strategies, index i (j), $i = 1{,}2$. Strategies 1 and 2 correspond to LNG and non-LNG strategies, respectively.

Parameters

M — market size.

k — demand self-price elasticity.

l — demand cross-price elasticity.

m — demand sensitivity for LNG switching effort of one liner company.

n — demand sensitivity for LNG switching effort of the liner company's rival.

r — investment cost for LNG retrofitting.

f — freight cost for liner companies.

Variables

φ_{ij} — price charged by the liner company that chooses strategy i if its rival chooses strategy j.

ω_{ij} — effort of LNG retrofitting by the liner company that chooses strategy i if its rival chooses strategy j.

π_{ij} — demand of the liner company that chooses strategy i if its rival chooses strategy j.

β_{ij} — payoff of the liner company that chooses strategy i if its rival chooses strategy j.

Mathematical model

$$\pi_{ij} = M - k\varphi_{ij} + l\varphi_{ji} + m\omega_{ij} - n\omega_{ji} \qquad \forall i \in, j \in I \tag{1}$$

$$\beta_{ij} = (\varphi_{ij} - f)(M - k\varphi_{ij} + l\varphi_{ji} + m\omega_{ij} - n\omega_{ji}) - r\omega_{ij}^2 \qquad \forall i \in I, j \in I \tag{2}$$

$$\pi_{ji} = M - k\varphi_{ji} + l\varphi_{ij} + m\omega_{ji} - n\omega_{ij} \qquad \forall i \in I, j \in I \tag{3}$$

$$\beta_{ji} = (\varphi_{ji} - f)(M - k\varphi_{ji} + l\varphi_{ij} + m\omega_{ji} - n\omega_{ij}) - r\omega_{ji}^2 \qquad \forall i \in I, j \in I. \tag{4}$$

Formula (1) calculate the demand value of the first liner company if it chooses strategy i when the other liner company chooses strategy j. Formula (2) define the payoff function of liner company 1 when liner company 1 chooses strategy i if liner company 2 chooses strategy j. Formula (3) and (4) introduce the demand and payoff functions for the second liner company. Recall that three scenarios are considered in this paper. The first scenario corresponds to both liner companies choosing LNG strategy (i.e., ω_{ij} and ω_{ji} are positive). Under this condition, the payoff function of liner companies 1 and 2 are both convex in φ_{ij}, φ_{ji}, ω_{ij} and ω_{ji}. The second scenario corresponds to one liner company choosing the LNG strategy and the other choosing non-LNG strategy (i.e., ω_{ij} is positive, and ω_{ji} is zero), which leads to that the payoff functions of liner companies 1 and 2 are convex in φ_{ij}, φ_{ji} and ω_{ij}. The last scenario is both liner companies choosing non-LNG strategy (i.e., ω_{ij} and ω_{ji} are zero), which leads to that payoff functions of both liner companies are convex in φ_{ij} and φ_{ji}.

Next, we introduce the temporal dynamic model of the liner companies' behavior based on the evolutionary game theory. First, three important definitions are concluded in the following.

$players$ two liner companies playing a competitive game in a shipping market.

$strategies$ two green strategies considered in the game (LNG and non-LNG strategies).

$payoffs$ profit gained by a player in each game.

The evolutionarily stable strategy is the basic conception of evolutionary game theory. We use a one-population game to decide evolutionary behaviors of liner companies and evaluate LNG or non-LNG strategies would be chosen. Recall that players will finally adopt their own strategy which offers a better-than-average payoff (Lin et al., 2021). Based on the related work of Barron (2013), a time-dependent formulae is proposed to obtain the time dependence in the proposed game model. Two strategies are considered in the game, which are the LNG strategy (denoted by S_L) and the non-LNG strategy (denoted by S_N). We also define percentage values of the population choosing LNG strategy and non-LNG strategy to be p_L and p_N, respectively. Hence, the set of strategies is defined as $\gamma = \{p_{S_L}, p_{S_N}\}$. The payoff of liner company 1 using S_i and its competitor choosing strategy S_j is defined as β_{ij}. The set including the percentage values of the population choosing different strategies is defined as γ. Hence, the expected payoff (denoted by P) of liner company 1 choosing strategies S_L and S_N can be calculated by formula (5) and (6), respectively. And the payoff matrix of the first liner company is $\begin{bmatrix} \beta_{ij} & \beta_{ij} \\ \beta_{ij} & \beta_{ij} \end{bmatrix}$. Besides, the expected payoff value of the population can be calculated by formulae (7).

$$P(S_L, \gamma) = \left(p_{S_L} \times \beta_{LL}\right) + \left(p_{S_N} \times \beta_{LN}\right) \tag{5}$$

$$P(S_N, \gamma) = \left(p_{S_L} \times \beta_{NL}\right) + \left(p_{S_N} \times \beta_{LN}\right) \tag{6}$$

$$P(\gamma,\gamma) = p_{S_L} \times P(S_L,\gamma) + p_{S_N} \times P(S_N,\gamma). \tag{7}$$

Recall that the evolutionary property of the evolutionary game theory, this study assumes that the percentage values of all strategies (γ) change over time, which means the strategy whose expected payoff is larger than the mean value is adopted by the majority. Hence, we use a replicator dynamic formulae (8) (Bomze, 1983) to model the above mentioned learning behavior.

$$\frac{dp_{S_L}(t)}{dt} = p_{S_L}(t) \times [P(S_L,\gamma(t)) - P(\gamma(t),\gamma(t))]. \tag{8}$$

Recall that p_{S_L} and p_{S_N} denote the percentage values of the population choosing LNG and non-LNG strategies, respectively, which means $p_{S_L}(t) + p_{S_N}(t) = 1,\ 0 \le p_{S_L}(t) \le 1$ and $0 \le p_{S_N}(t) \le 1$. It is noted that when the value of $\frac{dp_{S_L}(t)}{dt}$ equals zero, a stationary solution will be obtained in the above mentioned replicator dynamic formula, and the solution $\gamma^* = \{p^*_{S_L}, p^*_{S_N}\}$ denotes a stationary solution in the end.

This study considers a one-population model, and the evolutionarily stable strategy and payoff matrix must be symmetrical for two individuals in one population model (Xiao and Yu, 2006). Besides, in game theory, Nash equilibrium (Nash, 1950) means that strategies of each player are the best response in this game, which means the evolutionarily stable strategy is a Nash solution (Apaloo et al., 2014). More specifically, the stationary solutions are obtained when $\frac{dp_{S_L}(t)}{dt} = 0$, which is equivalent to

$$dp_{S_L}(t)/(p_{S_L}(t) \times p_{S_N}(t) \times ((\beta_{LL} - \beta_{NL}) \times p_{S_L}(t) - (\beta_{NN} - \beta_{LN}) \times p_{S_N}(t))) = dt. \tag{9}$$

According to Lin et al. (2021), the implicitly defined solution to formulae (9) is

$$\left((\beta_{LL} - \beta_{NL}) \times p_{S_L}(t) - (\beta_{NN} - \beta_{LN}) \times p_{S_N}(t)\right)^{\frac{1}{\beta_{LL}-\beta_{NL}} + \frac{1}{\beta_{NN}-\beta_{LN}}} / \left(|p_{S_N}(t)|^{\frac{1}{\beta_{LL}-\beta_{NL}}} \times p_{S_L}(t)^{\frac{1}{\beta_{NN}-\beta_{LN}}}\right) = Xe^t \tag{10}$$

where X is a positive constant. It is obvious when $t \to \infty$, the right side of formulae (10) (Xe^t) goes to infinity.

Hence, there are three cases about the stationary solutions for formulae (8):

(I) Firstly, the game has only one evolutionarily stable strategy if $(\beta_{LL} - \beta_{NL}) \times (\beta_{NN} - \beta_{LN}) < 0$. Hence when $\beta_{LL} - \beta_{NL} > 0$ and $\beta_{NN} - \beta_{LN} < 0$, p_{S_L} must go to one to make the left side approach infinity (i.e., evolutionarily stable strategy $\gamma^* = \{1,1\}$) while when $\beta_{LL} - \beta_{NL} < 0$ and $\beta_{NN} - \beta_{LN} > 0$, p_{S_L} must go to zero (i.e., evolutionarily stable strategy $\gamma^* = \{0,0\}$).

(II) When $\beta_{LL} - \beta_{NL} > 0$ and $\beta_{NN} - \beta_{LN} > 0$, the left side goes to infinite when $p_{S_L} \rightarrow$ 0 or 1. And there are three Nash equilibria: $\gamma^* = \{1,1\}$, $\gamma^* = \{0,0\}$ are evolutionarily stable strategies, but the mixed Nash $\{\frac{\beta_{NN}-\beta_{LN}}{\beta_{LL}-\beta_{LN}-\beta_{NL}+\beta_{NN}}, \frac{\beta_{LL}-\beta_{NL}}{\beta_{LL}-\beta_{LN}-\beta_{NL}+\beta_{NN}}\}$ is not evolutionarily stable strategy.

(III) When $\beta_{LL} - \beta_{NL} < 0$ and $\beta_{NN} - \beta_{LN} < 0$, the left side $\rightarrow 0$ when $p_{S_L} \rightarrow 0$ or 1, which leads to two pure Nash equilibria, $\gamma^* = \{1,1\}$ and $\gamma^* = \{0,0\}$, are not evolutionarily stable strategy. p_{S_L} will converge to the mixed Nash equilibria $\gamma^* = \{\frac{\beta_{NN}-\beta_{LN}}{\beta_{LL}-\beta_{LN}-\beta_{NL}+\beta_{NN}}, \frac{\beta_{LL}-\beta_{NL}}{\beta_{LL}-\beta_{LN}-\beta_{NL}+\beta_{NN}}\}$, and this Nash equilibria γ^* is evolutionarily stable strategy.

Recall that three scenarios are considered in this paper. The payoff function (i.e., β) is influenced by the strategies chosen by two players. Table 1 shows the payoff matrix of two selected liner companies.

Table 1: Payoff matrix of two selected liner companies

		Liner company 2	
		LNG	Non-LNG
Liner company 1	LNG	β_{LL}, β_{LL}	β_{LN}, β_{NL}
	Non-LNG	β_{NL}, β_{LN}	β_{NN}, β_{NL}

In terms of the scenario 1, both selected liner companies choose the LNG strategy, which means the results for two players are the same. The payoff of the liner company 1 under the scenario 1 can be calculated by formulae (11). Because of the symmetric property, the payoff of the liner company 2 under the scenario 1 can also be calculated by formulae (11).

$$\beta_{LL} = (\varphi_{LL} - f)(M - k\varphi_{LL} + l\varphi_{LL} + m\omega_{LL} - n\omega_{LL}) - r\omega_{LL}^2. \quad (11)$$

According to formulae (11) we can find the condition for concavity of β_{LL} in φ_{LL} and ω_{LL}. Formulae (12) shows the Hessian matrix of the payoff value in the first scenario.

$$H(\beta_{\varphi\omega}) = \begin{bmatrix} \frac{\partial^2\beta}{\partial\varphi^2} & \frac{\partial^2\beta}{\partial\varphi\partial\omega} \\ \frac{\partial^2\beta}{\partial\omega\partial\varphi} & \frac{\partial^2\beta}{\partial\omega^2} \end{bmatrix} = \begin{bmatrix} 2l-2k & m-n \\ m-n & -2r \end{bmatrix}. \tag{12}$$

Under the below conditions (13) and (14), the Hessian matrix is positive. Hence, the optimal values of the variables are calculated by formula (15)−(18).

$$2l-2k > 0 \tag{13}$$

$$(2l-2k)\times(-2r)-(m-n)^2 = 4kr-4lr-m^2-n^2+2mn > 0 \tag{14}$$

$$\varphi_{LL} = \frac{2Mr+2kfr+fm(n-m)}{4kr-2lr+m(n-m)} \tag{15}$$

$$\omega_{LL} = \frac{m(M+f(l-k))}{4kr-2lr+m(n-m)} \tag{16}$$

$$\pi_{LL} = \frac{2kr[M+f(l-k)]}{4kr-2lr+m(n-m)} \tag{17}$$

$$\beta_{LL} = \frac{r(4rk-m^2)(M+f(l-k))^2}{[4kr-2lr+m(n-m)]^2}. \tag{18}$$

In terms of scenario 2, the two selected liner companies choose different strategies. We assume that liner company 1 chooses the LNG strategy and liner company 2 chooses the non-LNG strategy. Hence, the payoff functions of liner companies 1 and 2 are denoted as β_{LN} and β_{NL}, respectively, and can be calculated by formula (19) and (20), respectively.

$$\beta_{LN} = (\varphi_{LN}-f)(M-k\varphi_{LN}+l\varphi_{NL}+m\omega_{LN})-r\omega_{LN}^2 \tag{19}$$

$$\beta_{NL} = (\varphi_{NL}-f)(M-k\varphi_{NL}+l\varphi_{LN}-n\omega_{LN})-r\omega_{LN}^2. \tag{20}$$

Similar to above, we find that under the second scenario, the payoff function of the first liner company is concave in φ_{GN} and ω_{GN}, and the payoff function of the other is concave in φ_{NG}. Thus, optimal values of variables of both liner companies can be calculated by formula (21)−(23), and (24)−(25), respectively.

$$\varphi_{LN} = \frac{2rk(2m+2kf+lf)+2Mr+mf(ln-2mk)}{2k(4rk-m^2)+l(mn-2rl)} \tag{21}$$

$$\omega_{LN} = \frac{m(2k+l)(M+f(l-k))}{2k(4rk-m^2)+l(mn-2rl)} \tag{22}$$

$$\beta_{LN} = \frac{2rk(4rk-m^2)(2k+l)^2(M+f(l-k))^2}{[2k(4rk-m^2)+l(mn-2rl)]^2 2k} \tag{23}$$

$$\varphi_{NL} = \frac{2r(2k+l)(M+kf)+Mm(m+n)-mf(m(k+l)-kn)}{2k(4rk-m^2)+l(mn-2rl)} \tag{24}$$

$$\beta_{NL} = \frac{k[M+f(l-k)]^2[4rk+2lr-m(m+n)]^2}{[2k(4rk-m^2)+l(mn-2rl)]^2}. \tag{25}$$

Under scenario 3, both liner companies adopt non-LNG strategy, which means the best results for both players are the same. We use β_{NN} to denote the payoff function of the liner company 1 and the values of β_{NN} can be calculated by formulae (26).

$$\beta_{NN} = (\varphi_{NN} - f)(M - k\varphi_{NN} + l\varphi_{NN}). \tag{26}$$

It is obvious that the second-order derivative of β_{NN} with respect to α_{NN} is $-2k < 0$, which means that under the third scenario, the payoff function of the first liner company (β_{NN}) is concave in φ_{NN}. Besides, optimal values of variables are calculated by formula (27)−(29).

$$\varphi_{NN} = \frac{M+fk}{2k-l} \tag{27}$$

$$\pi_{NN} = \frac{k[M+f(l-k)]}{2k-l} \tag{28}$$

$$\beta_{NN} = \frac{k[M+f(l-k)]^2}{(2k-l)^2}. \tag{29}$$

Optimal values of the variables of the second liner company are the same with those of the liner company 1.

4 Computational experiments

In order to analyze the market demands, pricing decisions, LNG switching effort, and payoff values for liner companies under three scenarios, we perform several computational experiments. More specifically, the optimal solutions under three scenarios are obtained by solving the pricing model. Then the evolutionary game theory model is solved to find LNG or non-LNG strategies will be chosen by the majority.

4.1 Experimental setting

The setting of all parameter values is firstly summarized. The shipping market size is set to 100. The values of own-price and cross-price elasticities of demand are set to 1.0 and 0.2, respectively. The values of demand sensitivity for LNG switching efforts of one liner company and its rival are set to 1.1 and 0.6, respectively. The investment cost for LNG switching is set to 0.35. And the freight cost for a liner company is set to 20. The above experimental setting is based on the data from related works (Astrom et al., 2018; Raj et al., 2018; Johari et al., 2019; and Lin et al., 2021)

4.2 Base analysis

For the base analysis, we present the results for three scenarios and compare the optimal values of variables under different scenarios.

Optimal values of decision variables (i.e., ω_{ij}, α_{ij}, π_{ij} and β_{ij}) under three different scenarios are recorded in Table 2. It is noted that when one liner company and its competitor choose different strategies (scenario 2), both of them can charge the highest prices. Besides, according to the results under scenario 2, the liner company choosing the green strategy can obtain the maximum payoff while its competitor needs to reduce its price to stay competitive, which leads to a lower payoff. Under scenario 3 (both liner companies choosing the non-green strategy), both of liner companies charge the least prices, but not obtain the least payoffs because they do not need to spend extra money to retrofit ships. Based on the evolutionary game model, we also obtain the evolutionarily stable strategy $\gamma = \{p_{S_L}, p_{S_N}\} = (0.7619, 0.2381)$, which indicates that choosing the LNG strategy is more beneficial and will be chosen by the majority of liner companies (76.19%).

Table 2: Optimal values of variables under different scenarios

Variables	Scenario 1 (LL)	Scenario 2 (LN)	Scenario 3 (NN)
LNG switching effort of liner company 1 (ω_{ij})	130.14	420.00	-
Price of liner company 1 (α_{ij})	102.82	402.98	66.67
Demand of liner company 1 (π_{ij})	82.82	267.27	46.67
payoff of liner company 1 (β_{ij})	930.82	9694.71	2177.78
LNG switching effort of liner company 2 (ω_{ji})	130.14	-	-
Price of liner company 2 (α_{ji})	102.82	735.45	66.67
Demand of liner company 2 (π_{ji})	82.82	4.58	46.67
payoff of liner company 2 (β_{ji})	930.82	3280.17	2177.78

4.3 Sensitivity analysis and managerial insights

Some model parameters may affect the decisions of the liner companies. In the remainder of this section, we examine the influence of the investment cost for LNG switching.

We study the influence of the investment cost (i.e., r) for LNG switching on the payoffs as shown in Fig. 1. When both liner companies choose the non-LNG strategy, both of companies do not need to pay the LNG investment cost, and the changes in LNG investment cost have no effect on payoffs of both liner companies. But when one liner company chooses the LNG strategy and its competitor chooses the non-LNG strategy, the payoff of the liner company choosing the LNG strategy is always higher than that of the liner company choosing the non-LNG strategy, which means that increasing LNG investment costs make liner companies choosing non-green strategy more competitive.

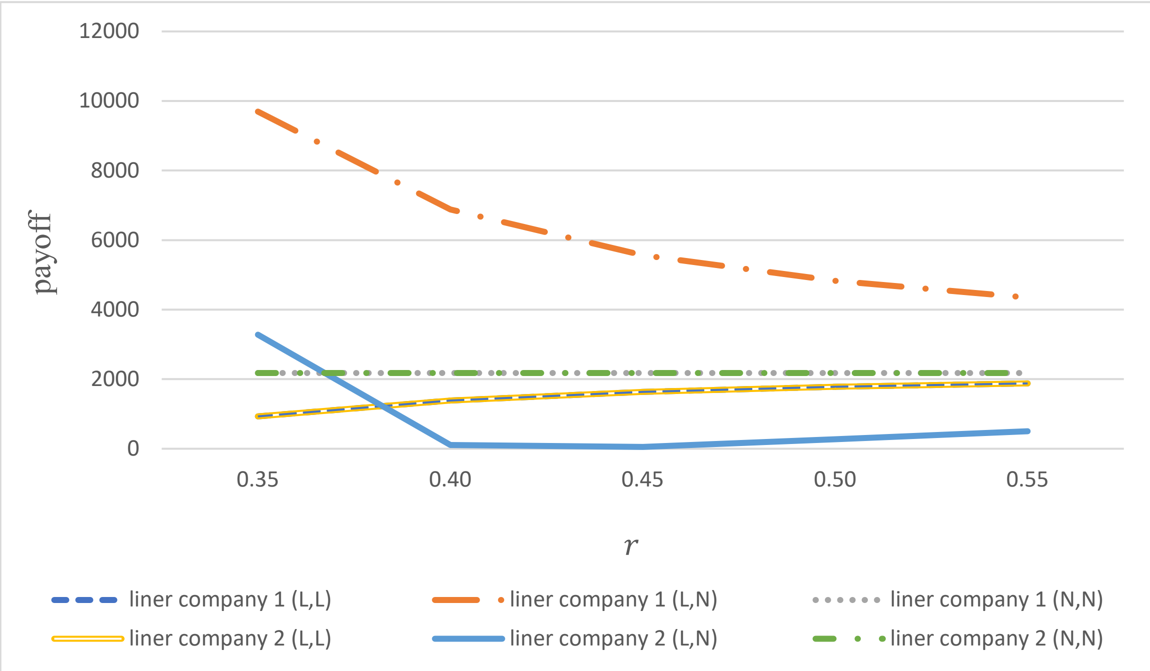

Figure 1: Influence of the investment cost (i.e., r) for LNG switching on the payoffs

5 Conclusions

This study develops an evolutionary game theory model to evaluate the LNG as a ship fuel for liner shipping. Each of two liner companies randomly selected from one population chooses either LNG strategy or non-LNG strategy in this game. Payoff functions are determined by the pricing decision and the LNG switching effort by two competitors. Hence, this study analyzes the optimal payoff values under different scenarios in order to obtain some management implications. This study may have two contributions by comparing with the related works.

(I) This study introduces the evaluation of LNG for propulsion for liner shipping using evolutionary game theory. We provide the quantitative methodologies to solve a pricing problem for maritime industry with the consideration of price elasticity, LNG investment, and market competition. Besides, we also consider some realistic operating limits, such as the demand sensitivity for LNG switching effort, which have been usually neglected in existing studies although these factors are important to the realistic green shipping.

(II) Based on the extensive computational study, including a simulated-data case and sensitivity analysis, we draw out some important managerial suggestions on green shipping. For instance, the majority of liner companies chooses the LNG strategy and the benefit of the LNG strategy is vilified. Besides increasing LNG investment costs make the liner company choosing non-green strategy more competitive.

However, this study also has limitations. Presently, we consider only one-population game. The possibility of two-population game can be analyzed in future studies. Besides, government subsidies can be considered in future studies because the investment in retrofitting ships using LNG is expensive.

Acknowledgements

This study is supported by the Research Grants Council of the Hong Kong Special Administrative Region, China (Project number 15202719) and the National Natural Science Foundation of China (Grant numbers 72071173, 71831008).

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