SHIP INVESTMENT: SHIP PRICE-FREIGHT RATE RELATIONSHIP, OPTION VALUE AND STRATEGIC BEHAVIOUR

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CERTIFICATE OF ORIGINALITY

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__________________(Signed)

Kou Ying (Name of student)

ABSTRACT

This thesis focuses on ship investment decision in the shipping industry. It addresses three specific research questions: 1) How does the ship investment cost, as represented by ship price, relate to the freight rate in the shipping market? What is the influence of the famous cyclic nature of freight rate on the ship price? 2) What is the minimal market freight for ship investment if a shipping company has an option to delay? 3) In a competitive market, how does the optimal capacity expansion decision of individual shipping company affect the overall market capacity in the shipping industry?

In the first part, a theoretical ship price-freight rate relationship is formulated from the ship investment decision of the individual ship-owner. To incorporate the possible structural changes, freight rate process is assumed to follow an extended mean-reverting process with a changing mean and several unknown structural changes over time. Theoretically, the sensitivity of ship prices to freight rate changes is found invariant to structural change. This result is verified by the empirical test. Empirical results also show that second-hand ship investors are more interested in short-term benefits comparing with the new-building ship investors.

Based on the theoretical ship price-freight rate relationship derived from the first part, the second part analyzes the minimal market freight rate necessary for profitable ship investment, if shipping companies take into account the option value of delay the investment decision to a later date. Since the traditional net present value method ignores uncertainty, especially the cyclic nature in shipping market, the minimal freight rate derived using the real option approach can provide a better decision on whether to invest immediately, or delay. Theoretically, trigger rates for ship

investment are developed under assumption of the geometric Brownian motion and the mean-reverting motion of freight rate for comparison. Empirical tests using monthly data show that most of the previous investment behaviour can be explained by the trigger rates obtained using the real option approach, especially when cyclic nature is clear.

The third research question comes from the phenomenon of recent ship investment behaviour in the shipping industry. After the financial crisis, the order volume of the new ships is still kept at a very high level. What are the motivations for these new orders facing an already over-crowded market? To investigate this issue, a duopoly game theoretic model is developed to study the impact of carriers' strategic capacity expansion behaviour in a competitive market. Results in this part show that capacity expansion is a rational decision during both peak and trough shipping markets. The benefit of expansion is greater when the competitor also expands. Such expansion behaviour leads to chronic oversupply in shipping and Prisoner's Dilemma. A numerical simulation is applied that confirms the analytical results.

This study contributes on the investment decision theory in several ways. First, it suggests a way to anticipate the movement of ship price through modelling the ship price-freight rate relationship taking into account structural change, both theoretically and empirically. Secondly, it fills in the gap by theoretically analyzing the ship investment decision using Real Option approach, and contributes on the investment decision theory for projects with huge capital cost, long lifespan, and cyclic future market condition. Thirdly, this study contributes to the literature by analyzing strategic capacity expansion in shipping and its impact on market oversupply. In practical terms, this study can help different players in the shipping industry to better understand the relationship between shipbuilding market and freight market, understand different investment strategies, as well as better recognize the role of individual shipping company's capacity expansion decision.

Keywords: Ship Investment, Structural Change, Option Pricing, Strategic Capacity Expansion

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Chapter 1: INTRODUCTION

This thesis addresses on the issue of ship investment behaviour. The aim of this chapter is to provide a brief introduction to the whole shipping industry. Specifically, it will first review the main shipping markets, and market conditions in the dry bulk shipping sector. It will be followed by proposing the research questions. At the end, it will present the thesis structure.

The focus on dry bulk shipping sector is because the data in empirical studies in this thesis are all collected from dry bulk shipping. In addition, dry bulk shipping has a perfect competition environment with no barriers of enter and exit. The competition level in other sector, such as the container shipping, is not as high as that in dry bulk shipping. Then the mechanism of price formation, the player's reactions or the investors' behaviour may be different. As this reason, this thesis only concentrates on the dry bulk shipping sector.

1.1 Shipping markets affected ship investment

Ship investment is not only a vital issue but also a difficult decision facing by many shipping companies because of the high degree of uncertainty in the shipping market. In addition to the construction lag, new ships require a long payback period due to high capital cost, during which many market volatilities may be encountered. A better strategy of ship investment not only saves a company's capital cost, but also promotes its future performance in the long-run. Thus, this thesis addresses the issue on ship investment decisions.

To investigate this issue, the first step is to understand the major factors in ship investment decisions. For a shipping company, the revenue-based factor comes from providing transport services in the freight market, while the cost-based factor includes ship price in either new-building or second-hand ship market. To understand the relationship between the freight and ship markets, the four markets in the shipping industry generalized by Stopford (1997) are introduced first.

Shipping is one of the world's most internationalized industries. To better understand the economic mechanisms, Stopford (1997) generalized the shipping industry into four seemingly separated but closely connected markets — the freight market for cargo transportation, the new-building market for ordering new ships, the second-hand market for trading old ships and the demolition market for scrapping ships. Among them, the freight market is a service market for sea transport while the other three markets are all dealing with ships and can be viewed as ship market.

The primary task of the shipping industry is to move cargoes around the word. Thus, price for sea transportation, which is called the freight rate in shipping terms, is always important. Since the shipping market is free to enter or exit, the freight rate is usually deemed as representing the interaction between demand and supply. The charge for using a ship on a specified voyage is called a voyage rate or a spot rate, while the rate for hiring a ship over a future period of time is defined as a time charter rate. No matter what kind of prices, the freight rate exhibits the well-known cyclic characteristics. Stopford (1997; 2009) has examined the short- and long-term cycles in the shipping industry and found that the average length is around 8 years. The formation of the shipping cycles is caused by some random events, such as the oil crisis (October 1973), the financial crisis (October 2008), and the starting or ending of a war (Iraq invades Kuwait 1990). As the structural changes of the freight rate occur randomly and cannot be pre-determined, the freight rate does not always keep at an equilibrium level but exhibits a dramatic fluctuation sometimes. As a result, the shipping environment is with high risk and uncertainty.

By providing the transportation services, carriers earn revenues from the freight market. High revenues may induce the shipping companies to expand their market shares. Thus, ship investment will be considered to expand the company's fleet sizes. One way of expansion is to order new ships in the new-building ship market. This behaviour increases the demand for new ships, which may lead to an increase of the new-building ship price. With the increasing delivery of new ships, the supply of the shipping services increases, which has a negative impact on the freight rate. A notable feature of new ship ordering is that there is a construction lag between ordering and delivering of a ship, which is around 1 to 4 years depending on the size of order-book held by the shipbuilders. Then there is a viewpoint that the price for a new-building ship reflects the expectations for the freight market. In reality, many new ordering are made when the freight rates are attractive, because a higher freight rate encourages banks to lend more money. However, due to the strong connections between the freight rate and the new-building ship price, it is also the time that the ship cost is high. Thus, the timing of investing in ships is an important question needs to be addressed.

Another way of expansion is to purchase old ships in the second-hand ship market. Unlike the construction of new ships, second-hand ships can be immediately put into the freight market to provide transportation services. For the shipping company who cares more about the short-term profit than the long-term benefit, it may rush to buy old ships instead of ordering new ones. Buying and selling behaviours in the second-hand ship market have no impact on the supply of the shipping services. The key function of the second-hand market is to reallocate ships among ship-owners. Second-hand ship price is in general lower than the new-building ship price because of its shorter lifespan. However, when the freight market is very attractive, the second-hand ship price could be higher than the equivalent new-building price, such as the case in 2007.

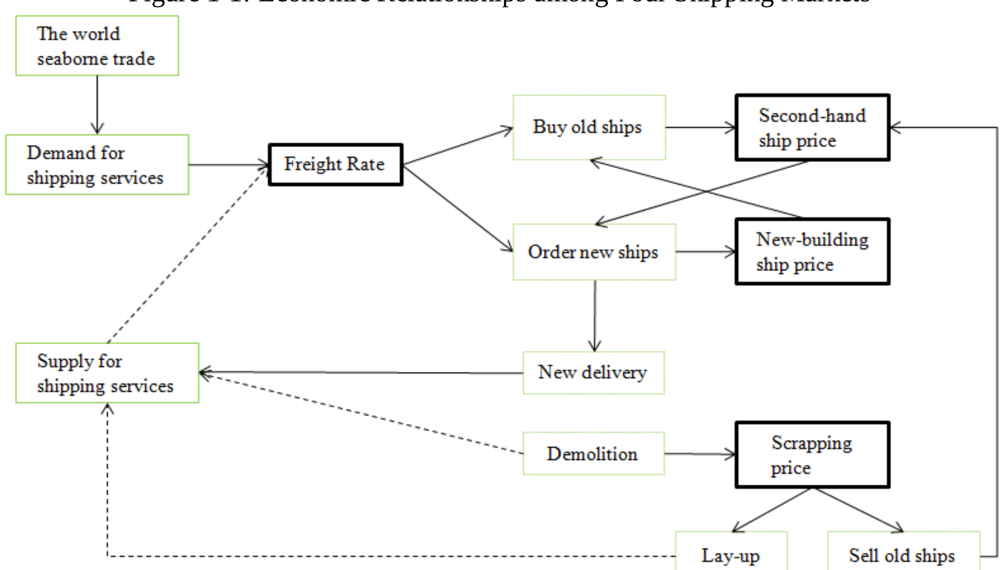
Ship has a finite lifespan around 25 to 30 years. When the ship retires from shipping services, it has to exit the shipping market. Ship demolition is a type of disposal when a ship becomes not economical to operate. Ship demolition recaptures the main material (steel) from ships, and thus the scrapping price is affected by the steel market. However, there are also times that demolition is not profitable since removing may cost more than the value of scrapped metal. Clearly, the demolition market decreases the supply of the shipping services.

An essential point of the four shipping markets is that they are not independent but closely connected to each other. The economic relationships between the four markets are examined in Figure 1-1, where the solid line indicates positive relationships while the dashed line shows the negative relationships. It can be seen that the global seaborne trade triggers the demand for shipping services. Cargo-owners who have the needs to transport their cargoes will enter into a special contract with the ship-owners, in which the freight rate is settled. Therefore, a high seaborne trade will push up the freight rate. An uptrend freight rate encourages the ship-owners to expand their services since the earnings of shipping services are high. If they rush to take advantage of the short-term benefit, they may choose to purchase old ships immediately. A thick trading of old ships will drive up the second-hand ship price, which may induce the ship-owners to order new ships instead. A heavy ordering of new ships will push up the new-building price. When the new ships enter into the freight market, the supply increases and the freight rate will drop. A continuous lower freight rate may cause the decease of second-hand and new-building ship price. If the second-hand price is lower than the scrapping price, ship-owners may have to scrap the ship, as it may not be sold out in the second-hand market nor the laid-up option is economical.

This thesis addressed on the ship investment decision, which involves the decision on ordering new or buying old ships. The main concern in this study is the markets affected the demand side of the relationships in Figure 1-1, i.e. the freight market, the new-building ship market and the second-hand ship market. Demolition market is not included in this study due to the limited historical number of ship demolition. In addition, demolition decision is more influenced by the ships' age restrictions but not the scrapping price, and thus ship-owners do not scrap ships to generate income.

Knowing the markets factors in the ship investment decision, in the next section, real conditions in these markets are presented.

Figure 1-1: Economic Relationships among Four Shipping Markets



Notes: The solid line indicates positive relationships, while the dashed line shows the negative relationships.

1.2 Market conditions in the dry bulk sector

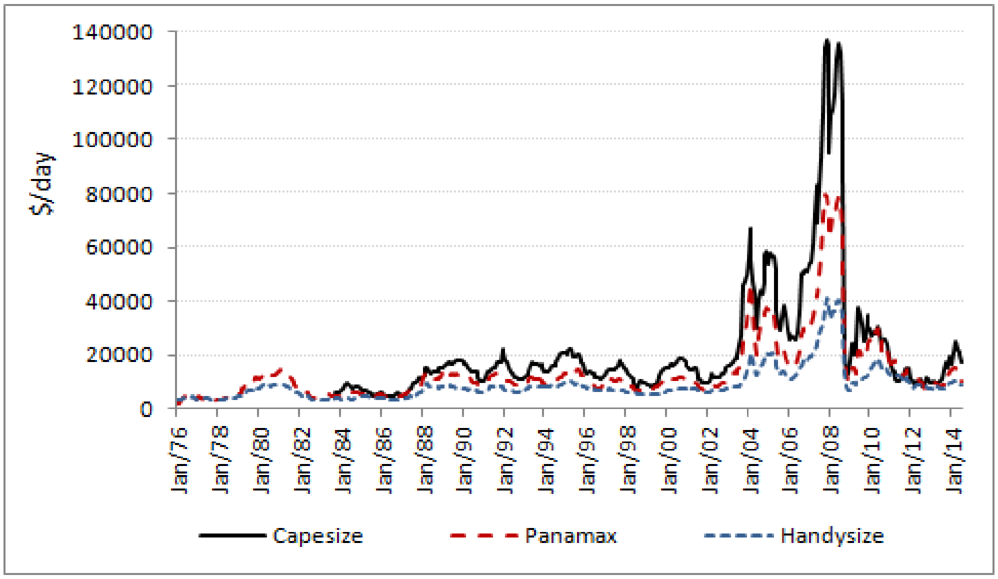
The dry bulk shipping sector deals with the carriage of unpackaged dry bulk cargo in large quantity, such as grains, coal, iron ore etc. Forced by the development of technology and economic reasons, dry bulk vessels grow in their sizes, capacities and efficiency.

Major size categories in the dry bulk sector are Capesize, Panamax and Handysize carriers. Capesize carriers are more than 80,000 DWT and mainly used to transport iron ore and coal. The name of this ship type is because Capesize carriers are too large to pass through the Suez or Panama Canals and must go around the Cape of Good Hope. Panamax carriers are 60000 to 80000 DWT and mainly used to carry coal and grain. Obviously, this ship type can pass through the Panama Canal. Handysize carriers, which are 15000 - 59000 DWT, are the most common size in the dry bulk sector, which accounts for more than 70% of all the bulk carriers[1]. They can carry a wide variety of cargoes including steel products, grain and minor bulk commodities.

Figure 1-2 plots monthly 1-year time charter rates for the three ship categories. It can be seen that the charter rates for the larger ships are in general higher than them for the smaller ships. Cyclic nature exhibits clearly in the figure. Charter rates are relatively stable before 2003. During 2003 to 2007, a dramatic fast growth occurs. In mid-2008, financial crisis suddenly drives the freight rate down to the pre-2003 level. Recently, the freight rate shows a slight recovery.

[1] Source: Clarkson Research Services Limited 2010

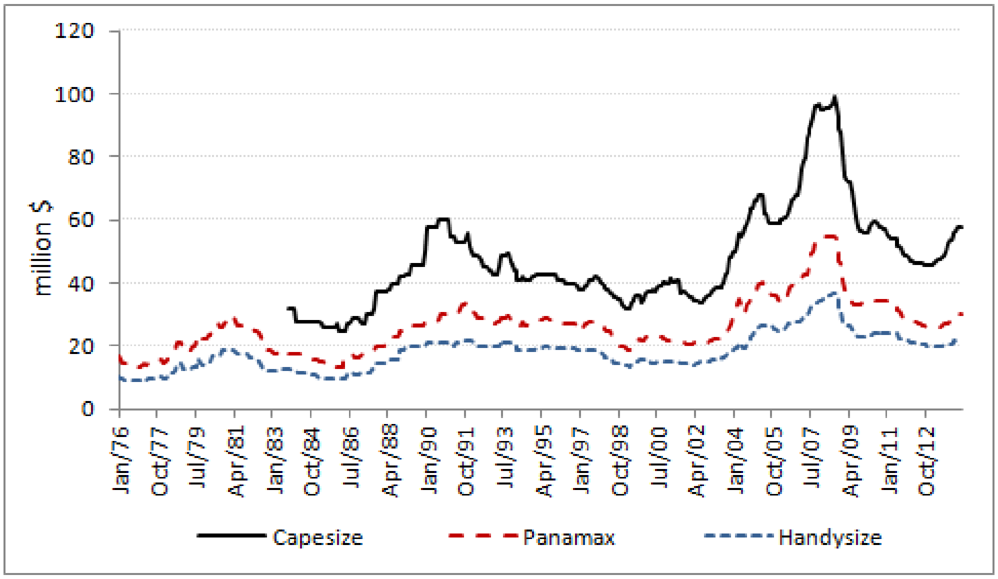
Figure 1-2: 1-year Time Charter Rates for Three Ship Categories (1976:01-2014:07)



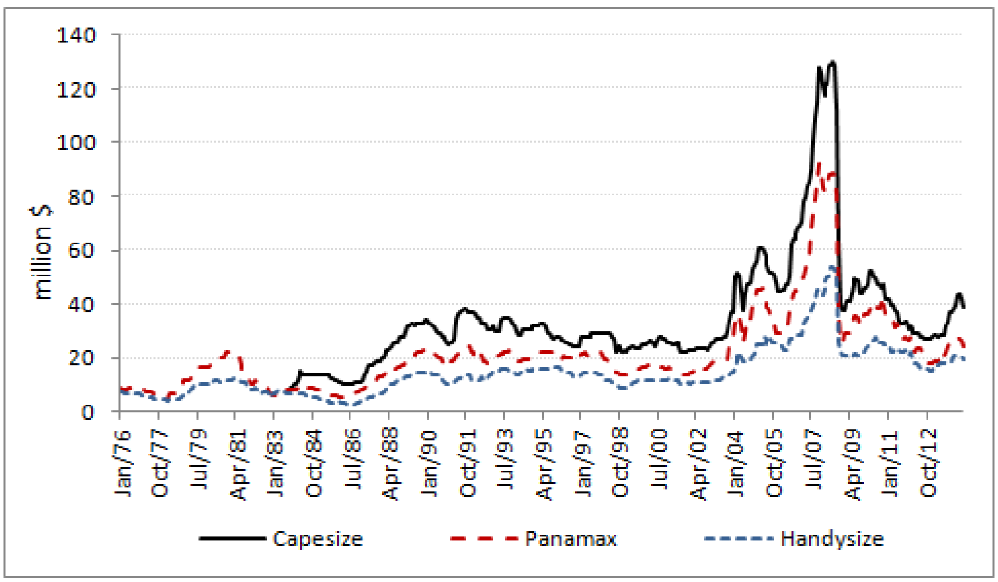
Data source: Clarkson Research Services Limited 2010

Figure 1-3 plots monthly ship prices (new-building and second-hand) for the three ship categories. Comparing new-building ship prices in Figure 1-3(a) with the second-hand ship prices in Figure 1-3(b), second-hand ship prices seem have a similar move pattern with the time charter rate in Figure 1-2, while new-building ship prices are smoother than both charter rates and second-hand ship prices. It can be seen that when the freight market is very prosperous, second-hand ship prices are even higher than the new-building ship prices, indicating that second-hand ship trading focuses more on the short-term benefit in practice.

Figure 1-3: Ship Prices for Three Ship Categories (1976:01-2014:06)



(a) New-building ship prices

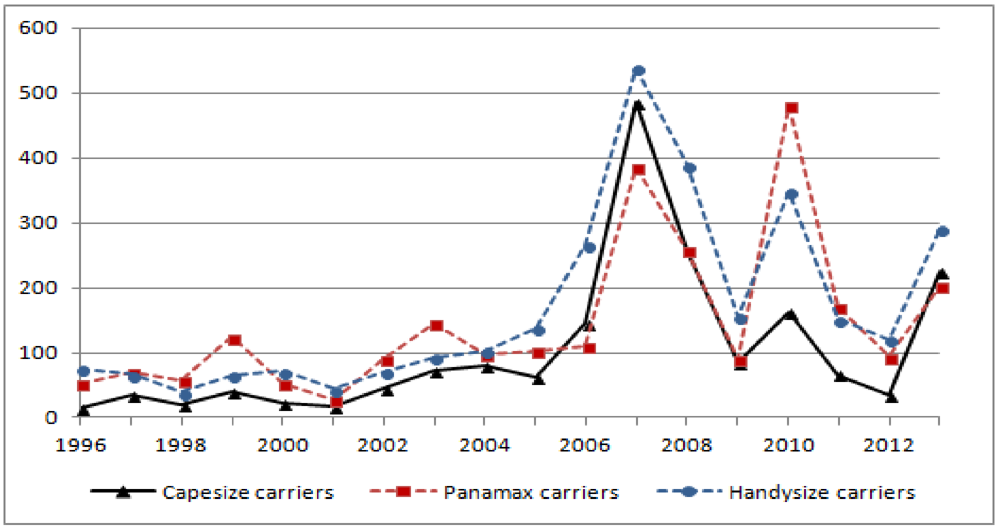


(b) Second-hand ship prices

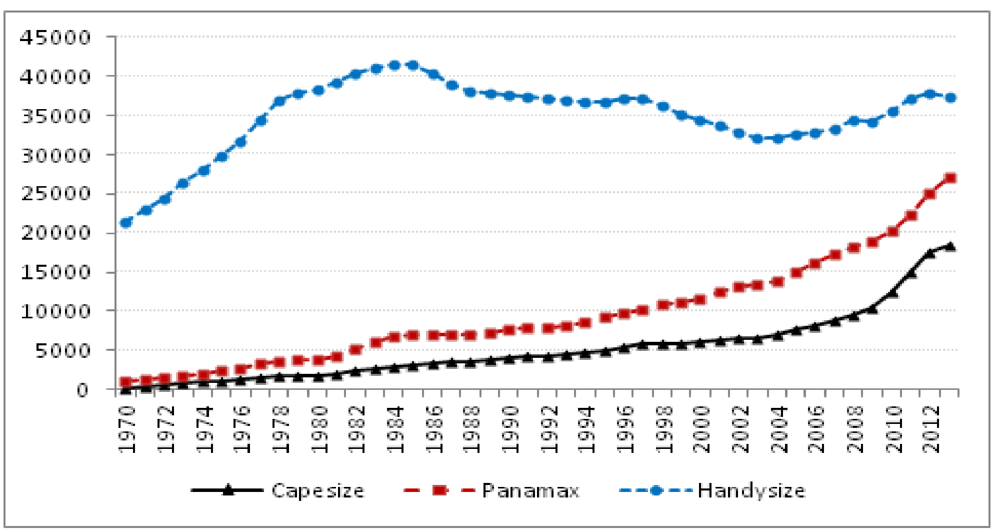
Data source: Clarkson Research Services Limited 2010

Figure 1-4(a) shows the annual contracting numbers in the new-building ship market. The most frequent ordering occurs in the year 2007, which corresponds to the most prosperous freight market. A notable phenomenon is that, after the financial crisis in 2008, the time charter rates remained at a relatively low level but there are still heavy new orders in this sluggish market. As shown in Figure 1-4(b), fleet sizes of these three ship types keep increasing after 2008. It not only happens in the dry bulk sector, but also in the liner market. From January to October, 2013, the total new orders for container vessels amounted to US $19.2 billion with total capacity of 1.7 million TEU, which is about four times as much as that of the previous year (Clarkson PLC, 2014).

Figure 1-4: Contracting Numbers and Fleet Sizes for Three Ship Categories (1996-2013)



(a) Contracting numbers for new-building ships

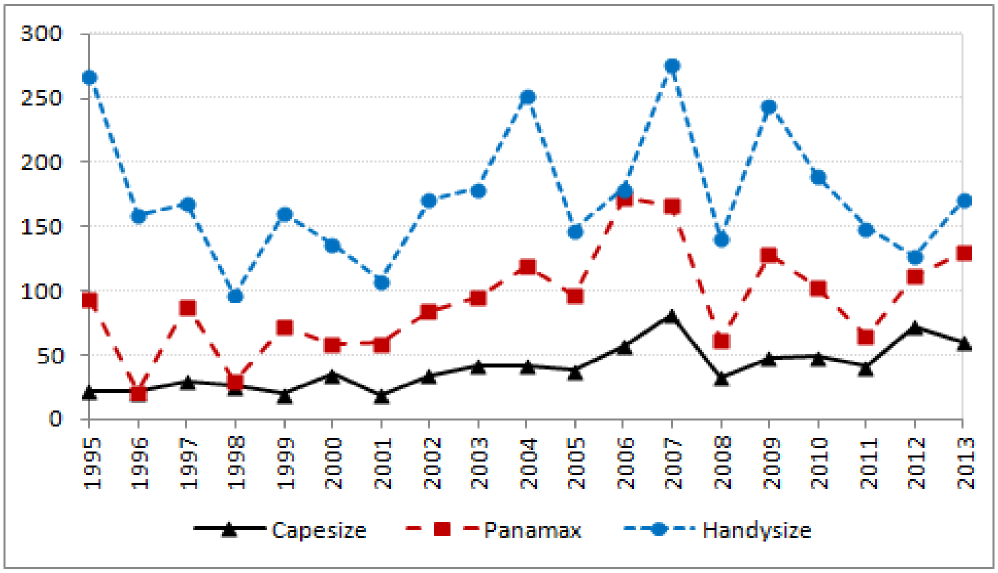


(b) Fleet sizes for three ship categories

Data source: Clarkson Research Services Limited 2010

Figure 1-5 represents the annual sales volumes in the second-hand ship market for the three ship types. The most frequently trading carrier is Handysize ship type. Comparing with the new ship ordering, the second-hand ship trading is relatively stable.

Figure 1-5: Sales Volumes for Three Ship Categories (1995-2013)



Data source: Clarkson Research Services Limited 2010

In practice, the freight rate has a clear cyclical nature. It seems that the connections between the freight rate and second-hand ship price are tighter than the connections between the freight rate and the new-building ship price. Then how does the ship investment cost, as represented by ship price, relate to the freight rate in the shipping market? What is the influence of the famous cyclic nature of freight rate on the ship price? How to make decisions on ship investment based on the relationship between the freight rate and ship prices? Even most people believe that a high freight rate is the motivation behind more new orders and second-hand purchases, new ordering was still high when the freight market is unrecovered. What is the reason behind this phenomenon? This thesis addresses on the ship investment decisions to answer the proposed questions above. In the next section, specific explanations of the research questions are provided.

1.3 Research questions

Question 1: The aim of this thesis is to investigate the ship investment decisions. The fundamental factors affected ship investment decisions are the project's cost and revenue, which are presents by the ship prices and the freight rate. The price of ships (both new and old) and the prevailing freight rate are the results of supply and demand in their respective markets: the new-building, second-hand and freight markets. As Figure 1-1 shows, these seemingly separate markets have one common factor: they are all strongly related to the demand for the seaborne trade. In practice, the freight rate and ship prices show strong connections (Figure 1-2 and Figure 1-3). However, not all changes in ship prices and freight rates are synchronised as the economic relationships analyzed in Figure 1-1. What is the real theoretical relationship between freight rate and ship prices? Particularly, the freight rate is influenced by the random structural changes and exhibit cyclic nature. Then how does the structural change affect the ship price-freight rate relationship?

To answer this question, the relationship between ship prices (both new and second-hand) and freight rate is modelled while considering the effect of structural change—assuming that ship-owners, when making a ship investment decision, weight the expected present value of future revenue against its current price. Studying the relationship between ship prices and the freight rate may have direct implications for the ship investment decisions because such a study can help shipping companies combine anticipated changes in ship prices with information concerning freight rate changes, providing better control over the financial risks involved in ship investment and thus maintaining a healthy cash flow. Information from such a study may also help asset players make better decisions about hedging, lending, ordering and purchasing. For shipyards, this information could help with the pricing of new ships and in judging whether to expand their capacity.

Question 2: Based on the ship price-freight rate relationship, how to decide whether and when to invest in ships? The second research question concentrates on the optimal timing of ship investment problem. The net present value (NPV) method and the real option approach (ROA) are used to derive a trigger rate. If the real freight rate is found to be higher than the trigger rate, investment should be made as soon as possible. Otherwise, it is better to postpone investment when the real rate is going up. There are very few analytical and quantitative studies on the trigger freight rate for ship investment under uncertainty by taking account of the option to delay an investment. This part of study is expected to fill the gap by theoretically analyzing the ship investment decision. It contributes to the investment decision theory applied to projects with huge capital cost, long lifespan and cyclical future market conditions. Practically, it also helps shipping companies to make investment decisions in different market conditions.

Question 3: The third research question comes from the phenomenon of recent ship investment behaviour in the shipping industry. After the financial crisis, the order volume of the new ships is still kept at a very high level. What are the motivations for these new orders facing an already over-crowded market? To investigate this issue, a duopoly game theoretic model is considered to study the impact of carriers' strategic capacity expansion behaviour in a competitive market. Research in this part offers an analysis on the impacts of explanation reveals that expanding capacity is a rational decision for the individual shipping company, not just when the market is good, but also at sluggish market. This expansion often leads to excessive supply and chronicle low freight rate in shipping, which is usually attributed to the "short memory" of the ship-owners. This explains the current heavy new orders in the shipping industry even when everyone is praying for the coming of recovery. It points out that asking the industry to refrain from expansion is not useful. For a shipping company, it is better to recognize this inherent nature in the shipping market. For the public agency, this may be one possible chance to upgrade the world shipping fleet to become more energy efficient and cost effective.

1.4 Structure of the thesis

Chapter 1 is a brief introduction of the background of this research. Since the purpose of this thesis is to study the ship investment decisions, factors related to this decision and practical situations in the markets related with this thesis are presented.

Chapter 2 reviews the literature relevant to the research questions proposed in Chapter 1. The review is divided into five parts: literature in the freight rate process, in the ship prices, in the freight rate-ship prices relationship, in the real option pricing model and in the strategic investment behaviour.

Chapter 3 investigates the first research question - ship price-freight rate relationship with considering the structural changes. A mathematical formulation for the ship price–freight rate relationship based on assumptions about the dynamic process of the freight rate and structural change is presented. This is followed by the statistical regression results for the theoretical models and a brief summary.

Chapter 4 analyzes the minimal market freight rate necessary for profitable ship investment, if shipping companies take into account the option value of delay the investment decision to a later date. Empirical tests and numerical experiments are then presented.

Chapter 5 discusses the third research question on the strategic investment decisions. A duopoly model is developed to take the competitor's response of capacity expansion into account. Numerical experiments are then provided.

Chapter 6 finally concludes the main results and contributions in this thesis, and then indicates the limitations and the directions of future studies.

Chapter 2: LITERATURE REVIEW

The aim of this chapter is to review previous studies on the research questions proposed in Chapter 1 and then identify the gaps of existing studies.

2.1 Literature in the freight rate process

Past studies on the freight rate have been focused on its formation (Tinbergen, 1934; Koopmans, 1939; Hawdon, 1978; Charemza and Gronicki, 1981; Beenstock, 1985; Beenstock and Vergottis, 1993), or the term structure between the spot and time charter rates (Zannetos, 1966; Hale and Vanags, 1989; Glen *et al*., 1981; Wright, 2000; Kavussanos and Alizadeh, 2002b; 2003), or the freight rate forecasting (Veenstra, 1997).

Tinbergen (1934) investigated the formation of the freight rate through a supply-demand equilibrium framework. He assumed a perfectly inelastic demand for shipping services on the demand side. On the supply side, the fleet size, freight rate and bunker price were assumed as the factors. Through equilibrium supply and demand assumption, he established that the freight rate is affected by the fleet size, demand and bunker price. Koopmans (1939) applied the models proposed by Tinbergen (1934) in the tanker sector. One notable contribution is that he provided the shape of the supply curve in tanker shipping. Beenstock (1985) and Beenstock and Vergottis (1993) also used the supply-demand equilibrium framework to determine the spot rate in freight market. The only difference with Tinbergen (1934) is that the demand is assumed to be affected by the freight rate and worldwide trade.

The only different work is Charemza and Gronicki (1981). They considered a disequilibrium supply-demand model for investing the determinants of the freight rate, and found that the freight market supply is influenced by the changes of the fleet size and freight rates.

For the assumption of the supply-demand equilibrium framework, it is similar to the assumption about the mean-reverting process, which is a stochastic process proposed by Uhlenbeck and Ornstein (1930) and can be also named as the OU process. However, the formal assumption of this process is very limited in maritime studies. It first appeared in the work by Bjerksund and Ekern (1995), its lognormal process in the work by Tvedt (1997) and its non-liner process in the work by Adland and Cullinane (2006). Nevertheless, the mean-reverting process is actually a popular assumption in financial economics. Typical discussions on this process can be found in Dixit and Pindyck (1994) and Metcalf and Hassett (1995). The applications of the OU process are widely, such application to stock prices (Poterba and Summers, 1988), exchange rates (Jorion and Sweeney, 1996) and oil prices (Dias and Rocha, 1999).

However, doubt has been cast over the assumption about the mean-reverting process in relation to the freight rate, as empirical evidence shows that the latter is not stable. If a time series satisfies a mean-reverting process, it is an AR(1) process at a discrete time, indicating that it is stationary by a unit root test. However, a body of empirical studies accepts that the freight rate contains a unit root (Veenstra and Franses, 1997; Kavussanos and Alizadeh, 2002b; Alizadeh and Nomikos, 2007). Koekebakker et al. (2006) summarized the unit root test results from the past studies and concluded that, except for spot rates and BFI in the work by Tvedt (2003), all the results show that freight rates are a non-stationary process. Spot rates and BFI (Tvedt, 2003) appear stationary only when US dollars are converted to Japanese yen, and Tvedt (2003) argued that it is the direct result of a Japanese-dominated market. However, the time charter rates in these studies were found non-stationary even when being measured by Japanese yen. In truth, the traditional unit root test is based on a linear environment. Adland and Cullinane (2006) investigated this issue using a non-linear model and found that the freight rate should follow the OU process in the long run, but in the short run departs from its long-term level. It implies that there might be a shift of mean in the OU process. Note that literature listed in Koekebakker *et al.* (2006) used data samples before 2000. Freight rates in bulk shipping registered a dramatic increase in 2007 and a fast decrease in 2008, and only until recently had freight rates seemingly reverted to the level before 2003. Therefore, it is likely that the stationarity of freight rates in different periods may be different, which requires further investigation.

2.2 Literature in the ship prices

The existing studies on ship prices can be generally categorized into three groups. The first group uses the traditional econometric approach to explore the determinants of ship prices (Hawdon, 1978; Strandenes, 1984; Beenstock, 1985; Beenstock and Vergottis, 1989a; 1989b; Tsolakis *et al.*, 2003; Haralambides *et al*., 2004). The second group studies on efficient and rational in the second-hand ship market (Hale and Vanags, 1992; Glen, 1997; Kavussanos and Alizadeh, 2002a). The third group uses the time series model to study the ship price series itself (Kavussanos, 1996; 1997) or the short-run links between ship prices (Kou *et al.*, 2014).

The determinants of ship prices are examined by artificial selection (Hawdon, 1978), by using the supply-demand equilibrium model (Haralambides *et al*., 2004; Tsolakis *et al.*, 2003), or by using the capital asset theory (Strandenes, 1984; Beenstock, 1985; Beenstock and Vergottis, 1989a; 1989b). Hawdon (1978) assumed that the new-building ship price is linearly related to the factors of the freight rate, freight rate lag, fleet size and the price of steel. The freight rate is found to have a significant impact.

Tsolakis *et al*. (2003) used the Error Correction Model (ECM) to analyze the determinants of second-hand ship prices under the supply-demand equilibrium model. Haralambides *et al.* (2004) extended Tsolakis *et al*. (2003)'s research to include both second-hand and new-building ship prices. Their results showed that freight rate affects the new-building ship price for Capesize and Handysize carriers but does not affect the Panamax carriers. Strandenes (1984) studied the relationship between the time charter rate and the second-hand ship price. She explained the second-hand price as a function of discounted earnings at current market and the market replacement value of the ship which was assumed to be equal to the corresponding new-building price. Beenstock (1985) and Beenstock and Vergottis (1989a; 1989b) argued that the supply-demand framework is not appropriate for determining ship prices, since a ship is a real capital asset and therefore its price depends on expectations. Therefore, they incorporated future market expectations into the determination of ship prices and modelled these prices in a forward-looking way by considering ships as capital assets. However, in their studies, no construction lag of new-building ships is assumed.

The second group on ship prices studies the efficiency in the second-hand ship market by testing the validity of the Efficient Market Hypothesis (EMH) (Hale and Vanags, 1992; Glen, 1997; Kavussanos and Alizadeh, 2002a). This kind of studies is intended to show whether the change of second-hand ship price for one ship type can be used to improve the predictability of the change of second-hand ship price for another ship type. This kind of information can be used in the decision on what kind of second-hand ship type should be purchased.

The third group on ship prices uses the time series models to deal with the properties of ship prices. Kavussanos (1996; 1997) examined the fluctuation of the price series over time. Kou *et al*. (2014) studied the short-run links between the new-building and second-hand ship prices. They found that one-directional lead-lag relation exist between two ship prices. Particularly, directions of ship price movements in dry bulk and tanker shipping sectors are opposite.

2.3 Literature in ship price-freight rate relationship

Literature reviewed in Section 2.2 show that econometric studies are often applied to study the determinants of ship prices, and the freight rate is usually considered as one of the factors (Strandenes, 1984; Beenstock, 1985). With the development of econometric methodologies, time series models are introduced to study the relationship between variables. A typical method is called co-integration analysis.

Co-integration tests usually adopt the Engle-Granger two-step method (Engle and Granger, 1987) or the Johansen co-integration method (Johansen, 1988; 1991), which is widely applied in shipping economics. For example, Hale and Vanags (1992) examined the validity of the efficient market hypothesis (EMH) in the second-hand ship market. Glen (1997) extended Hale and Vanags' (1992) co-integration test in his analysis of market efficiency in the dry bulk sector. Alizadeh and Nomikos (2007) investigated the co-integrated relationship between five-year-old ship prices and one-year time charter rates in the dry bulk sector. Results suggested that these two variables are co-integrated in every ship segment. Causality between them is from the time charter rate to second-hand ship price. Xu *et al*. (2011) used panel co-integration to test the dynamic relationship between the freight rate and new-building ship price in dry bulk sector. They found that freight rate leads the new-building ship price in the dry bulk sector.

However, when there are structural changes in the data sample, traditional co-integration tests may not be reliable. To solve this problem, Gregory and Hansen

(1996) proposed a co-integration test with one structural change. They developed three single-equation regression models that allow structural changes in the intercept or slope, and applied a unit root test to the residuals. As noted, this method is used to enhance the stability of the test results, not to assess the different relationships among the subsamples separated by the structural change.

Apart from the co-integration analysis, Lunde (2002) developed a continuous time model to bridge the freight rate and ship price based on net present value criteria. Alizadeh and Nomikos (2012) explained second-hand ship value as the discounted present value of a series of forward freight rates plus resale value under a discrete time framework. Analyses from these studies have shown that the relationship between ship price and freight earning in shipping markets contains important information about the future behaviour of ship prices.

It has been discussed that the freight rate process has its cyclic nature and may have influence on the ship price-freight rate relationship. Until now there has been a lack of research on the effect of structural change on the freight rate and the ship price–freight rate relationship. Structural change is important, as it contains valuable information on the formation of shipping cycles. Since the recent worldwide financial crisis, this topic has become particularly important within the shipping industry, due to obvious structural change in the shipping market.

2.4 Literature in the real option pricing model

The ROA has been widely applied to evaluate investment decisions under uncertainty. The pioneer work was done by Tourinho (1979), who used the concept of option value to evaluate natural resource conservation under price uncertainty. Many research works have since developed. The notable contributions were made by

Brennan and Schwartz (1985), McDonald and Siegel (1986), and Dixit and Pindyck (1994).

Brennan and Schwartz (1985) used the ROA to evaluate the copper mine investment in which the present value of this project is determined by copper prices and inventory levels. They suggested solving the model numerically since no analytic solution was provided.

McDonald and Siegel (1986) examined the investment decisions on the installation of an irreversible project with the value of waiting taken into consideration. Uncertainty was allowed for in both cost and benefit. The trigger ratio between total cost and total revenue was developed theoretically. Numerical examples were given in which parameters were arbitrarily imposed.

Dixit and Pindyck (1994) synthesized several of the past ideas and gave a whole framework on the issue of investment under uncertainty. They considered not only an individual firm's decision but also the investment in a competitive environment using the ROA. Therefore they concentrated more on theoretical development and empirical examples were very limited.

Dixit and Pindyck's theoretical models have since been applied to various areas, such as energy saving investment (Lin & Huang, 2011), urban development (Bar-Ilan & Strange, 1996), and technological innovations (Grenadier & Weiss, 1997).

The most common assumption of the ROA is that cash flow follows the GBM process, as suggested in the early works by Pindyck (1982; 1988), Abel (1983), Brennan and Schwartz (1985), McDonald and Siegel (1986) and Dixit (1989). However, many economic variables exhibit a tendency of reverting to its long-term average. In such cases, the OU process is a more appropriate assumption. In comparison with the GBM process, the OU process is not frequently applied because of its complexity. The discussion on its applicability can be found in the works by Bhattacharya (1978), Metcalf and Hassett (1995), Schwartz (1997), Sarkar (2003) and Tsekrekos (2010). In fact, the OU specification in the above works is known as a geometric OU process (Metcalf & Hassett, 1995; Schwartz, 1997) or a modified OU process in which diffusion is proportional to output price (Bhattacharya, 1978; Sarkar, 2003; Tsekrekos, 2010). There has been no empirical test on the validity of these two types of the OU process. The classical arithmetic OU process is only found in the work by Sødal *et al.* (2008), in which the freight rate differential between the dry and the wet bulk is assumed to follow the classical arithmetic OU process with the aim of analyzing when to switch between the dry and the wet bulk market for a combination carrier, and used the Augmented Dickey Fuller (ADF) test to check this assumption.

The ROA has been successfully applied to other fields, but only sparsely used in maritime studies. Bendall and Stent (2005; 2007; 2003) published a series of papers using the ROA to carry out case studies. Bendall and Stent (2003) described the investment strategy in a declining and competitive market. In 2005, they analyzed different ways of allocating container ships on the Singapore-Klang-Penang route. In 2007, they studied the investment in a new container vessel servicing from the east coast of Australia to New Zealand. All these papers feature the ROA to ship investment projects under uncertainty, but do not provide any theoretical demonstration. Yet, there is still a lack of theoretical understanding of the application of the ROA on ship investment decisions.

In summary, although the real option approach has been proven an efficient tool in analyzing investment projects under uncertainty, it has not been sufficiently utilized in ship investment decisions, and therefore an analytical and quantitative evaluation of the optimal timing of ship investment decisions with the option of delay taken into account is still found lacking.

2.5 Literature in strategic investment behaviour

Ship investment strategy is usually analyzed using ship financing methods or econometric-based methods. For example Bendall (2003), Bendall and Stent (2005) and Dikos (2008) used real option analysis to study ship investment, and found that companies value flexibility when making investment decisions. For the econometric-based approach, Alizadeh and Nomikos (2007) compared the ratio of the second-hand ship price and freight rate with its long-run average. If this ratio is larger, it indicates that ship prices are too high, and thus expected to fall. Similarly, Merikas *et al.* (2008) used price ratio between the second-hand and new-building ship price as a decision-making tool to decide whether to buy old or to order new ships. Fan and Luo (2013) applied a binary logit model and a nested logit model to examine the ship investment and choice decision. They found different capacity expansion behaviours between large companies and smaller ones, as well as preference orders for new orders and second-hand ships, as well as ship size categories.

Another direction of ship investment emphasized the determinants of ship investment. For example, Marlow (1991a; 1991b; 1991c) studied the fiscal and financial ship investment incentives, as well as their effectiveness in the UK, and found that incentives have not affected the size of the UK fleet. Thanopoulou (2002) discussed ship investment from the viewpoints of operational constraints, risk and investment attitudes. She concluded that the lack of constraints in bulk shipping increases its speculative opportunities and enhances its competitiveness.

However, little effort has been made to analyze the strategic ship investment behaviour in a competitive environment. Neglecting competitors' strategic response may weaken the competitive position of the shipping company. On the other hand, recognizing such strategic behaviour and anticipating the possible consequences can help both shipping companies to make informed decision.

Game theory is widely applied in analyzing the strategic behaviour of market players in transportation research, such as in the airline hub competition by Hansen (1990), liner shipping alliance (Sjostrom, 1989; Pirrong, 1992; Telser, 1996; Abito, 2005; Fusillo, 2003) and port capacity competition (Luo *et al*., 2012; Ishii *et al.*, 2013). Till now, rarely no works have been conducted on investigating the ship investment behaviour by using game theory models in either liner shipping or bulk shipping.

Ship investment decision is similar to the issues on capacity expansion. For the topic on capacity expansion, game-theoretical models are widely used, such as in electricity generation capacity (Chuang *et al*., 2001; Pineau and Murto, 2003; Murphy and Smeers, 2005), in port capacity expansion (De Borger *et al*., 2008; Anderson *et al*., 2008; Luo *et al*., 2012; Ishii *et al*., 2013), in airline competition (Hansen, 1990; Martin and Socorro, 2009; Martin and Roman, 2003), in public transport system (Hollander and Prashker, 2006; Van Vugt *et al*., 1995; Roumboutsos and Kapros, 2008; Wang and Yang, 2005). The models in these studies are from Cournot game in single period (Chuang *et al*., 2001) to dynamic games in infinite horizon (Wang and Yang, 2005), from price completion (Wang and Yang, 2005; Ishii *et al*., 2013), quantity competition (Chuang *et al*., 2001; Martin and Socorro, 2009), to including both (Luo *et al.*, 2012).

Among them, Luo *et al*. (2012) developed a two-stage duopoly model to study port capacity development. Their model comprises the pricing and capacity expansion strategies between two ports with different competitive conditions. In the capacity investment game, they found that both competitors will be more inclined to expand when the total market share is increasing, and the new port with smaller capacity, lower investment cost and higher price sensitivity will be more likely to expand.

Martin and Roman (2003) presented a two-stage spatial competition game to analyze the airlines' hub location problem in the South-Atlantic airline market. Airlines first sequentially choose where to locate their hubs. This decision will affect the airlines' market share. Once the locations have been chosen, airlines compete in each city-pair setting frequencies to obtain the highest market share. Results show that Madrid, Lisbon and Sao Paulo airports are going to play an important role.

Wang and Yang (2005) applied game theory to model the strategic interactions between the operators in a deregulated bus market, taking into account the price and service frequency competition. In the first stage, the incumbent decides its fare and frequency of its service. In stage two, the potential entrant decides whether to enter after observing the incumbent's choice, and if it chose to enter, the entrant decides its fare and frequency. This two-stage game is then extended to a multi-period game in an infinite time horizon. Results from welfare discussion showed that deregulation in the bus industry does increase the attractiveness of public transport and brings benefits to the society.

Although the issue faced in our research also belongs to the capacity expansion, ship investment decision in shipping has its own particular features. The competition in our study is not a direct price or quantity competition. The players in our game are shipping companies. They are the price takers, who have no influence on the freight rate. Our aim is to analyze the investment behaviour of the shipping company, thus what the shipping company decide is whether to invest or not, but not the investment quantity. This decision seems like the decision by the entrant in Wang and Yang (2005). The company with more ships has a higher traffic capability and occupies more market share. This situation is as the hub location issue in Martin and Roman (2003), good location obtaining more market share. After decision-making on the ship investment, shipping companies adjust their ship speed to maximize their profit. Comparison of profits from investing and not investing shed light on which strategy is more benefit. If results show investment is a dominant strategy, then overbooking behaviour can be explained. In summary, this is the first attempt to use game theory to explain the investment behaviour in shipping industry. The research can help decision makers making the best competition strategy and improving the company's position level in the market.

Chapter 3: MODELLING THE RELATIONSHIP BETWEEN SHIP PRICE AND FREIGHT RATE ALONG WITH STRUCTURAL CHANGES

The fundamental factors affected ship investment decisions are the project's cost and revenue, which are presented as the ship price and the freight rate. This chapter examines the relationship between these two variables. Particularly, the freight rate is influenced by the random events, such as the economic recession, the oil crisis and the start or end of a war. Thus, the freight rate shows dramatic changes sometimes, which is called “Structural Changes” in this Chapter. Then how do the structural changes affect the ship price-freight rate relationship? To answer this question, the long-term ship price–freight rate relationship is modelled based on ship investment decisions, with the assumption that the freight rate follows an extended mean-reverting process. Theoretically, the sensitivity of ship prices to freight rate changes is found invariant to structural change. Empirically, this result is verified. It is also found that the sensitivity is lower for larger ships and for new ships, and second-hand ship investors are more interested in short-term benefits.

3.1 Introduction

This chapter examines the relationship between the freight rate and ship prices, incorporating the influence of structural changes. The usual method for studying any relationship between market prices is co-integration analysis – a data-driven method that is particularly useful for testing the existence of long-term statistical relationships among underlying variables. However, it is often applied in exploratory research where such relationships cannot be established by economic theory.

Realising that there might be structural changes in the data generation process, Gregory and Hansen (1996) developed a co-integration test that incorporated structural change to examine whether a long-term statistical relationship existed. Note that this test was not intended for use in finding relationships separated by the breakpoint—the time of structural change—but rather to enhance the stability of the test result on co-integration. Thus, there is a gap in efforts to discover ship price–freight rate relationships in different shipping cycles.

A proper understanding of the freight rate process is essential in modelling the ship price–freight rate relationship. The bulk shipping market is usually regarded as very competitive (Zannetos, 1966; Stopford, 2009), and the freight rate oscillates around its long-term equilibrium; that is, the long-term marginal cost of providing such services. Therefore, it should follow a mean-reverting process rather than a random walk. However, due to the existence of shipping cycles and structural changes, empirical analyses using different sample sizes can generate different results. This implies that the traditional OU process, which assumes a constant mean, may not be sufficient to describe the movement of the freight rate, because the mean may change during different shipping cycles or due to structural changes.

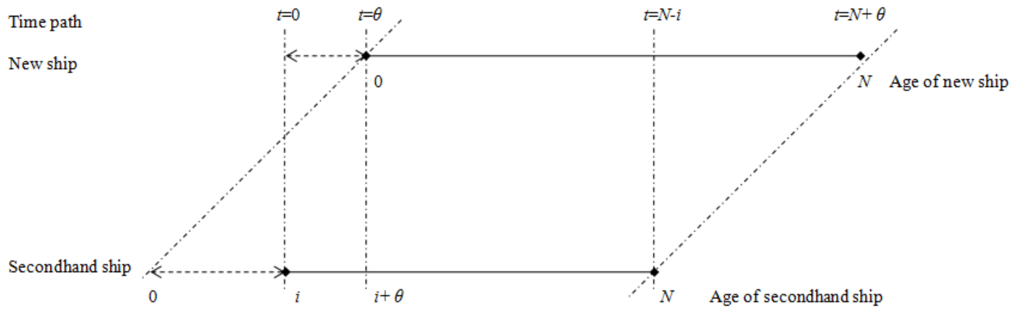
Therefore, in this chapter, the relationship between ship prices (both new and second-hand) and freight rate while considering the effect of structural change is modelled — assuming that ship-owners, when making a ship investment decision, weight the expected present value of future revenue against its current price. To illustrate the difference, the freight rate following a traditional OU process is first modelled and then the OU process accommodated the effect of structural change is extended. Empirical tests are conducted using the monthly data on freight rates, new-building prices and second-hand prices for three vessel sizes in the dry bulk sector. To investigate the effect of structural change, the data sample is automatically divided into six sub-periods.

This part of study makes two important contributions. First, it is a novel attempt to theoretically and empirically model the relationship between shipping markets while considering structural change, suggesting a way to anticipate the movement of ship prices when a structural change occurs. Second, it is the first attempt to model the freight rate process with structural changes—a common phenomenon in shipping cycles. Theoretically, the extended OU model provides an explanation for why empirical tests on the freight rate process often result in a unit root. This model can also be used to model other financial processes with similar properties to the freight rate, such as oil prices, stock prices and interest rates.

3.2 Theoretical relationships between ship prices and freight rate

In this section, a theoretical relationship between ship prices and the freight rate is setup, starting with the basic assumption that the freight rate follows a traditional OU process, through to the extended OU process with structural change. First, a problem where an individual shipping company faces the decision over whether or not to purchase a ship (new or second-hand) is considered. The differences between two decisions are illustrated in Figure 3-1.

Figure 3-1: Decision Making Framework for Ordering New or Buying Second-hand Ships



Notes: The solid lines indicate that the ships are operated in the freight market.

If the company decides to order a new ship now (t=0), it needs to wait θ years due to the construction lag. If the ship can sail for N years, then it will retire from the active fleet at $\theta+N$. If the company purchases an i-year-old second-hand ship of an identical deadweight and ship type, the ship can be put into its active fleet at t=0 and can be withdrawn at time N-i.

Denote $R(t)$ as the time-charter rate at time t, which represents the net earnings of the ship as the operating and voyage costs are paid by the charterer. Denote P_t^{new} and P_t^{old} as the new and second-hand ship prices at t, respectively. For simplicity, assuming no re-selling during the whole lifespan, then at time 0 the net present value (NPV) for ordering a new ship and purchasing a second-hand ship can be written as:

$$\begin{cases} NPV_0^{old} = E_0\left[\int_{t=0}^{t=N-i} R(t)e^{-rt}dt\right] - P_0^{old} \\ NPV_0^{new} = E_0\left[\int_{t=\theta}^{t=\theta+N} R(t)e^{-rt}dt\right] - P_0^{new} \end{cases} \tag{3-1}$$

where E is the operator for expectation and r is a discount rate, which is assumed to be consistent over the lifetime of the ship. This discount rate reflects the time preference of investors in the market, taking into account the risks in the future market situation. Normally, the higher the perceived risks, the higher the discount rate investors use in their decision process.

If the NPV>0, the ship-owner purchases or orders more ships, but the price for a new order or second-hand ship increases, which can reduce the NPV. If NPV<0, no ordering or purchasing occurs and the market price for a new order or second-hand ship decreases, which pushes up the NPV. Therefore, the equilibrium condition is NPV=0. Under this assumption, Equation (3-1) changes to

$$\begin{cases} P_0^{old} = E_0\left[\int_{t=0}^{t=N-i} R(t)e^{-rt}dt\right] \\ P_0^{new} = E_0\left[\int_{t=\theta}^{t=\theta+N} R(t)e^{-rt}dt\right] \end{cases} \tag{3-2}$$

implying that at equilibrium, the market price of ships should be equal to the present value of expected future earnings. This defines the theoretical relationship between the ship price and the expectation of future revenue. Next, the relationship between the expected value and the current freight rate is discussed.

3.2.1 The future freight rate follows the OU process

The freight rate is modelled as a random process first, in which there is no future structural change. Theoretically, in the long run, the freight rate is determined by the interaction of supply and demand, which fluctuates in the short term but moves towards a long-term equilibrium level (Stopford, 2009). In this sense, it is appropriate to model the change in the freight rate using the OU process formatted as Equation (B. 1) in Appendix B.

Substituting Equation (B. 2) (Appendix B) into Equation (3-2):

$$\begin{cases} P_0^{old} = \int_0^{N-i}\left[me^{-rt} + (R_0 - m)e^{-(u+r)t}\right]dt = \frac{m}{r}\left(1 - e^{-r(N-i)}\right) + \frac{R_0-m}{u+r}\left(1 - e^{-(u+r)(N-i)}\right) \\ P_0^{new} = \int_\theta^{\theta+N}\left[me^{-rt} + (R_0 - m)e^{-(u+r)t}\right]dt = \frac{m}{r}\left(e^{-r\theta} - e^{-r(\theta+N)}\right) + \frac{R_0-m}{u+r}\left(e^{-(u+r)\theta} - e^{-(u+r)(\theta+N)}\right) \end{cases} \tag{3-3}$$

Because this relationship is annual, the subscript 0 can be changed to t, indicating the price-freight relationship for each year. Define $G(x)=G_x=\frac{1-e^{-x(N-i)}}{x}$, which is the present annuity value (PV) factor for a second-hand ship of age i with a discount rate x and number of periods N-i; and $K(x)=K_x=\frac{e^{-\theta x}(1-e^{-xN})}{x}$, which is the annuity PV factor for new ships with a number of periods equal to $N+\theta$. Compared with the second-hand ships, the new ships have no earnings in the first θ years due to the construction lag, but can be used for $\theta+i$ more years after the end of the second-hand ship's useable life. Given that a ship can typically be used for 30 years, the PV of the earnings in the $\theta+i$ years is usually much smaller than that in the first θ years. Therefore, $K_x<G_x$. Letting $\rho=\mu+r$, for any time t, Equation (3-3) can be simplified as:

$$\begin{cases} P_t^{old} = G_\rho R_t + m\left(G_r - G_\rho\right) \\ P_t^{new} = K_\rho R_t + m\left(K_r - K_\rho\right) \end{cases} \tag{3-4}$$

Equation (3-4) gives the theoretical price-freight relationship, which states that ship prices are determined by both freight revenue and the mean. Because both G_x and K_x are decreasing functions, and $r<\rho$, the values in parentheses in Equation (3-4) are positive. Given that only R_t relates to time t, Equation (3-4) states that the relationship between ship prices and the freight rate has a fixed intercept and slope. This over-simplified result is due to the assumption that the freight rate follows a traditional OU process with a constant mean over the whole period. To obtain a more realistic ship price–freight rate relationship, the assumption is relaxed to allow for a shifting mean with structural breaks.

3.2.2 Extended OU process with structural change (equilibrium level changes over time)

The OU process is extended in two ways. First, given the cyclical nature of the shipping market, it is not reasonable to assume a fixed 'mean' for the freight rate process over the whole sample period. Therefore, the OU process in Equation (B. 1) (Appendix B) is first extended to accommodate the changing mean m_t:

$$dR_t=u(m_t-R_t)dt+\sigma dz \tag{3-5}$$

where m_t is the long-term equilibrium level of R_t. The expectation of Equation (3-5) is:

$$E(dR_t)=E[\mu(m_t-R_t)dt] \tag{3-6}$$

which can be rewritten as:

$$\frac{dE(R_t)}{dt}+uE(R_t)=um_t \tag{3-7}$$

Equation (3-7) is an ordinary differential equation with the solution:

$$E[R_t]=ce^{-ut}+e^{-ut}*\int um_t e^{ut}dt \tag{3-8}$$

where c is the integration constant.

Second, major events such as a major financial crisis, an oil crisis or the start or end of a war, can have a significant effect on general trends in the shipping market and cause structural changes in the mean. To allow for such changes, the mean using the following equation is modelled:

$$m_t=(a+\Delta aD_t)+(b+\Delta bD_t)t \tag{3-9}$$

where D_t is a dummy variable that is equal to 1 after the breakpoint and Δa and Δb are the changes in the intercept and slope in m_t if there is a structural change. Here, m_t is two straight lines separated by one breakpoint. The challenge of having more than one breakpoint will be explained in the next section.

Substituting m_t into Equation (3-8):

$$E[R_t] = ce^{-ut} + \left[(a + \Delta aD_t) + (b + \Delta bD_t)t - \frac{b+\Delta bD_t}{u}\right] \tag{3-10}$$

When t=0, from Equation (3-10) it can be got $c = R_0 - \left[(a + \Delta aD_t) - \frac{b+\Delta bD_t}{u}\right]$. Thus,

$$E[R_t] = \left(a + \Delta aD_t - \frac{b+\Delta bD_t}{u}\right) + \left[R_0 - \left(a + \Delta aD_t - \frac{b+\Delta bD_t}{u}\right)\right]e^{-ut} + (b + \Delta bD_t)t \tag{3-11}$$

Substituting Equation (3-11) into Equation (3-2):

$$\begin{cases} P_0^{old} = \int_{t=0}^{t=N-i}\left[\left(a + \Delta aD_t - \frac{b+\Delta bD_t}{u}\right)e^{-rt} + \left(R_0 - a - \Delta aD_t + \frac{b+\Delta bD_t}{u}\right)e^{-\rho t}\right]dt + \int_{t=0}^{t=N-i}(b + \Delta bD_t)te^{-rt}dt \\ P_0^{new} = \int_{t=\theta}^{t=N+\theta}\left[\left(a + \Delta aD_t - \frac{b+\Delta bD_t}{u}\right)e^{-rt} + \left(R_0 - a - \Delta aD_t + \frac{b+\Delta bD_t}{u}\right)e^{-\rho t}\right]dt + \int_{t=\theta}^{t=N+\theta}(b + \Delta bD_t)te^{-rt}dt \end{cases} \tag{3-12}$$

Integrating Equation (3-12) and following the same reasoning as in Section 3.1, the ship price-freight rate relationship at any time t can be obtained:

$$\begin{cases} P_0^{old} = G_\rho R_t + C^{old} + \Delta C^{old}D_t \\ P_0^{new} = K_\rho R_t + C^{new} + \Delta C^{new}D_t \end{cases} \tag{3-13}$$

where $C^{\mathrm{old}} = a\left(G_r - G_\rho\right) + b\left[\frac{G_r-(N-i)e^{-r(N-i)}}{r} - \frac{G_r-G_\rho}{\mu}\right]$, $\Delta C^{\mathrm{old}} = \Delta a\left(G_r - G_\rho\right) + \Delta b\left[\frac{G_r-(N-i)e^{-r(N-i)}}{r} - \frac{G_r-G_\rho}{\mu}\right]$, $C^{\mathrm{new}} = a\left(K_r - K_\rho\right) + b\left[\frac{K_r+(\theta e^{-r\theta}-(N+\theta)e^{-r(N+\theta)})}{r} - \frac{K_r-K_\rho}{\mu}\right]$ and $\Delta C^{\mathrm{new}} = \Delta a\left(K_r - K_\rho\right) + \Delta b\left[\frac{K_r+(\theta e^{-r\theta}-(N+\theta)e^{-r(N+\theta)})}{r} - \frac{K_r-K_\rho}{\mu}\right]$.

Equation (3-13) shows the modified ship price–freight rate relationship when there is one breakpoint. Comparing with Equation (3-4), the changes after the breakpoint only apply to the intercepts. This implies that a structural change in the freight rate only shifts ship prices up or down, but does not change their response to changes in the freight rate.

Next, discussions turn to analyze how the changes in slope (Δa) and intercept (Δb) affect ΔC. This discussion helps us to understand how any structural change in the freight rate changes the price-freight relationship. To simplify the discussion, let $A^{old}=G_r-G_\rho$, $A^{new}=K_r-K_\rho$, $B^{old}=\frac{G_r-(N-i)e^{-r(N-i)}}{r} - \frac{A^{old}}{\mu}$ and $B^{new}=\frac{K_r+(\theta e^{-r\theta}-(N+\theta)e^{-r(N+\theta)})}{r} - \frac{A^{new}}{\mu}$, then

$$\begin{cases} C^{old} = aA^{old} + bB^{old} \\ C^{new} = aA^{new} + bB^{new} \end{cases} \text{and} \begin{cases} \Delta C^{old} = \Delta aA^{old} + \Delta bB^{old} \\ \Delta C^{new} = \Delta aA^{new} + \Delta bB^{new} \end{cases} \quad (3\text{-}14)$$

First, both A^{old} and A^{new} are positive because both G_x and K_x are decreasing functions of x, and $\rho > r$. The signs of B^{old} and B^{new} are hard to detect mathematically. Therefore, the discussion on the sign of the ΔC—the effect of a structural break on the intercept of the ship price–freight rate relationship—is left to the empirical test in Section 3.3.

3.2.3 Identify the structural change breakpoints

This section explains the method used to identify breakpoints in a sample, which extends Gregory and Hansen's (1996) method, which only allowed for one breakpoint during the sample period.

For each sample period, the range of observations for the potential breakpoint is determined according to Zivot and Andrews (1992) and Gregory and Hansen (1996). For a sample of n observations, the possible breakpoints are in the interval [$0.15n$, $0.85n$]. The 15 per cent on either side of the sample is left due to computational requirements.

For each possible breakpoint in the interval, a regression according to the statistical equation is run:

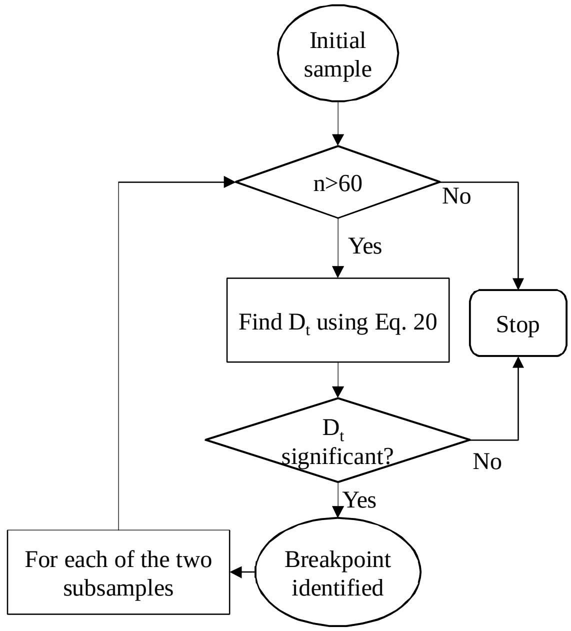
$$R_t = a + \Delta a D_t + bt + \Delta bt D_t + \varepsilon_t \tag{3-15}$$

The structural change breakpoint is then the breakpoint that minimises the sum of the squared errors among all possible breakpoints:

$$\min_{D_t} \sum \varepsilon_t^2 \tag{3-16}$$

This method can identify one breakpoint in one sample. For multiple breakpoints, the 'divide-and-conquer' strategy is adopted, as shown in Figure 3-2. For each subsample separated by the breakpoint, if the size of the subsample is larger than 60 observations (5 years for monthly data), the process is repeated to determine whether the generated new dummy variable D_t is significant. If yes, then it is a new breakpoint in the subsample; otherwise, there is no breakpoint in this particular subsample.

Figure 3-2: Flow Diagram for Automatically Identifying Breakpoints



3.3 Empirical analysis

In this section, the data used for the study, together with some descriptive statistics, are introduced. The regression results for the ship price–freight rate relationship under different assumptions are presented, along with explanations.

3.3.1 Data description

The data used in this paper consist of monthly new-building prices, five-year-old ship prices and one-year time-charter rates for three sizes of carrier – Capesize, Panamax and Handysize. Data are collected from Clarkson Research Services Limited 2010 (CRS) and originally quoted in million dollars for ship prices and dollars/day for time-charter rates. The latter are converted to a monthly rate for consistency. Due to the data availability, the sample period is from January 1976 to July 2012, except for the Capesize prices, which are from October 1983 to July 2012.

The descriptive statistics of 1-year time-charter rate (TC) are shown in Table 3-1. They reveal that the mean and standard deviation for larger ships are larger than those for smaller ships. The TC distribution is skewed to the right, and the sample distribution is more concentrated to its mean than the normal distribution, as suggested by the kurtosis statistics.

Table 3-1: Descriptive Statistics of TC (000$/month)

	Capesize	Panamax	Handysize
Mean	680.514	415.852	266.518
Median	450.000	320.100	219.000
Maximum	4116	2381.250	1224.000
Minimum	134.250	65.100	92.4
Standard Deviation	714.299	388.984	194.272
Skewness	2.979	3.033	2.757
Kurtosis	12.430	13.363	11.915
Jarque-Bera	1793.681	2637.748	2009.773
(Prob.)	(0.0000^{***})	(0.0000^{***})	(0.0000^{***})

Notes: Prob. is the test statistics for TC following a normal distribution; *** denotes the rejection of the null hypothesis at the 1% significance level.

3.3.2 Empirical results under traditional OU process

In this section, the parameters in Equations (B. 1) and (3-4) are estimated, and present the statistical equation of the ship price-freight rate relationship. Parameters estimation in Equation (B. 1) is given by Appendix B Equation (B. 4).

The regression results of Equation (B. 3) and the computed parameters in Equation (B. 4) in Appendix B are summarized in Table 3-2. The *t*-statistics indicate that the b estimators are significant at the 1 per cent significance level for all three carriers. The estimation of the OU process gives an R^2 of 94.1 per cent and a DW statistic of 1.3181.

Table 3-2: Regression Results for Equation (B. 3) and Parameter Estimates for Equation (B. 4)

Mean reversion: $R_t = a + bR_{t-1} + \varepsilon_t$			
	Capesize	Panamax	Handysize
$\hat{a}$	21.222 (0.1029)	9.086 (0.0927)	5.121 (0.0784)
$\hat{b}$	0.970(0.0000***)	0.979(0.0000***)	0.982 (0.0000***)
S.E. of regression	174.389	77.050	35.782
R^2	0.941	0.961	0.966
Durbin-Watson stat.	1.3181	0.7937	0.9173
m	707.4	432.7	284.5
u	0.0305	0.0212	0.0182
σ	177.052	437.300	287.088

Notes: *** denotes the rejection of null hypothesis at 1% significance level.

The regression results for the price-freight relationship based on Equation (3-4) are given in Table 3-3. From Equation (3-4), it is clear that $G_r - G_\rho = c/m$. Since G_ρ, c and m are available, G_r, ρ and r can be calculated, and these are also included in Table 3-3.

Based on Table 3-3, three interesting results are noted. First, it shows that G_ρ are smaller for the larger ships, namely $G_\rho^{\text{Cap}} < G_\rho^{\text{Pan}} < G_\rho^{\text{Han}}$. Similar relationships can be found for K_ρ. G_ρ and K_ρ are the annuity PV factors with discount rate $r+\mu$. A larger G means decision makers perceive less risk and volatility when investing in such a ship category. As ships are used to earn freight revenue, when there are fewer risks and less volatility, the freight revenue is a better indicator of the pricing of a ship. As freight rate for smaller vessels is less volatile than that for larger ones (Kavussanos, 1996; 1997), the prices of smaller ships are more sensitive to changes in the freight rate.

Second, G_ρ is higher than K_ρ for all three ship types, indicating that new-building prices are less sensitive to freight rate changes than those of second-hand vessels. This is consistent with the analytical result that $K_x < G_x$. Although a new ship lasts longer than a second-hand ship, it cannot be used to make profit right after the ship purchasing decision, which has a greater effect on the PV at time t. Therefore, the price of second-hand ships has a closer link to the current freight rate.

Third, the discount rates for second-hand ships are much higher than those for new orders, revealing the time-preference of ship-owners; that is, those who order new ships value long-term benefits more than second-hand purchasers.

Table 3-3: Ship Price-Freight Rate Relationship without Structural Change

$P_t^{old}=G_\rho R_t+c$					
	G_ρ	c	ρ	G_r	r
Capesize (346 obs.)	29.691***	14985.3	0.034	40.875	0.0244
Panamax (439 obs.)	37.720***	6057.337	0.027	51.719	0.019
Handysize (439 obs.)	43.397***	2670.887	0.023	52.785	0.0189
$P_t^{new}=K_\rho R_t+c$					
	K_ρ	c	ρ	K_r	r
Capesize (346 obs.)	18.533***	34873.78	0.028	67.832	0.0111
Panamax (439 obs.)	18.745***	18496.29	0.0275	61.491	0.012
Handysize (439 obs.)	25.309***	2670.887	0.023	65.105	0.0115

Notes: *** denotes the rejection of null hypothesis at 1% significance level.

3.3.3 Empirical results for the freight rate under extended OU process

This section presents the empirical results of the price–freight relationship under an OU process with structural change, beginning with the identification of the breakpoints.

Panel A in Table 3-4 summarizes the breakpoints for the three ship types by the method discussed in Section 3.2, together with the sample start and end times. Six breakpoints are identified for Panamax and Handysize ships, and four for Capesize vessels. Panel B in Table 3-4 shows the duration of the subsamples, each of which includes only one breakpoint. For example, subsample I is from the starting date for the whole sample to TB_2, with TB_1 as its breakpoint.

Table 3-4: Breakpoints for the Three Ship Types and Duration of Subsamples

Panel A: Breakpoints for the three ship types								
	Start	TB_1	TB_2	TB_3	TB_4	TB_5	TB_6	End
Panamax	1976.01	1981.09	1982.12	1987.11	2002.04	2007.01	2008.09	2012.07
Handysize	1976.01	1981.10	1982.08	1988.01	2001.08	2007.01	2008.10	2012.07
Capesize	1983.10			1987.11	2003.09	2007.04	2008.10	2012.07

Panel B: Duration of subsamples						
Subsample	I	II	III	IV	V	VI
Panamax/ Handysize	Start ~ TB_2	TB_1~TB_3	TB_2~TB_4	TB_3~TB_5	TB_4~TB_6	TB_5~End
Capsize			Start ~ TB_4	TB_3~TB_5	TB_4~TB_6	TB_5~End

The estimated parameters for Equation (3-9) for all subsamples and ship types are shown in Table 3-5. Here, the results for Panamax ships are explained, as the other two vessel types can be interpreted similarly. The equations for Panamax vessels are plotted in Figure 3-3, together with the corresponding freight rate (the curve) and the overall mean (the dotted line) identified in Section 3.2 and in Table 3-2.

Table 3-5: Estimated Results for Equation (3-9)

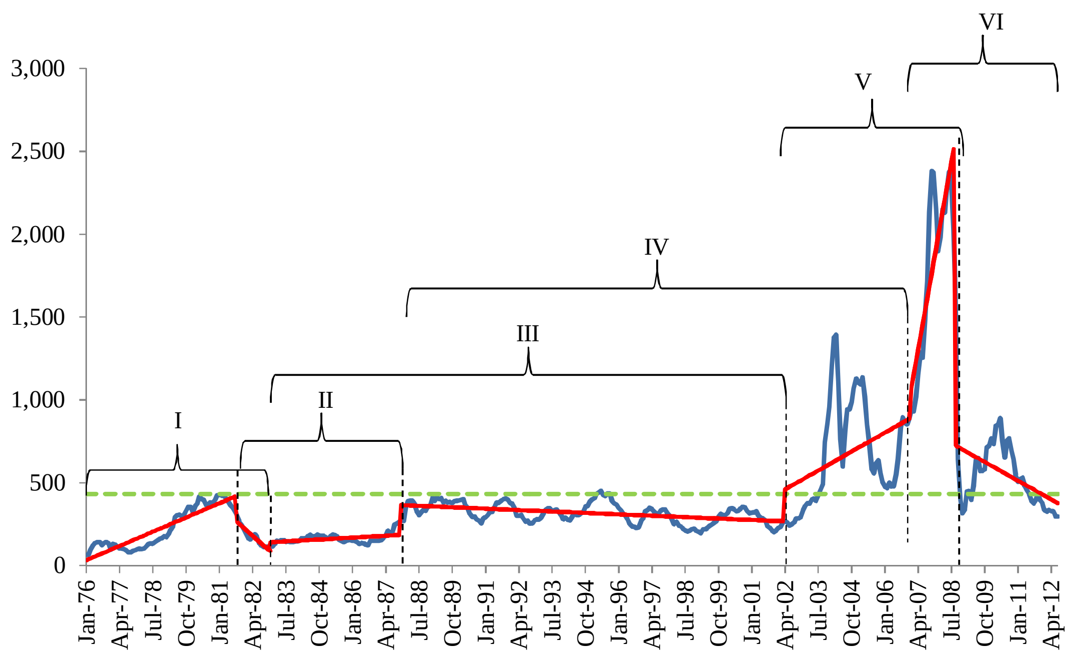
	obs	a	Δa	b	Δb	$\overline{m}_t$ (t<TB)	$\overline{m}_t$ (t>TB)
Panamax							
I	84	32.734***	1001.87***	5.734***	-17.119***	225.33	175.02
II	74	263.849***	-133.825***	-12.122***	12.877***	175.02	163.27
III	232	141.358***	258.013***	0.756**	-1.326***	163.27	316.72
IV	230	365.742***	-1220.529***	-0.570**	8.172***	316.72	673.25
V	77	460.388***	-3680.558***	7.602***	67.834***	673.25	1796.31
VI	67	1079.67***	-205.959	75.436***	-82.960***	1796.31	550.19
Handysize							
I	79	71.952***	596.357**	2.855***	-9.836***	169.02	155.17
II	75	186.589***	-88.283***	-6.981***	7.452***	155.17	118.06
III	228	103.009***	160.941***	0.470***	-0.764***	118.06	221.12
IV	228	244.882***	-986.964***	-0.293***	5.984***	221.12	367.68
V	86	185.566***	-1356.694***	5.691***	22.531***	367.68	945.52
VI	67	663.300***	-273.872***	28.222***	-29.021***	945.52	354.68
Capsize							
III	239	217.902***	249.567***	-0.798	0.597	198.74	438.57
IV	233	457.602***	1661.148***	-0.201	-3.600	438.57	1316.75
V	61	1396.566***	-1637.555	-3.801	71.327***	1316.75	3236.61
VI	64	2662.633***	-1593.413***	67.526***	-79.159***	3236.61	639.0

Notes: ** indicates statistical significance at 5% level; *** indicates significance at 1% level.

In subsample I, the mean increased in the first five years and then decreased sharply, which corresponds to the severe world economic recession in July 1981. The average of m_t is 225.33 before TB_1, and 175.02 thereafter; both values are less than the mean for Panamax ships for the whole sample (432.7 in Table 3-2).

Compared with subsample I, the shape of m_t in subsample II shows the opposite situation. The freight rate increases gradually after TB_2, but the average of m_t after TB_2 is 163.27, which is still less than 175.02 (the average of m_t before TB_2).

Figure 3-3: Results of m_t from the Six Subsamples for Panamax Carriers



Notes: The blue solid line indicates the real-time charter rates R_t; the red solid line indicates m_t; and the green dash line represents m.

The structural change is clear in subsample III. m_t almost follows two almost horizontal lines, indicating that the freight rate is relatively stable except at the breakpoint.

In subsample IV, a significant structural change occurs in 2002. The freight rate increases much faster after the breakpoint, which corresponds to the period of fast growth in China.

The freight rate increases even faster in subsample V. The average m_t after the structural change is 1796.31, four times the overall mean of 432.7. Considering that the mean in this subsample is much higher than the overall mean, it is clear that using the traditional OU process is not sufficient to model the freight rate change over the whole period.

In subsample VI, m_t has a similar pattern to that in subsample I, except that the freight rate is much higher. The identified breakpoint is September 2008, and only the slope change is significant, indicating that the freight rate returns to around the 2007 level.

In summary, the slopes of the freight rate after the breakpoints, $b+\Delta b$, are negative for subsamples I, III and VI. Among them, the $\overline{m}_t$ mean value increases after the breakpoint in subsample III, which is the opposite of the case for I and VI. In subsamples II, IV and V, $b+\Delta b$ increase after the breakpoints. The $\overline{m}_t$ in sub-period II decreases after the breakpoint, while that in IV and V subsequently increases. Similar results can be found for the Handysize freight rate.

Comparing the three ship types, the mean freight rate $\overline{m}_t$ increases with ship size. This is consistent with the expectations of there being different freight rates for different ship sizes.

3.3.4 Empirical results on ship price-freight rate under extended OU process

To test the validity of Equation (3-13), a regression between the ship prices and freight rates for each subsample is first ran, with both slope and intercept dummies for structure changes, namely, $P^{old}=\alpha_1*R_t+\beta_1*R_tD_t+c^{old}+\Delta c^{old}D_t$ and $P^{new}=\alpha_2*R_t+\beta_2*R_tD_t+c^{new}+\Delta c^{new}D_t$. The slope dummies ($\beta_1$ and β_2) are not significant for almost all of the subsamples. This confirms the theoretical result in Equation (3-13) that the marginal effect of the freight rate on ship prices does not change after the breakpoint. This statistical result reflects the pricing behaviour in the ship market. Although large structural changes do have significant effects on both the freight rate and ship prices, they do not occur very often. For day-to-day ship transactions, buyers and sellers make reference to the current freight rate changes when determining prices. Therefore, structural changes do not have a significant effect on how ship prices respond to the freight rate change. However, these infrequent changes do have a significant effect on ship prices, as they generate a long-term imbalance between supply and demand in the ship market.

Thus, the empirical analyses for ship price–freight rate relationships with structural changes are based on Equation (3-13). Table 3-6 summarizes the estimation parameters for Equation (3-13) for all of the subsamples and ship types, and the results are subsequently explained.

G_ρ is higher than K_ρ in every subsample, indicating that new-building prices are less sensitive to the freight rate change than second-hand vessel prices. These results are in line with the results obtained with the traditional OU process. However, looking at these two parameters over different periods, it can be seen that the G_ρ is more stable, whereas K_ρ has a larger variance and shows a clear decreasing trend over time. This indicates that in recent years, the freight rate has become a less important factor in new-building prices.

Comparing the results from identical subsamples for all three ship types, the finding that G_ρ and K_ρ are smaller for larger ships still holds true; that is, $G_\rho^{\mathrm{Cap}}<G_\rho^{\mathrm{Pan}}<G_\rho^{\mathrm{Han}}$ and $K_\rho^{\mathrm{Cap}}<K_\rho^{\mathrm{Pan}}<K_\rho^{\mathrm{Han}}$, except in the case of subsample VI for Handysize carriers. This finding confirms the results obtained with the traditional OU process, demonstrating that smaller ship prices are more sensitive to changes in freight rate.

In Table 3-6, ρ can be calculated because G_ρ is available. Eliminating B^{old} and B^{new} in Equation (3-15), it is clear that A^{old} and A^{new} can be obtained, $A^{old}=(b\Delta C^{old}-C^{old}\Delta b)/(b\Delta a-a\Delta b)$ and $A^{new}=(b\Delta C^{new}-C^{new}\Delta b)/(b\Delta a-a\Delta b)$. Given that b, Δb, a and Δa are available from Table 3-5, and C^{new}, ΔC^{new}, C^{old} and ΔC^{old} are in Table 3-6, A^{old} and A^{new} can be computed. Then the discount rate r for each period can be estimated, and these estimates are shown in Table 3-7.

Table 3-6: Ship Price-Freight Rate Relationship with Structural Change

	Panamax	P^{old}		P^{new}		
	G_ρ	C^{old}	ΔC^{old}	K_ρ	C^{new}	ΔC^{new}
I	42.656***	2807.98***	356.66	39.907***	10919.3***	5537.341***
II	41.218***	3422.045***	-2056.008***	28.407***	18515.14***	-6543.073***
III	30.661***	3089.724***	6186.215***	25.482***	12449.65***	5371.111***
IV	25.437***	10930.42***	2357.191***	15.453***	20997.16***	-458.134
V	27.091***	12174.33***	13337.26***	12.227***	22710.85***	5549.822***
VI	31.690***	17249.12***	-1477.319	10.719***	30969.98***	-2660.092
	Handysize					
I	38.832***	1440.78***	1133.521***	47.633***	4998.972***	3759.763***
II	14.073	6416.190***	-2713.874***	20.514***	12966.87***	-3946.415***
III	35.109***	1218.866**	4114.767***	27.658***	8176.942***	4113.665***
IV	35.592***	5226.808***	136.753	26.593***	12526.21***	-1960.008***
V	33.424***	6160.703***	4879.235***	19.795***	13065.47***	1360.453***
VI	29.683***	14576.71***	-2637.2429*	7.279***	26260.39***	-4771.427***
	Capesize					
III	25.084***	8039.105***	9214.39***	18.138***	24466.55***	9982.437***
IV	17.704***	20490.33***	8498.941***	9.183***	38376.67***	10136.74***
V	18.976***	27314.17***	23953.63***	5.605***	53224.81***	21996.40***
VI	22.112***	41118.32***	-13210.98**	6.951**	70864.58***	-16081.37

Note: ** indicates statistical significance at 5% level; *** indicates significance at 1% level.

Table 3-7: Estimated r for Each Subsample (Unit: %)

Panamax	I	II	III	IV	V	VI
P^{old}	1.97	1.92	1.86	1.55	**2.54**	2.01
P^{new}	1.02	0.66	0.97	0.86	**1.75**	1.59
Handysize						
P^{old}	2.17	1.94	1.86	1.59	**2.34**	1.66
P^{new}	1.05	0.71	0.95	0.86	**1.56**	1.20
Capsize						
P^{old}			1.60	1.35	**2.54**	2.22
P^{new}			0.89	0.69	**1.48**	0.14

Note: Bold fonts indicate the maximum value

The discount rate r in Table 3-7 follows a similar pattern in the traditional OU process for the same time period, namely the r from the P^{old} equation is larger than that from the P^{new} equation, indicating that the second-hand ship investors are more interested in short-term benefits comparing with the new-building ship investors. The reason is that second-hand ships can be obtained immediately, and thus can generate benefits as soon as they are put into the market. In contrast, new-building ships need to wait for their constructions. The lag between ordering and delivery of the new-building ships cause the investors more care about their future benefits. However, comparing the values for different subsamples, it is noticed that subsample V has the highest r of all three ship types. This corresponds to the time when the freight rate is very high and volatile. Intuitively, this is also the time when ship investors focus more on short-term freight revenue than its long-term benefits, because the higher the freight rate, the more urgent the need for shipping companies to acquire the vessel and put it into its active fleet. This explains why r is higher is this period.

Because the sign of ΔC—the intercept for the ship price–freight rate relationship after the breakpoint—cannot be determined theoretically, it is compared to the change in the freight rate after the breakpoint. Table 3-8 summarises the change in the freight rate (Δa and Δb), the new slope for the mean of the freight rate ($b+\Delta b$), the intercept change in the ship price–freight rate relationship (ΔC^{old} and ΔC^{new}) and the change in the mean freight rate ($\overline{m}_t$).

Table 3-8: Comparing the Signs of ΔC^{old} and ΔC^{new}

		Δa	Δb	$b+\Delta b$	ΔC^{old}	ΔC^{new}	$\overline{m}_t$
I	Panamax	+	-	-	+	+	-
	Handysize	+	-	-	+	+	-
II	Panamax	-	+	+	-	-	-
	Handysize	-	+	+	-	-	-
III	Panamax	+	-	-	+	+	+
	Handysize	+	-	-	+	+	+
	Capesize	+	0	-	+	+	+
IV	Panamax	-	+	+	+	-	+
	Handysize	-	+	+	+	-	+
	Capesize	+	0	-	+	+	+
V	Panamax	-	+	+	+	+	+
	Handysize	-	+	+	+	+	+
	Capesize	-	+	+	+	+	+
VI	Panamax	-	-	-	-	-	-
	Handysize	-	-	-	-	-	-
	Capesize	-	-	-	-	-	-

Notes: 0 means that Δb is not significant.

Clearly, Panamax and Handysize ships have similar trends for all of the subsamples, indicating that they have similar long-term freight rate and ship price trends. In most cases, the ΔCs change in the same direction as the average mean after the breakpoint, indicating that the long-term effects of structural changes on the freight rate and ship price are in the same direction. Opposite directions only occur in subsample I, and that for new orders for Panamax and Handysize ships in subsample IV. Therefore, it is clear that if a structural change results in a general increase or decrease in the freight rate, the level of ship prices will also increase or decrease correspondingly. However, if it results in a very high and volatile freight rate (subsample IV), the level of new ship prices may decrease, because ship-owners are then more interested in purchasing second-hand ships rather than ordering new ships. The result in subsample I is an exception, perhaps because not enough months have passed since the breakpoints, or perhaps as a result of certain other factors that were not considered in this study. From this, it can be seen that although structural change does not affect the sensitivity of ship prices with respect to freight rate changes, it does prompt a general shift in ship prices.

3.4 Chapter conclusion

This chapter analyses the relationship between ship prices and freight rates in a cyclical shipping market under possible structural changes. Theoretical relationships were formulated under the assumption that a long-term equilibrium exists between the present value of future income from a ship and the ship price, and the future income following an extended mean-reverting process. These relationships under different assumptions are tested using the observed monthly data on ship prices and time-charter rates for different ship sizes. To incorporate the effect of structural change, the regression models are ran over six subsamples that allowed one structural change in each period.

Our theoretical analysis and empirical test yield some useful findings on the relationship between ship prices and freight rates. First, a structural change in the freight rate process only affects the level of ship prices, not their sensitivity to the freight rate. Second, the prices of smaller ships are more sensitive to changes in the freight rate, and second-hand ship prices are more sensitive to changes in the freight rate than new-building prices. Third, the discount rate for second-hand ships is larger than that for new ships, implying that second-hand ship investors value short-term benefits more than new ship investors. The discount rate also increases over time, implying that investors put more emphasis on the short-term benefits today than they did before. Fourth, structural changes typically affect the long-term trends of freight rate and ship price in the same direction, but if it results in a high and volatile freight market, the price of new ships may decrease.

In this study, the freight rate process is modelled, allowing a shifting mean with structural changes. The trend of the mean determines the long-term variation in the shipping cycle. Modelling this long-term cycle can further help with the modelling of the ship price–freight rate relationship.

Chapter 4: SHIP INVESTMENT UNDER UNCERTAINTY

Based on the theoretical ship price-freight rate relationship derived from the Chapter 3, this Chapter will analyze the minimal market freight rate necessary for profitable ship investment, if shipping companies take into account the option value of delay the investment decision to a later date. Since the traditional net present value method ignores uncertainty, especially the cyclic nature in shipping market, the minimal freight rate derived using the real option approach can provide a better decision on whether to invest immediately, or delay. Theoretically, trigger rates for ship investment are developed under assumption of the geometric Brownian motion and the mean-reverting motion of freight rate for comparison. Empirical tests using monthly data show that most of the previous investment behaviour can be explained by the trigger rates obtained using the real option approach, especially when cyclic nature is clear.

4.1 Introduction

The timing of ship investment is no doubt a vital issue faced by many shipping companies because of the high degree of risk and uncertainty in the shipping market. In reality, heavy investment usually happens when the freight market is prosperous even though it is also the time that the investment cost is also high. In addition to the long payback period, new ships require months to years to be constructed, during which various changes possibly happen in the freight market. The lag between the payment of investment cost and the return of investment revenue makes new ship investment decision even more difficult. Choosing an optimal timing to invest in ships not only benefits a company’s capital cost savings, but also promotes its future performance in the long run. Thus, whether and when to invest in ships are always essential to the success of a shipping company.

Traditionally, the net present value (NPV) method is commonly adopted in investment evaluation. Once the NPV is positive, the project should go ahead. However, this approach is a static analysis which ignores the future uncertainties. As Karakitsos & Varnavides (2014) pointed out that under conditions of uncertainty the NPV method does not work. It has to be adjusted to include a hurdle rate, which is the minimum rate of return on an investment, in order to compensate for risk. This hurdle rate can be viewed as the price of exercising the option to invest. Thus, the real option approach (ROA) incorporating the uncertainties in the future provides a more flexible and accurate evaluation on the ship investment project than the NPV method.

However, ROA has sparsely applied in maritime studies, although it has been studied extensively in other areas (Dixit, 1989; Abel, 1983; Dias & Rocha, 1999). The reason behind this phenomenon may be that the ROA largely depends on the assumption of the stochastic process of future net cash flow. Previous studies commonly used Geometric Brownian motion (GBM) because it is easily managed and has a closed-form solution (Pindyck, 1982; 1988; Abel, 1983; Brennan & Schwartz, 1985; McDonald & Siegel, 1986; Dixit, 1989). However, the freight rate which represents the cash inflows in shipping is determined by the market supply and demand (Stopford, 2009). Theoretically, it should oscillate around its long-term equilibrium level. Then the mean-reverting process, also called the Ornstein-Uhlendbeck (OU) process, is a more realistic choice to describe such process (Schwartz, 1997; Sarkar, 2003) although most of the past empirical tests do not support this assumption (Kavussanos & Alizadeh, 2002b; Veenstra & Franses, 1997; Alizadeh & Nomikos, 2007). In contrast to GBM, the OU process is difficult to solve theoretically. Its solutions can be only found numerically or empirically. Since most of the above tests were based on a long time series, it is interesting to find out whether the OU process is more appropriate in some periods and the GMB process is better in other periods.

The aim of this research is to examine whether and when to invest in new ships incorporating the option to delay. Instead of deriving an optimal timing t to make this decision, the minimal market freight rate necessary for profitable ship investment is analyzed, which is called as "trigger rate" in the whole part. Investment is recommended to be made immediately if the real freight rate level is higher than this trigger rate. Otherwise, investment is suggested to be suspended till the real freight rate goes up to the trigger rate. The starting point of the theoretical modelling is to make a proper assumption on the freight rate process and then establish a long-term return function on ship investment. Different with past studies, the cash flows of ship investment project starts with a lag due to the construction of a new-building ship and this project has a finite time horizon because of the ship's limited lifespan. Theoretically, trigger rate for new ship investment under two different assumptions on the process of the freight rate - the GBM and OU process – are derived. Empirically, we found that the trigger rate using the ROA provides a stricter rule on immediate investment decision than the NPV method. Moreover, previous investment behaviour is well explained by the trigger rate obtained using the ROA with taking into account the cyclical nature of freight rate movement.

This paper makes the first attempt to provide a clear investment rule for the new ship investment timing decision with considering the option to delay. It fills the gap by theoretically analyzing the trigger rate for ship investment decision using the more accurate OU assumption on freight rate process, and empirically calculating the trigger rates with considering the shipping cyclical nature. It contributes to the investment decision theory applied to projects with huge capital cost, long lifespan and cyclical market conditions. Practically, it gives shipping companies a clear rule on ship investment decision and helps them to make investment decisions in different market conditions.

4.2 Theoretical trigger rate for ship investment

This section formulates the theoretical conditions for ship investment by comparing two evaluation methods: first NPV, then ROA. In either method, a situation in which an individual shipping company has to decide whether to order a new ship at current time (t=0) is considered. If order, it needs to wait θ years due to the construction lag and use the ship for N years. Denote R_t as the time-charter rate at time t, which is the net earnings of the ship. For simplicity, the ship is assumed not to be traded in the second-hand market, and have no salvage value at the end of the lifespan. The present value of the total earnings if the ship-owner orders the ship at time 0 can be written as:

$$V_0(R) = E\left\{\int_{t=\theta}^{t=N+\theta} R_t e^{-rt} dt\right\} \tag{4-1}$$

where r is the discount rate, and E is the operator for expectation.

From Equation (4-1), the return on investment depends on the random variable R. To further analyze Equation (4-1), a proper assumption of the specific form of the random process R is required. The most common assumption is the GBM process, which gives a closed-form solution. However, the OU process seems more realistic in our case. Since R may follow different stochastic processes in different shipping cycles, both the GBM and OU processes will be analyzed in the following subsection.

4.2.1 Trigger rates from geometric Brownian motion

If R follows the GBM process as formatted in Equation (A. 1) in Appendix A, from Equation (4-1), the total return $V_0(R_t)$ equals:

$$V_0(R_t)=R_0 K_\delta \tag{4-2}$$

where $K_\delta = \frac{e^{-\delta\theta} - e^{-\delta(N+\theta)}}{\delta}$ is the present annuity value factor and δ=r-α, which is the shortfall between the discount rate r and the expected growth rate of R. It makes sense that δ is usually assumed to be larger than 0 (Dixit and Pindyck, 1994). Equation (4-2) shows a theoretical relationship between the freight rate and the expected total revenue under the GBM assumption.

After obtaining the present value of all future chartering income, the NPV method can be used to evaluate the investment. From Equation (4-2), the NPV for investing in a new ship under the GBM process is:

$$NPV = V_0(R_t) - P_0 = R_0 K_\delta - P_0 \tag{4-3}$$

where P_0 is the price of the new ship at time t=0. Equation (4-3) shows that NPV≥0 is the same rate that enables $R_0 K_\delta \geq P_0$. Define the trigger rate, $R^*_{\mathrm{G-NPV}}$, as the freight rate that satisfies $R^*_{\mathrm{G-NPV}} K_\delta = P_0$, i.e.

$$R^*_{\mathrm{G-NPV}} = \frac{P_0}{K_\delta} \tag{4-4}$$

then whenever a shipping chartering rate R_0 satisfies $R_0 \geq R^*_{\mathrm{G-NPV}}$, it is a good time to invest in a new ship according to the NPV rule.

Next, the trigger rate under ROA, where the shipping company has an option to delay is derived. At time 0, if the company chooses to invest immediately, based on Equation (4-3), its net payoff is the NPV (i.e. $V_0(R_t)–P_0$). If the company postpones this investment to a short time interval dt, the net payoff at time dt, $F_{dt}(R_t, P_t)$, equals to $V_{dt}(R_t)–P_{dt}$. Since the focus is on the time-charter rate, for the sake of simplicity, the change in ship price in the interval of dt is ignored (i.e. $F_{dt}(R_t)=V_{dt}(R_t)–P_0$). Discounting the expected net payoff to current time, the problem for the decision market is to choose the investment that provides a higher net payoff:

$$F_0(R_t) = \max\{V_0(R_t) - P_0,\ e^{-rdt}E_0[F_{dt}(R_t)]\} \tag{4-5}$$

Then the trigger rate in ROA, $R^*_{\mathrm{G-ROA}}$, is the time-charter rate that equalizes the two choices (i.e., $V_0(R_t)–P_0=e^{-rdt}E_0[F_{dt}(R_t)]$).

According to Equation (4-A. 9) in Appendix 4-A, the trigger rate $R^*_{\mathrm{G-ROA}}$ satisfies:

$$R^*_{\mathrm{G-ROA}} = \frac{\lambda_1 P_0}{(\lambda_1 - 1)K_\delta} \tag{4-6}$$

where $\lambda_1 = \left(\frac{1}{2} - \frac{\alpha}{v^2}\right) + \sqrt{\left(\frac{1}{2} - \frac{\alpha}{v^2}\right)^2 + \frac{2r}{v^2}}$. Clearly, $R^*_{\mathrm{G-ROA}}$ is affected by the determinants of the freight rate (α, v), the discount rate r, the construction lag of the new ships θ, the lifespan of the ship N, and the present new-building ship price P_0. Since $\lambda_1>1$, it has $\frac{\lambda_1}{\lambda_1 - 1} > 1$ in Equation (4-6). Comparing with $R^*_{\mathrm{G-NPV}}$ in Equation (4-4), $R^*_{\mathrm{G-ROA}} > R^*_{\mathrm{G-NPV}}$, showing that trigger rate from ROA is higher than that from NPV rule using GBM.

From Appendix 4-A Equation (4-A. 11), the expected value from the investment is:

$$F_0(R_t) = \begin{cases} \frac{R_0 K_\delta}{\lambda_1} & R_0 < R^*_{\mathrm{G-ROA}} \text{ (postpone investment)} \\ R_0 K_\delta - P_0 & R_0 \geq R^*_{\mathrm{G-ROA}} \text{ (immediate investment)} \end{cases} \tag{4-7}$$

At a certain trigger rate, as the freight rate goes down, the return on investment immediately becomes less. If the freight is less than $R^*_{\mathrm{G-ROA}}$, it is better to postpone the investment.

4.2.2 Trigger rates from mean-reverting motion

If R follows the OU process as Equation (B. 1) in Appendix B, substituting Equation (B. 2) into Equation (4-1):

$$V_0(R) = R_0 K_\rho + m\left(K_r - K_\rho\right) \tag{4-8}$$

where ρ=u+r, K_ρ=$\frac{e^{-\rho\theta} - e^{-\rho(N+\theta)}}{\rho}$ and K_r=$\frac{e^{-r\theta} - e^{-r(N+\theta)}}{r}$.

The NPV for investing in new ships in the OU process is:

$$NPV = V_0(R_t) - P_0 = R_0 K_\rho + m\left(K_r - K_\rho\right) - P_0 \tag{4-9}$$

By following the analysis of the NPV rule in Section 4.2.1, NPV≥0 is equivalent to the trigger rate that makes the NPV positive. The trigger rate, $R^*_{\mathrm{OU-NPV}}$, can be written as:

$$R^*_{\mathrm{OU-NPV}} = \frac{P_0 - m\left(K_r - K_\rho\right)}{K_\rho} \tag{4-10}$$

For the ROA, the optimal expected value is the same as shown in Equation (4-5), except that the underlined assumption of the stochastic process is different. Appendix 4-B gives the development process of the trigger rate in the OU process. According to Equation (4-B. 12) in Appendix 4-B, the trigger rate in the OU process, which is named as $R^*_{\mathrm{OU-ROA}}$, satisfies:

$$K_\rho X(R^*_{\mathrm{OU-ROA}}) - \left[R^*_{\mathrm{OU-ROA}} K_\rho + m\left(K_r - K_\rho\right) - P_0\right] X'(R^*_{\mathrm{OU-ROA}}) = 0 \qquad (4\text{-}11)$$

where $X(R) = H_1(R) - Ky(R)^{1-b} H_2(R)$, where $H_1(R) = H\left(\frac{r}{2u}, \frac{1}{2}, y(R)\right)$, $H_2(R) = H\left(\frac{r}{2u} + \frac{1}{2}, \frac{3}{2}, y(R)\right)$ and $H(\cdot)$ is the confluent hypergeometric function (see Appendix 4-B); $y(R) = \frac{u(m-R)^2}{\sigma^2}$; $K = \frac{\Gamma(b)\Gamma(\gamma-b+1)}{\Gamma(2-b)\Gamma(\gamma)}$ where $\Gamma()$ is the Gamma function.

Clearly, $R^*_{\mathrm{OU-ROA}}$ is affected by the determinants of the time charter rate (u, m, σ), the discount rate r, the construction lag θ, the lifespan of the ship N, and the present new-building ship price P_0. Obviously, no closed-form solution is available for $R^*_{\mathrm{OU-ROA}}$. Comparison between $R^*_{\mathrm{OU-NPV}}$ and $R^*_{\mathrm{OU-ROA}}$ is not realized. Empirical studies will be conducted to further explain the theoretical results in the next section.

The present expected return on investment at time 0 is (Equation (4-B. 13)):

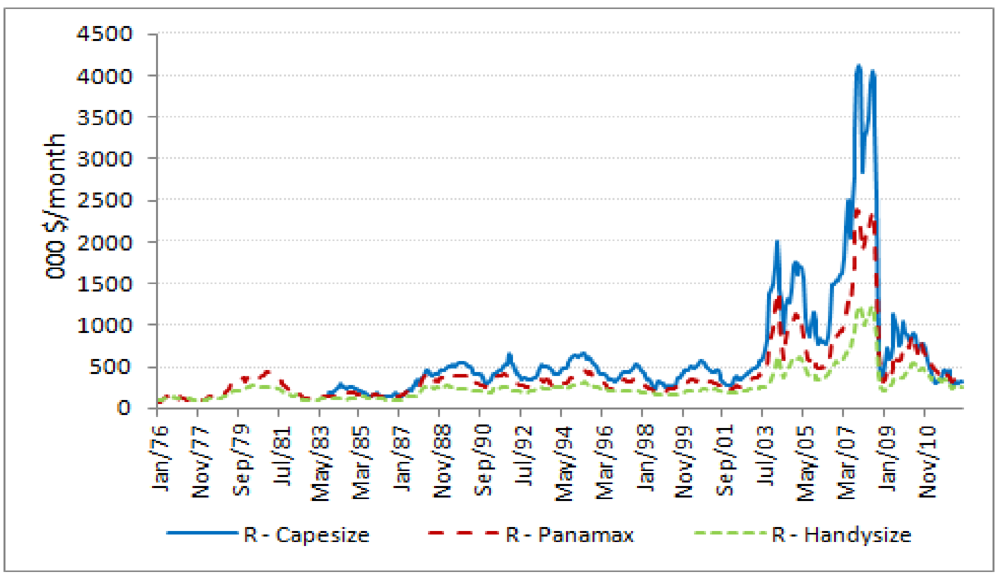
$$F_0(R_t) = \begin{cases} R_0 K_\rho + m\left(K_r - K_\rho\right) - P_0 & R_0 \geq R^*_{\mathrm{ROA}} \text{ (immediate investment)} \\ \frac{K_\rho X(R_0)}{X'(R_0)} & R_0 < R^*_{\mathrm{ROA}} \text{ (postpone investment)} \end{cases} \qquad (4\text{-}12)$$

The upper equation in Equation (4-12) describes the NPV of the investment. As the real time-charter rate falls, immediate investing becomes less valuable. The likelihood of investment postponement increases. Expected value from the postponement is shown in the bottom equation in Equation (4-12).

4.3 Empirical analysis and numerical experiments

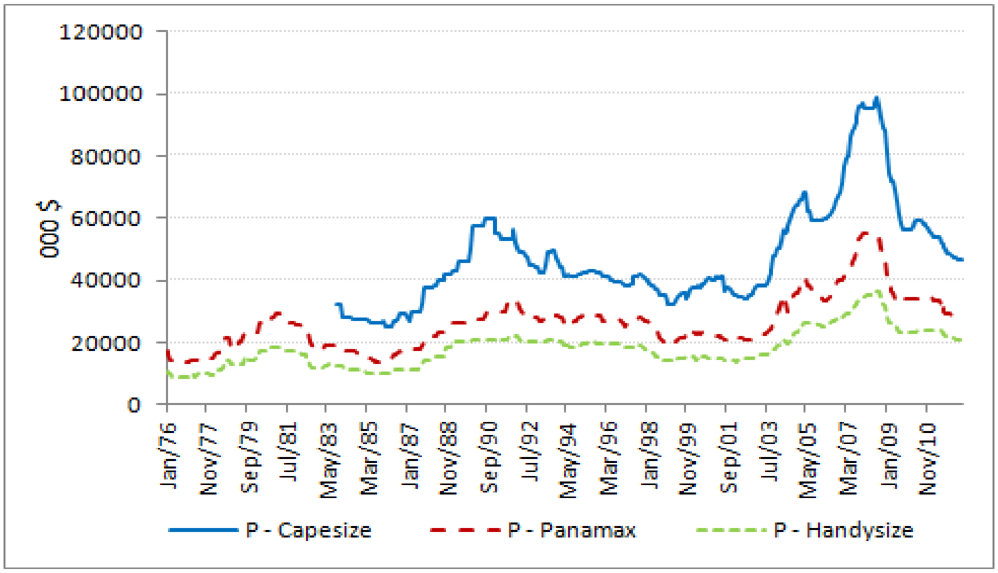
In this section, our empirical analysis is described. The data used in this research consists of monthly new-building prices (P) and 1-year time-charter rates (R) for carriers of three different sizes — Capsize, Panamax and Handysize, collected from Clarkson Research Services Limited 2010 (CRS), and originally quoted in million dollars for ship prices and dollars/day for time-charter rates. For consistency, ship prices are converted to thousand dollars, and time-charter rates are converted to thousand dollars per month. The sample period is from January 1976 to July 2012, except for Capesize prices, whose sample period spans from Oct 1983 to July 2012. Figure 4-1 depicts the time-charter rate and new building price in the whole sample.

Figure 4-1: Time-charter Rate and New-building Prices over the Study Period



(a) 1-year time-charter rate

Figure 4-1: Time-charter Rate and New-building Prices over the Study Period (Continued)



(b) New-building price

Notes: The blue solid line indicates Capesize carriers; the red dash line indicates Panamax carriers and the green dash line represents Handysize carriers.

4.3.1 Basic trigger rates from the whole sample

In this section, trigger rates using the whole sample period are estimated. The first step is to examine whether the stochastic assumption – GBM or OU process - holds for the freight rate process. Using the method discussed in Appendix A and B, the estimated results of the freight process for the whole sample are summarized in Table 4-1. For the whole data sample, the results reject the null hypothesis that β_2 is equal to zero. Different from previous studies, the ADF test rejects the null hypothesis that R is non-stationary, implying that the freight rate R follows the OU process.

Table 4-1: Empirical Test Results of R for the Whole Sample

		OU process		GBM process	
Ship types	Whole sample	ADF *t*-Statistic	(*p*-value ADF)	β_2	(*p*-value of β_2)
Capesize	1983.10-2012.07	-3.0805	(0.0290*)	0.3452	(0.0000**)
Panamax	1976.01-2012.07	-3.3532	(0.0132*)	0.4327	(0.0000**)
Handysize	1976.01-2012.07	-3.6389	(0.0054**)	0.4967	(0.0000**)

Notes: * denotes the rejection of the null hypothesis at the 5% significance level, while ** denotes the rejection of the null hypothesis at the 1% significance level.

Next, since R is the OU process, u, m and σ need to be estimated first, and then trigger rates $R^*_{\mathrm{OU-NPV}}$ and $R^*_{\mathrm{OU-ROA}}$ can be calculated based on Equations (4-10) and (4-11).

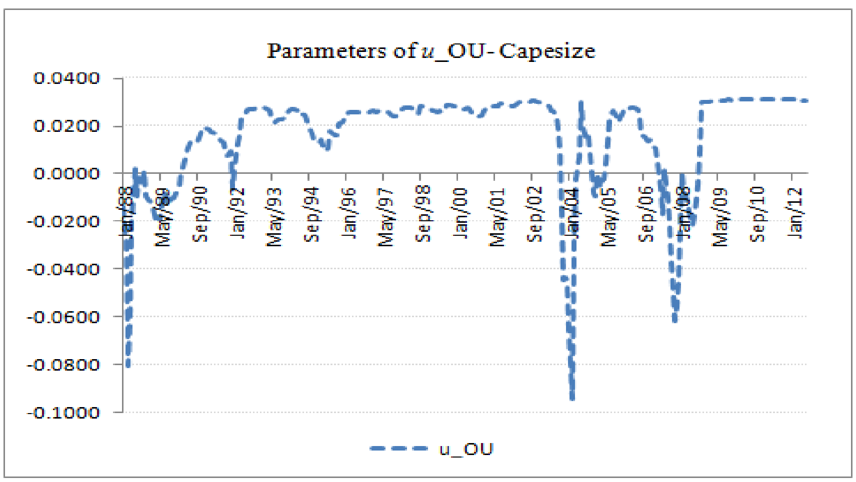
Following the method in Dixit and Pindyck (1994), the discrete-time counterpart of the OU process for R can be written as Equation (B. 3), and the relationship between the estimated parameters in Equation (B. 3) and the continuous-time version of the OU process is given in Equation (B. 4). A predominant way to obtain those parameters is to regress Equation (B. 3) using the whole sample. Clearly, only one set of parameters can be obtained. However, the behaviour of the market freight rate and people's perception about the market change over time. To study the dynamics of these parameters, pre-Jan-1998 data sample is used as the base sample. "Jan 1988" is chosen as there should be enough data available for parameter calculation and the time around "Jan 1988" is found to be the structural change point in Chapter 3. From the regressed estimator of the base sample, the first group of u, m and σ is obtained, denoted as u_1, m_1 and σ_1 respectively. Then, in adding one new data "Feb 1988" to the base sample, another group of u, m and σ is found. Using the same way, three time series of such parameters are finally generated, denoting them as u_OU, m_OU and σ_OU respectively. The descriptive statistics of these series are summarized in Table 4-2, and their detailed trends are shown in Figure 4-2. In general, the parameters of smaller ships are smaller than those of larger ships. From the figure, it can be seen that the long-term equilibrium mean and reverting speed exhibit sudden changes mainly during the period 2003-2008, which corresponds to the time that shipping market shows dramatic jump-up and jump-down.

Table 4-2: Descriptive Statistics of u_OU, m_OU and σ_OU

	Mean	Median	Max	Min	S.D.	Jarque-Bera	(Prob.)
Capesize							
u_OU	0.0160	0.0256	0.0315	-0.0947	0.0206	721.7036	(0.0000*)
m_OU	598.9666	442.3197	3201.1	-2733.7	2014.4	$5.06*10^5$	(0.0000*)
σ_OU	62.7550	29.0307	184.7750	18.4401	57.1122	86.0683	(0.0000*)
Panamax							
u_OU	0.0150	0.0200	0.0273	-0.0813	0.0144	4192.1	(0.0000*)
m_OU	373.4748	310.3616	11182	-4504.5	818.3937	$1.7*10^5$	(0.0000*)
σ_OU	32.7284	18.1421	79.4999	17.4301	22.7191	71.6465	(0.0000*)
Handysize							
u_OU	0.0099	0.0146	0.0180	-0.0509	0.0117	1236.1	(0.0000*)
m_OU	265.8121	220.2244	4308.1	-679.9049	349.2516	0.9*105	(0.0000*)
σ_OU	15.2846	9.6121	36.9166	8.8254	9.8076	109.7188	(0.0000*)

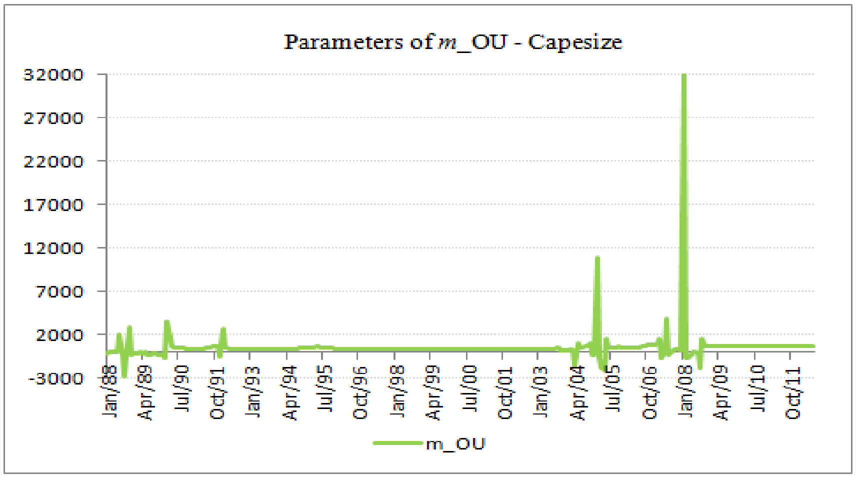
Notes: Prob. is the test statistics for the series following a normal distribution; * denotes the rejection of the null hypothesis at the 5% significance level.

Figure 4-2: Parameters of u_OU, m_OU and σ_OU Evolving with Time

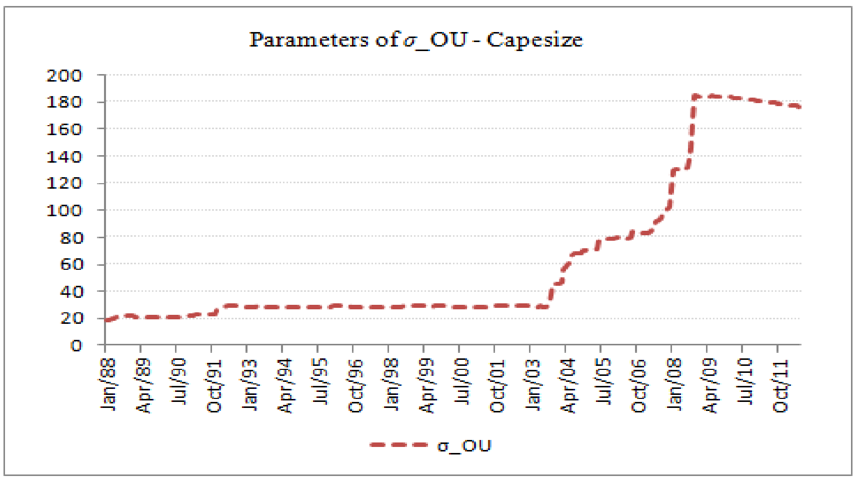


(a) u_OU for Capesize carries

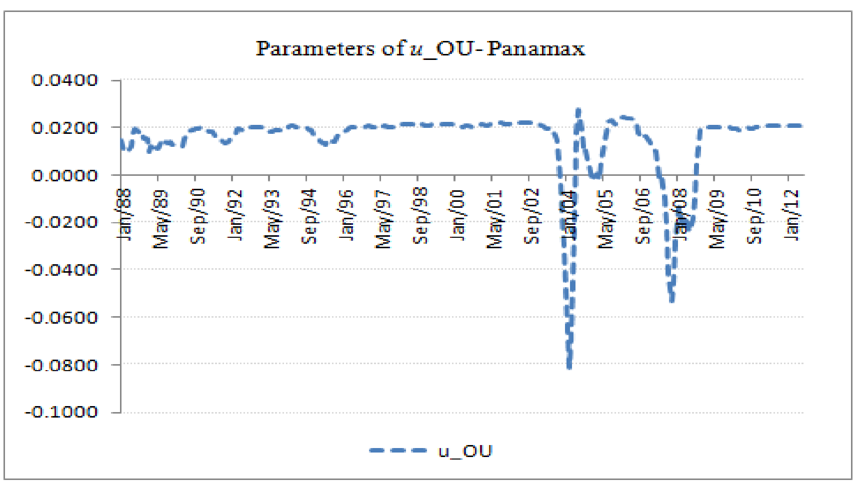
Figure 4-2: Parameters of u_OU, m_OU and σ_OU Evolving with Time (Continued)



(b) m_OU for Capesize carries

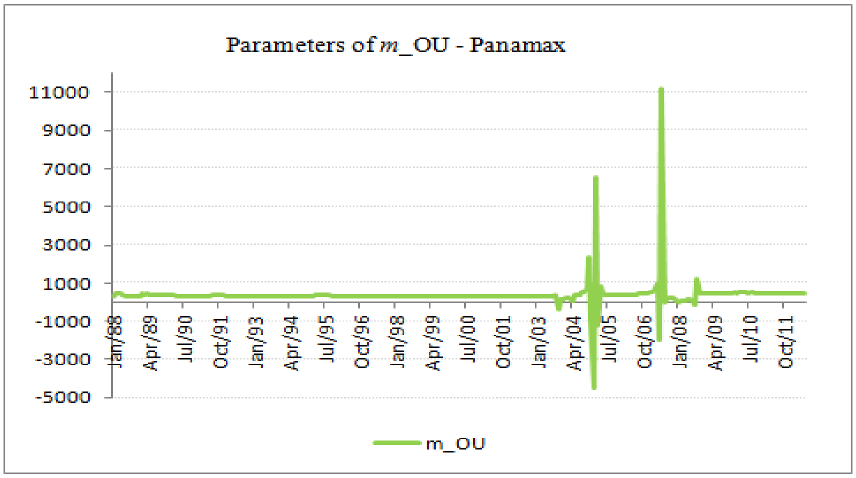


(c) σ_OU for Capesize carries

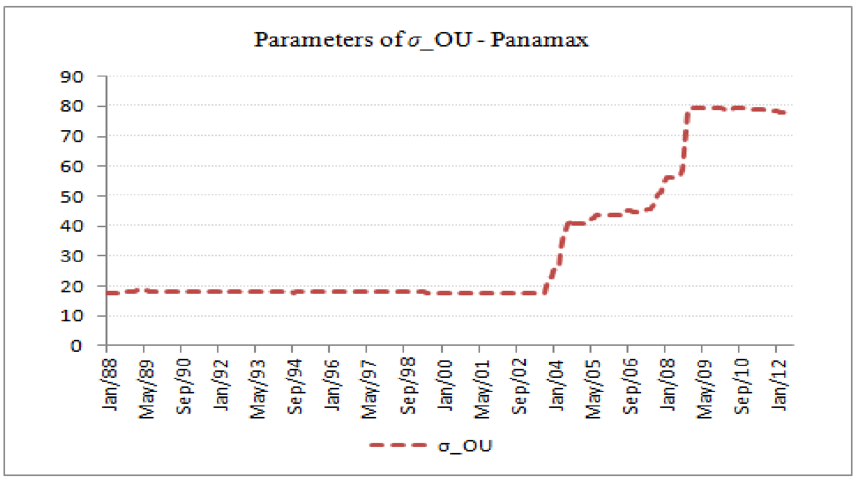


(d) u_OU for Panamax carries

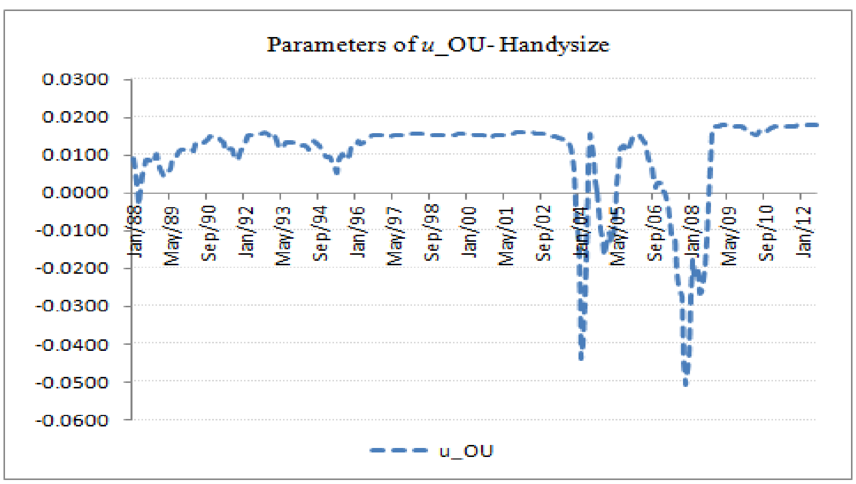
Figure 4-2: Parameters of u_OU, m_OU and σ_OU Evolving with Time (Continued)



(e) m_OU for Panamax carries

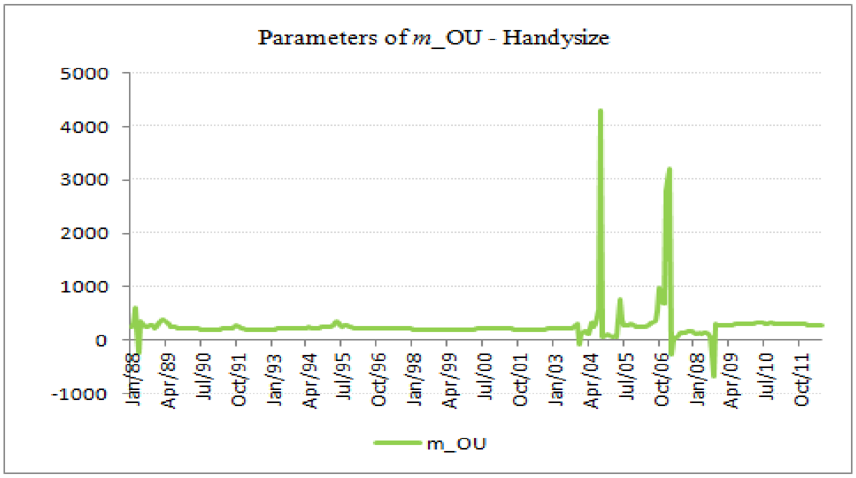


(f) σ_OU for Panamax carries

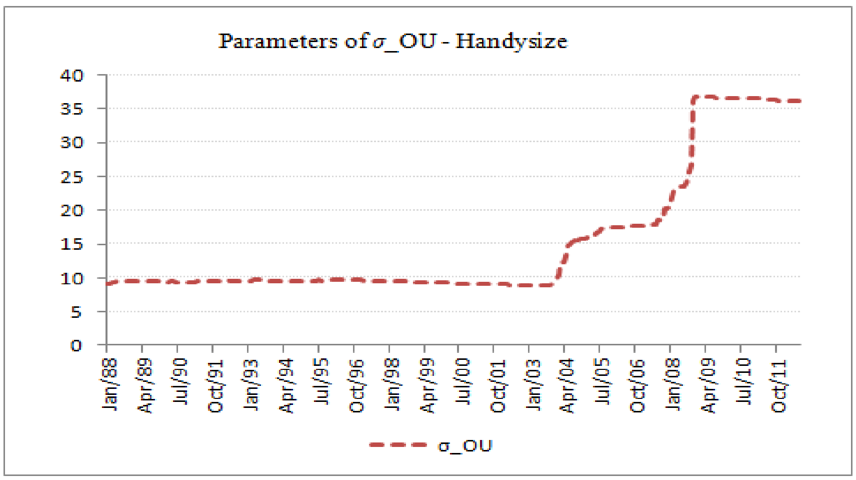


(g) u_OU for Handysize carries

Figure 4-2: Parameters of *u*_OU, *m*_OU and *σ*_OU Evolving with Time (Continued)



(h) *m*_OU for Handysize carries



(i) *σ*_OU for Handysize carries

Notes: (a), (b) and (c) represent the parameters for Capesize carriers, (d), (e) and (f) present the parameters for Panamax carriers and (g), (h) and (i) are the parameters for Handysize carriers.

To capture the most common phenomena in the shipping market, we set the base parameters of u, m and σ equal to the median value of their respective series for the whole sample analysis, and then carry out the sensitivity analysis to allow for a range of change. In the following analysis, we assume that the construction lag and lifespan of the new ship are 2 years and 25 years respectively, which are equivalent to θ=24 and N=300 months based on the monthly data. To calculate the trigger prices, the new-building prices of different ship types are also required. Aug. 2004 is chosen randomly as the base ship prices to give an example (i.e. P_{cap}=59000, P_{pan}=33000 and P_{han}=20500). After that dynamic ship price series is used to generate dynamic trigger rates over the whole sample.

For the discount rate r, different with the common method that setting it to a number varying between 0.1 and 0.15 per year (Schwartz, 1997), it will be estimated based on the theoretical ship price-freight rate relationship. According to Kavussanos and Alizadeh (2002a), theoretical ship price at time t should be equal to the present value of expected future earnings plus the present value of the expected resale price. Since no re-selling is occurred in the lifespan, the theoretical relationship between R and P can be derived from Equation (4-9) when NPV=0 and P_0 is re-written as P_t:

$$P_t=K_\rho R_t+C+\varepsilon_t \tag{4-13}$$

where $C=m(K_r-K_\rho)$. Running Equation (4-13), the estimators of K_ρ and C can be obtained, denoted them as $\widehat{K_\rho}$ and $\hat{C}$. Using $\widehat{K_\rho}$ and $\hat{C}$, the estimator of K_r can be generated, and then r is obtained.

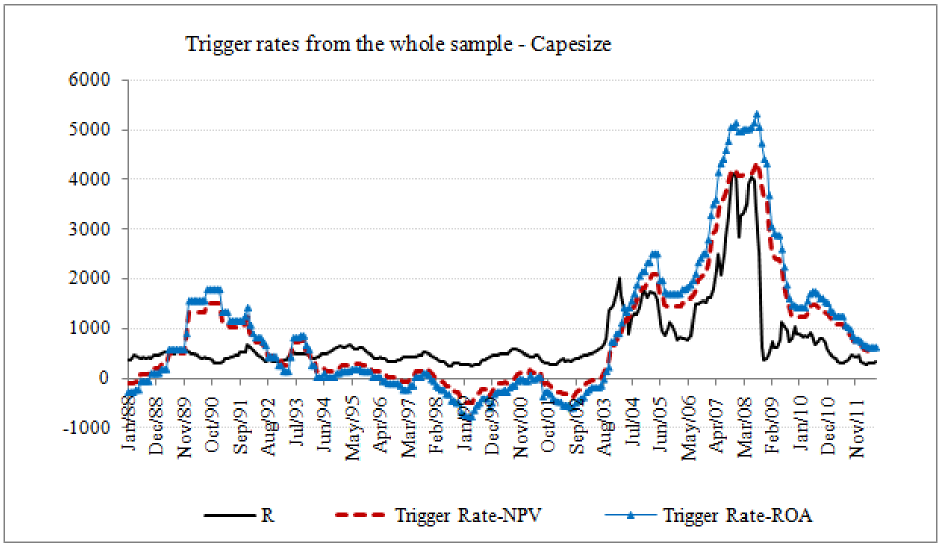
All the base parameters and the calculated trigger rates are shown in Table 4-3. The information in Table 4-3 can be used in the ship investment decision. For example, the trigger rate for NPV is 683.18, while that of the ROA is 786.7 for Panamax carriers. The real time-charter rate for such vessels in August 2004 is 941.25, which is higher than the trigger rates from both methods. Thus, investing immediately is a better choice.

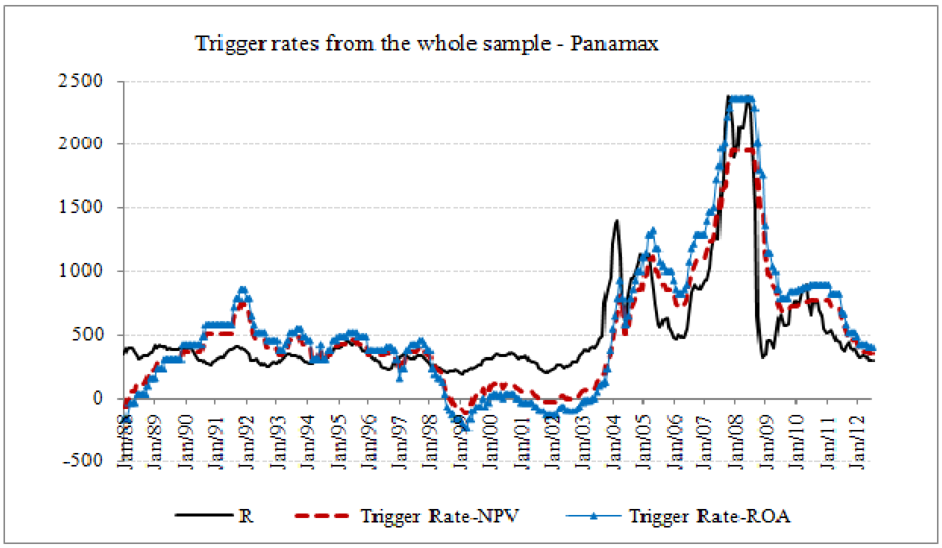
Table 4-3: Basic Parameters and Calculated Trigger Rates in the Whole Sample

	Base Parameters						Trigger Rates	
	u (%)	m	σ	r	P	R_0	R^*_{NPV}	R^*_{ROA}
Capesize	2.56	442.32	29.03	0.0073	59000	1312.5	1447.39	1706.2
Panamax	2	310.36	18.14	0.0088	33000	941.25	683.18	786.7
Handysize	1.46	220.22	9.61	0.0089	20500	481.89	298.96	336.81

The dynamic trigger rates $R^*_{\mathrm{OU-NPV}}$ and $R^*_{\mathrm{OU-ROA}}$ are then generated using dynamic ship prices from period 1988 to 2012. Relationship between the real time-charter rate R_0 and the trigger rates $R^*_{\mathrm{OU-NPV}}$ and $R^*_{\mathrm{OU-ROA}}$ for three ship types are plotted in Figure 4-3. Although relationship between trigger rates from NPV and ROA cannot be seen theoretically due to no closed-form solution is found for ROA, empirical results show some implications. It can be seen that when $R_0<\min\{R^*_{\mathrm{OU-NPV}}, R^*_{\mathrm{OU-ROA}}\}$, there exists relationship $R^*_{\mathrm{OU-ROA}}>R^*_{\mathrm{OU-NPV}}$, while when $R_0\geq\max\{R^*_{\mathrm{OU-NPV}}, R^*_{\mathrm{OU-ROA}}\}$, there exists $R^*_{\mathrm{OU-ROA}}\leq R^*_{\mathrm{OU-NPV}}$. It indicates that when immediate investment is recommended by the NPV rule, it may not pass the ROA criterion; while postponing investment is recommended by the NPV rule, it must be true that postponing investment is also recommended by the ROA rule. This result shows that the immediate investment criterion from ROA is stricter because it takes into account the future uncertainties.

Figure 4-3: Dynamic Trigger Rates from the Whole Sample





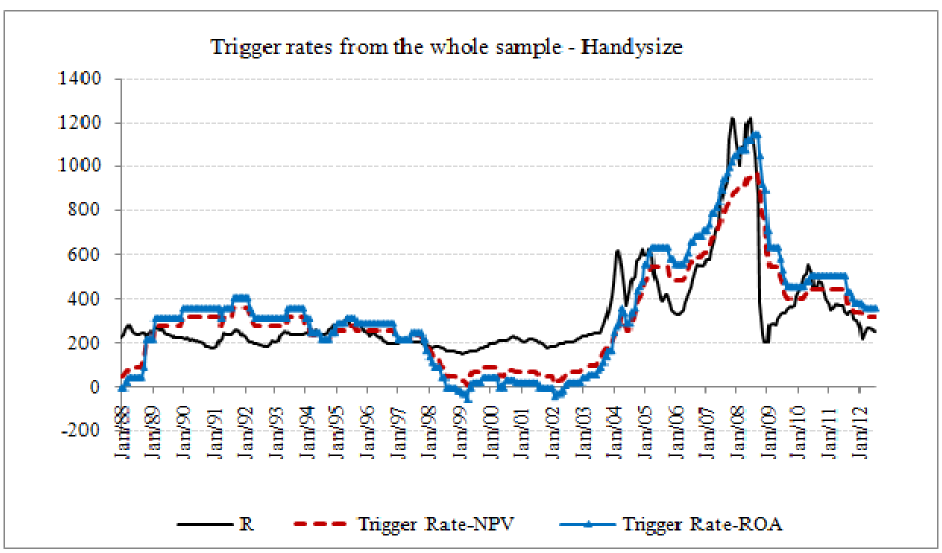
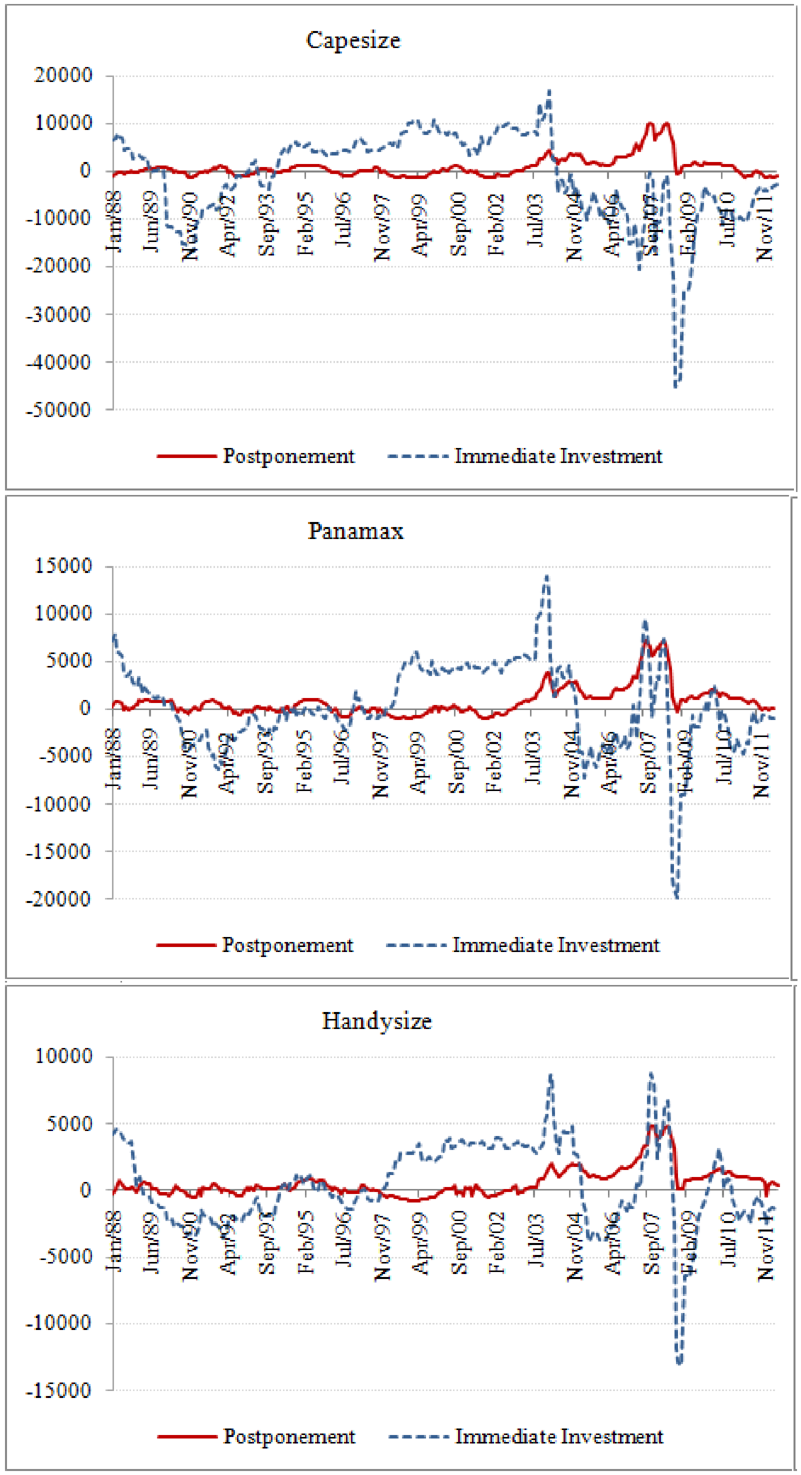


Figure 4-4 presents the expected revenues from immediate investment and postponement using the ROA. The solid and dashed lines plot the upper and bottom equations in Equation (4-12), meaning revenues from postponement and immediate investment, respectively. The shape of optimal decision $F_0(R)$ in Equation (4-12) is the upper bound of two lines in Figure 4-4. Comparing with the results of trigger rates in Figure 4-3, it can be seen that, when the real time-charter rate is higher than the trigger rate from ROA, revenues from immediate investment is higher than revenues from postponement, while when the real time-charter rate is lower than the trigger rate from NPV, the solid line is higher than the dashed line, indicating revenues from postponement is larger. Since the calculation is based on the whole sample, the figure may not reflect the exact ship investment behaviour in the past. A better explanation will be provided in Section 4.3.3, which distinguishes the investment behaviour in a specific time period as shown in Table 4-5.

Figure 4-4: Expected Revenues from Immediate Investment and Postponement for the Whole Sample



Notes: The red solid line stands for the revenues from postponement, while the blue dashed line stands for the revenues from immediate investment.

4.3.2 Sensitivity analysis on basic results

Then the sensitivity of the results in Section 4.3.1 is analyzed due to the changes in the basic parameters. The sensitivity analysis can help investors anticipate the possible changes in trigger rates and make decisions in an uncertain environment. Based on Table 4-2, the range of the parameters are set up as follows: $u \in [0.006, 0.032]$, $m \in [200, 500]$, $\sigma \in [5, 100]$ and $r \in [0.005, 0.012]$. In this section, Panamax carriers are using as an example, base ship prices are assumed the same as shown in Table 4-3 (i.e. P_{pan}=33000) and the real charter rate is allowed to change from 100 to 2000, which is based on a rough range showed in Figure 4-1(a). The sensitivity analysis results are listed in Table 4-4. Here, we only consider the parameters' impact on the trigger rates based on $R^*_{\text{ou-ROA}}$, and the underlined numbers indicate the return on immediate investment.

Table 4-4: Sensitivity Analysis of the Parameters in Table 4-3

Basic parameters: u=0.02, m=310.36, σ=18.14, r=0.0083, θ=24 and N=300											
Sensitivity of u				Sensitivity of m				Sensitivity of σ			
	$R^*_{\text{OU-ROA}}$	R_0	$F_0(R)$		$R^*_{\text{OU-ROA}}$	R_0	$F_0(R)$		$R^*_{\text{OU-ROA}}$	R_0	$F_0(R)$
u=0.01	527.55	300	1235.8	m=260	927	300	363.7	σ=5	653.2	300	-89.7
		600	$\underline{5258.3}$			600	1454.3			600	1052.4
		900	$\underline{15781}$			900	2395.5			900	$\underline{5660.8}$
u=0.02	667.81	300	149.5	m=320	620.52	300	-23.9	σ=45	741.57	300	646.5
		600	1329.2			600	$\underline{1307.6}$			600	2588.1
		900	$\underline{5660.8}$			900	$\underline{6360.7}$			900	$\underline{5660.8}$
u=0.03	904.34	300	5.2	m=380	240.52	300	$\underline{29.2}$	σ=85	856.77	300	1385.1
		600	721			600	$\underline{5344.5}$			600	3122.3
		900	1275.7			900	$\underline{10718}$			900	$\underline{5660.8}$
Sensitivity of r				Sensitivity of θ				Sensitivity of N			
	$R^*_{\text{OU-ROA}}$	R_0	$F_0(R)$		$R^*_{\text{OU-ROA}}$	R_0	$F_0(R)$		$R^*_{\text{OU-ROA}}$	R_0	$F_0(R)$
r=0.007	310.36	300	114.0	θ=12	449.26	300	210.0	N=18	841.28	300	149.2
		600	$\underline{5500.7}$			600	$\underline{5327.8}$			600	1326.5
		900	$\underline{11311}$			900	$\underline{12875}$			900	$\underline{3078.6}$
r=0.009	834.37	300	165.5	θ=20	579.06	300	167.5	N=26	651.94	300	149.5
		600	1268.3			600	$\underline{1857.4}$			600	1329.2
		900	$\underline{3053.7}$			900	$\underline{7875.2}$			900	$\underline{5902.2}$
r=0.011	1302.9	300	201.1	θ=28	775.94	300	133.5	N=34	570.69	300	149.6
		600	1113.3			600	1186.9			600	$\underline{1791.8}$
		900	1893.0			900	$\underline{3612.8}$			900	$\underline{7166.6}$

Notes: Underlined numbers indicate the return on immediate investment.

For the reverting speed u, from Table 4-4, it can be seen that the trigger rates for investing are 527.55 when u=0.01. With the increasing of u, the trigger rates go up and the underlined $F_0(R)$ becomes less, indicating immediate investment is not recommended. The trigger rates with the changing speed are plotted in Figure 4-5(a), which shows that u has a positive effect on $R^*_{\text{ou-ROA}}$. For a 1% increase in the reverting speed, the trigger rate increases by around 25-35%.

For the long-term equilibrium level m, Figure 4-5(b) shows that $R^*_{\text{ou-ROA}}$ decreases with m increasing, indicating that normal investment is recommended when the mean level is high. Table 4-4 shows that the underlined numbers increase with m, indicating that immediate investment is favourable, because a higher m normally implies a high freight rate while the freight rate does not deviate much from *m* for the OU process. Then the NPV is more likely to be large.

For the volatility σ, Figure 4-5(c) shows that an increase in uncertainty increases $R^*_{\mathrm{ou-ROA}}$. The result implies that when the market exhibits a higher risk, investment should be postponed unless the true real charter rate is very high. However, it seems that $R^*_{\mathrm{ou-ROA}}$ is not sensitive to the change of σ. By increasing the value of σ by 5, the trigger rate only increases by around 1-2%.

Figure 4-5(d) shows the changes of $R^*_{\mathrm{ou-ROA}}$ with the change of the discount rate *r*. It can be seen that $R^*_{\mathrm{ou-ROA}}$ goes up fast when *r* is smaller than 0.007 and that the growth of $R^*_{\mathrm{ou-ROA}}$ tends to slow down afterwards. $R^*_{\mathrm{ou-ROA}}$ seems sensitive to the discount rate *r*. It increases almost 2.7 times when *r* increases from 0.007 to 0.009. As a high discount rate can reduce the return on investment, the underlined $F_0(R)$ becomes less (Table 4-4), indicating more investment will be postponed. For a 0.1% increase in *r*, the trigger rate increases by around 15-30% after *r* is 0.009.

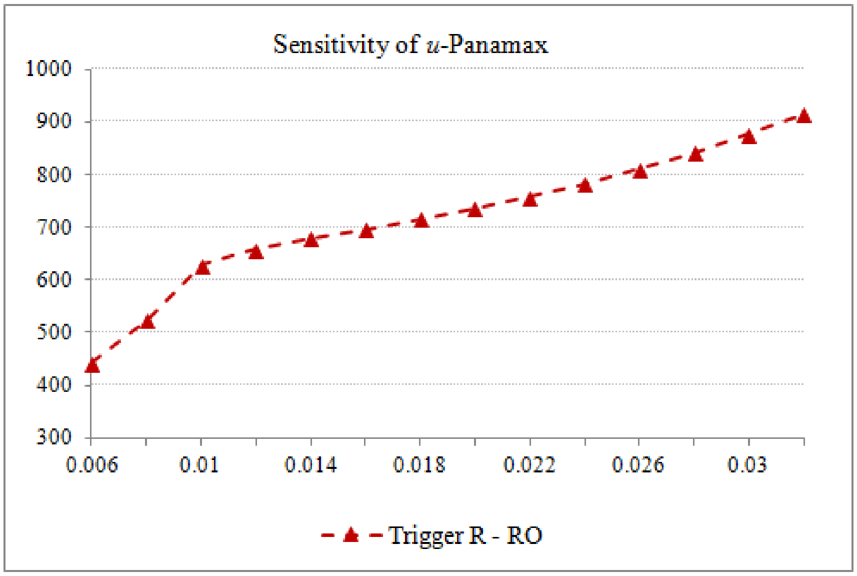
For the construction lag θ, it has a positive effect on $R^*_{\mathrm{ou-ROA}}$. This result shows that, when the new-building lag is shorter, for example θ=12, $R^*_{\mathrm{ou-ROA}}$ becomes smaller (449.26), fewer $F_0(R)$ values get underlined, and more immediate investments are preferred. Figure 4-5(e) shows that if θ increases by 1 month, $R^*_{\mathrm{ou-ROA}}$ increases by around 3-4%.

The lifespan *N* has a negative effect on $R^*_{\mathrm{ou-ROA}}$. The longer the ship can sail, the lower the trigger rate is, and the more likely immediate investment is recommended. This result is reasonable because a ship has a longer period to earn more profit with a longer lifespan. Then it is more likely that the revenue can exceed the cost. Figure 4-5(f) gives the sensitivity of trigger rates with the change of the lifespan of a ship. If

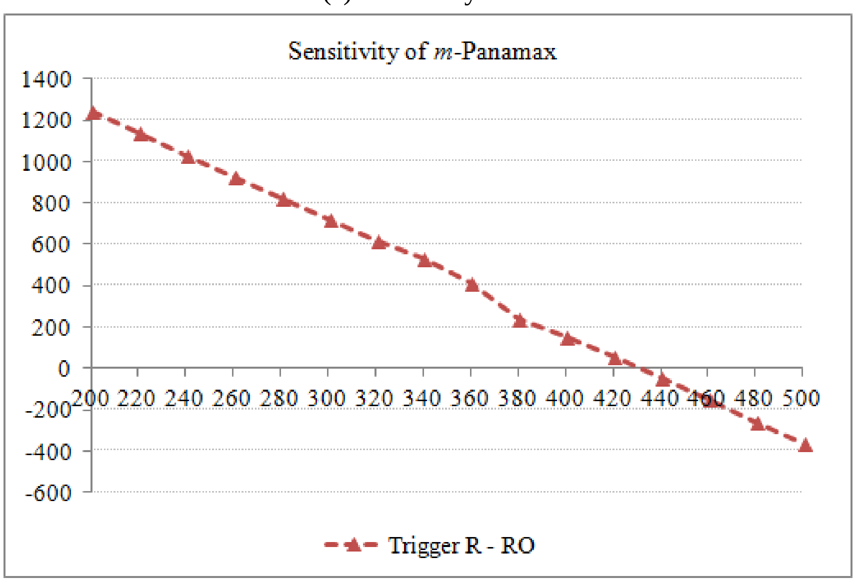
N increases by one year, $R^*_{\mathrm{ou-ROA}}$ can decrease by 11-12%.

In summary, the parameters like reverting speed, market volatility, discounted rate and construction lag can increase the trigger rate, while the long-term mean and the ship's lifespan have a negative impact on the trigger rate. In addition, the trigger rate is very sensitive to the change of the long-term mean and discount rate.

Figure 4-5: Sensitivity of Parameters from the Whole Sample

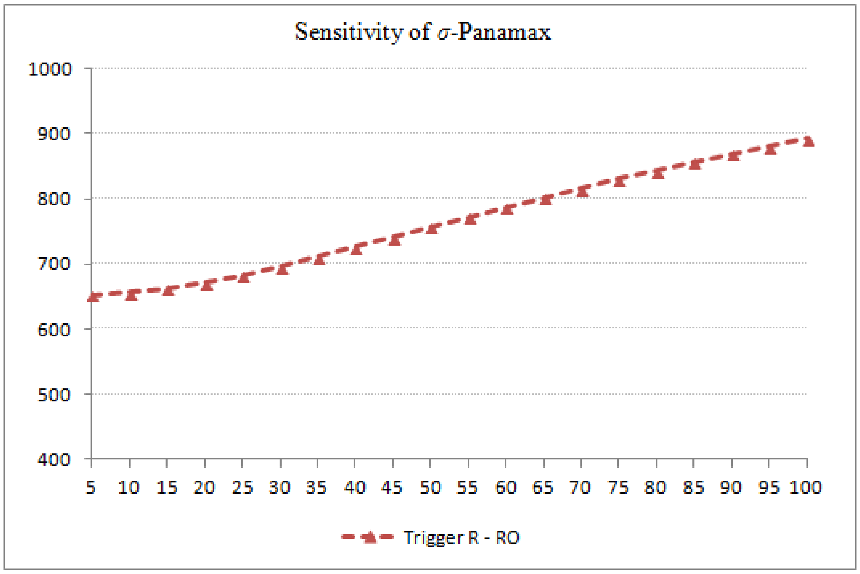


(a) Sensitivity of u

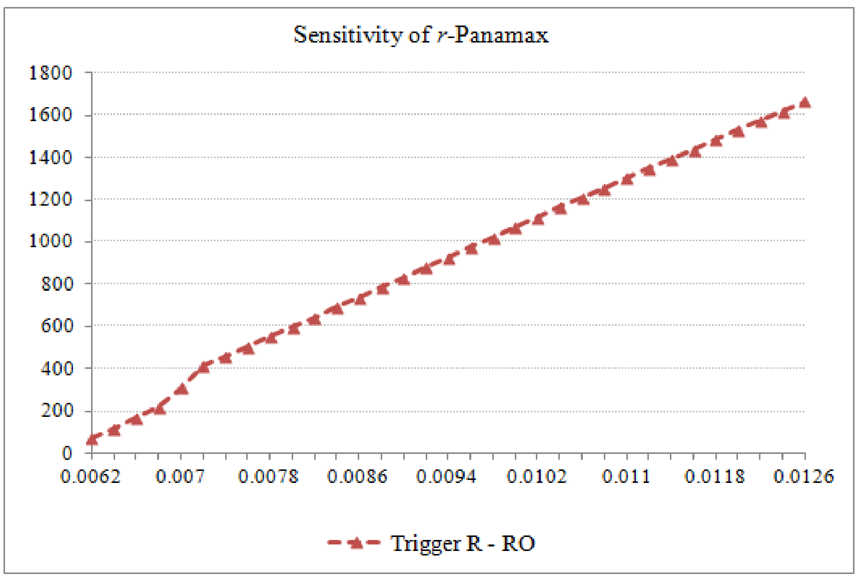


(b) Sensitivity of m

Figure 4-5: Sensitivity of Parameters from the Whole Sample (Continued)

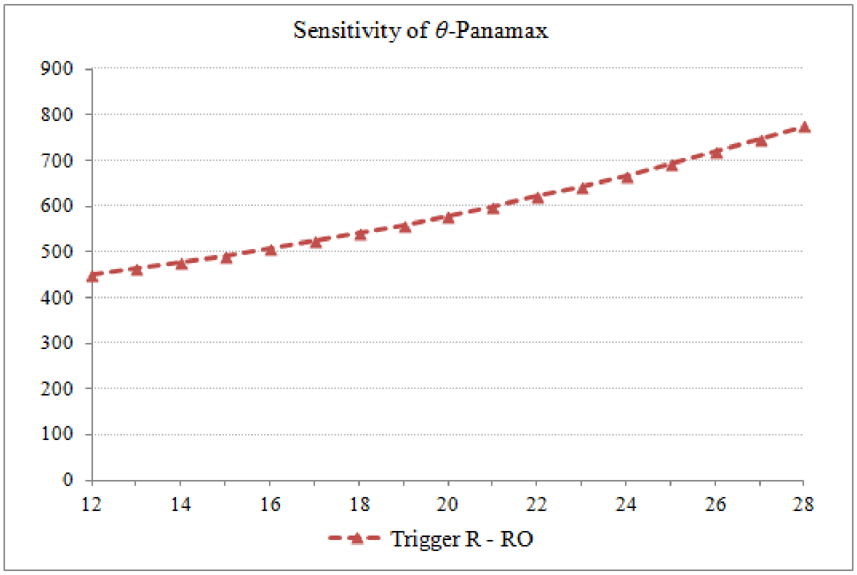


(c) Sensitivity of σ

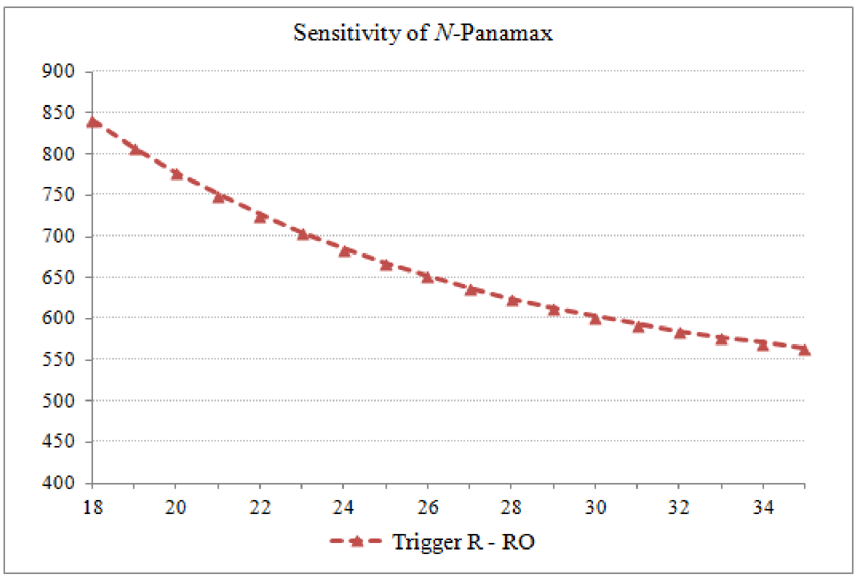


(d) Sensitivity of r

Figure 4-5: Sensitivity of Parameters from the Whole Sample (Continued)



(e) Sensitivity of θ



(f) Sensitivity of N

Notes: The horizontal axis is the underlying parameters and the vertical axis represents the trigger rates from ROA.

4.3.3 Trigger rates considering shipping cycles

Empirical results from the ADF test for the whole sample shows that R follows the OU process during the period 1976-2012. This result is contradicted with most of the empirical evidence in the past (Veenstra & Franses, 1997; Kavussanos & Alizadeh, 2002b; Alizadeh & Nomikos, 2007). It may mainly caused by the different data samples chosen in the respective works. The freight rate process exhibits its famous cyclical nature. As shipping cycles may have a significant impact on the results of the freight rate, ignoring this nature may result in a wrong estimation. Therefore, in this subsection, we estimate the trigger rates with taking into account of the shipping cycles.

To distinguish these cycles, the breakpoints suggested by Chapter 3 are applied directly. Chapter 3 identified six breakpoints for Panamax and Handysize ships, while four breakpoints were identified for Capesize vessels. However, in this Chapter, since the pre-1988 data is treated as the base sample (subsection 4.3.1), only shipping cycles after Jan-1988 are taken into account in this subsection. Table 4-5 summarizes the duration of each sub-period for all the ship types.

Table 4-5: Duration of Sub-period for the Three Ship Types

Sub-periods	I	II	III	IV
Capesize	1988.01~2003.08	2003.09~2007.03	2007.04~2008.09	2008.10~2012.07
Panamax	1988.01~2002.03	2002.04~2006.12	2007.01~2008.08	2008.09~2012.07
Handysize	1988.01~2001.07	2001.08~2006.12	2007.01~2008.09	2008.10~2012.07

After knowing the durations of sub-periods, a new set of parameters are required for each sub-period. The estimated results of the freight process for each sub-period are summarized in Table 4-6. Sub-periods I and IV can be generally described as the OU process, and sub-period III is a GBM process for all the three ship types. The results in sub-period II are different in ship types. R for Capesize carriers is a GBM process; but for Panamax and Handysize carriers, neither the GBM nor OU process is acceptable. In the end, we distinguish two kinds of sub-periods, one is called “OU” sub-periods, which assumes all sub-periods follow the OU process. However, it may not appropriate to use Equations (B. 3) and (B. 4) to estimate the sub-period parameters for R, especially for sub-period II and III. New method is needed to generate the "OU" sub-period's parameters. The other type of sub-periods is called "Mixed" sub-periods, which assumes sub-period I and IV follow the OU process while sub-period II and III follow the GBM process.

Table 4-6: Empirical Test Results of the Freight Rate Process in Sub-periods

			OU process		GBM process	
			ADF t-Statistic	(p-value ADF)	β_2	(p-value of β_2)
Capesize	I	1988.01-2003.08	-2.6764	(0.0800)	0.3794	(0.0000**)
	II	2003.09-2007.03	-2.5445	(0.1124)	0.2573	(0.0947)
	III	2007.04-2008.09	-1.9132	(0.3184)	0.1210	(0.6879)
	IV	2008.10-2012.07	-7.4413	(0.0000**)	0.3527	(0.0154*)
Panamax	I	1988.01-2002.03	-3.5570	(0.0076**)	0.3361	(0.0000**)
	II	2002.04-2006.12	-1.7822	(0.3855)	0.4879	(0.0001**)
	III	2007.01-2008.08	-2.2719	(0.1905)	0.5198	(0.0431*)
	IV	2008.09-2012.07	-6.5879	(0.0000**)	0.5308	(0.0001**)
Handysize	I	1988.01-2001.07	-2.6974	(0.0766*)	0.3240	(0.0000**)
	II	2001.08-2006.12	-1.9169	(0.3227)	0.5795	(0.0000**)
	III	2007.01-2008.09	-2.0160	(0.2780)	0.5547	(0.0454*)
	IV	2008.10-2012.07	-5.9904	(0.0000**)	0.5244	(0.0001**)

Notes: * denotes the rejection of the null hypothesis at the 5% significance level, while ** denotes the rejection of the null hypothesis at the 1% significance level.

To generate a more accurate sub-period mean level, method in Chapter 3 Section 3.2 is applied, which allows R_t to fluctuate around changing means based on Equation (3-15). Since m_t is a liner series in each sub-period in this part, the period mean level, named as m^p (p=I, II, III, IV), is set equal to the average level of m_t. In addition, the period volatility σ^p is equal to the standard deviation of Equation (3-15). The period discount rate r^p is estimated using Equation (4-13). Based on the estimator of $\widehat{K_\rho}$ from (4-13), parameter ρ^p is obtained. Then the period reverting speed, u^p is generated.

For the GBM process, Equations (A. 5) and (A. 6) in Appendix A are used to generate a series of α and v with the same base sample as the OU process, and then assume the period parameters equal to the median value of each sub-period. For the

GBM, it is only considered in periods II and III. The estimated parameters of all the sub-periods and ship types are shown in Table 4-7. It can be seen that, for the "OU" sub-periods, the parameters in period I are close to our base setting in Table 4-3, while the parameters in periods II, III and IV are all higher than the base parameters except Capesize carriers in period IV.

Table 4-7: Parameters for "OU" and "Mixed" Sub-periods

Capesize: base parameters are m=442.32, r=0.0073, u=0.0256 and σ=29.03							
Sub-periods		m^p	r^p	u^p	σ^p	α^p	v^p
I	1988.01-2003.08	438.37	0.0077	0.0211	31.5700	-	-
II	2003.09-2007.03	1316.75	0.0151	0.0339	198.3069	0.0121	0.0932
III	2007.04-2008.09	3236.61	0.0210	0.0326	475.4158	0.0150	0.0987
IV	2008.10-2012.07	598.0741	0.0076	0.0273	111.3431	-	-
Panamax: base parameters are m=310.36, r=0.0088, u=0.02 and σ=18.14							
Sub-periods		m^p	r^p	u^p	σ^p	α^p	v^p
I	1988.01-2002.03	316.15	0.0092	0.0134	18.3301	-	-
II	2002.04-2006.12	673.25	0.0151	0.0173	106.2067	0.0100	0.0852
III	2007.01~2008.08	1796.31	0.0214	0.0175	166.7076	0.0127	0.0878
IV	2008.09-2012.07	550.19	0.0119	0.0234	113.3116	-	-
Handysize: base parameters are m=220.22, r=0.0089, u=0.0146 and σ=9.61							
Sub-periods		m^p	r^p	u^p	σ^p	α^p	v^p
I	1988.01~2001.07	221.1213	0.0093	0.0116	8.9449	-	-
II	2001.08~2006.12	367.6805	0.0131	0.0092	37.6716	0.0051	0.0531
III	2007.01~2008.09	945.5200	0.0183	0.0191	86.0221	0.0077	0.0582
IV	2008.10~2012.07	354.68	0.0110	0.0317	35.6281	-	-

The trigger rates from the sub-periods are then generated based on the parameters in Table 4-7. Results from “OU” sub-periods are plotted in Figure 4-6 and results from “Mixed” sub-periods are plotted in Figure 4-7. The main difference shows that the trigger rates during periods II and III exhibit extremely dramatic changes while the trigger rates from the "Mixed" sub-periods are smoother. Figure 4-8 and Figure 4-9 plot the expected total returns from immediate investment and postponement. It shows clearly that the returns from “Mixed” sub-periods are much higher than returns from the “OU” sub-periods. It indicates that GBM assumption may be too optimistic about the market. In order to see the results from the whole sample, the "OU" sub-periods and the "Mixed" sub-periods more clearly, in the next subsection, the immediate investment results suggested by these three kinds of samples are compared.

Figure 4-6: Trigger Rates from "OU" Sub-periods

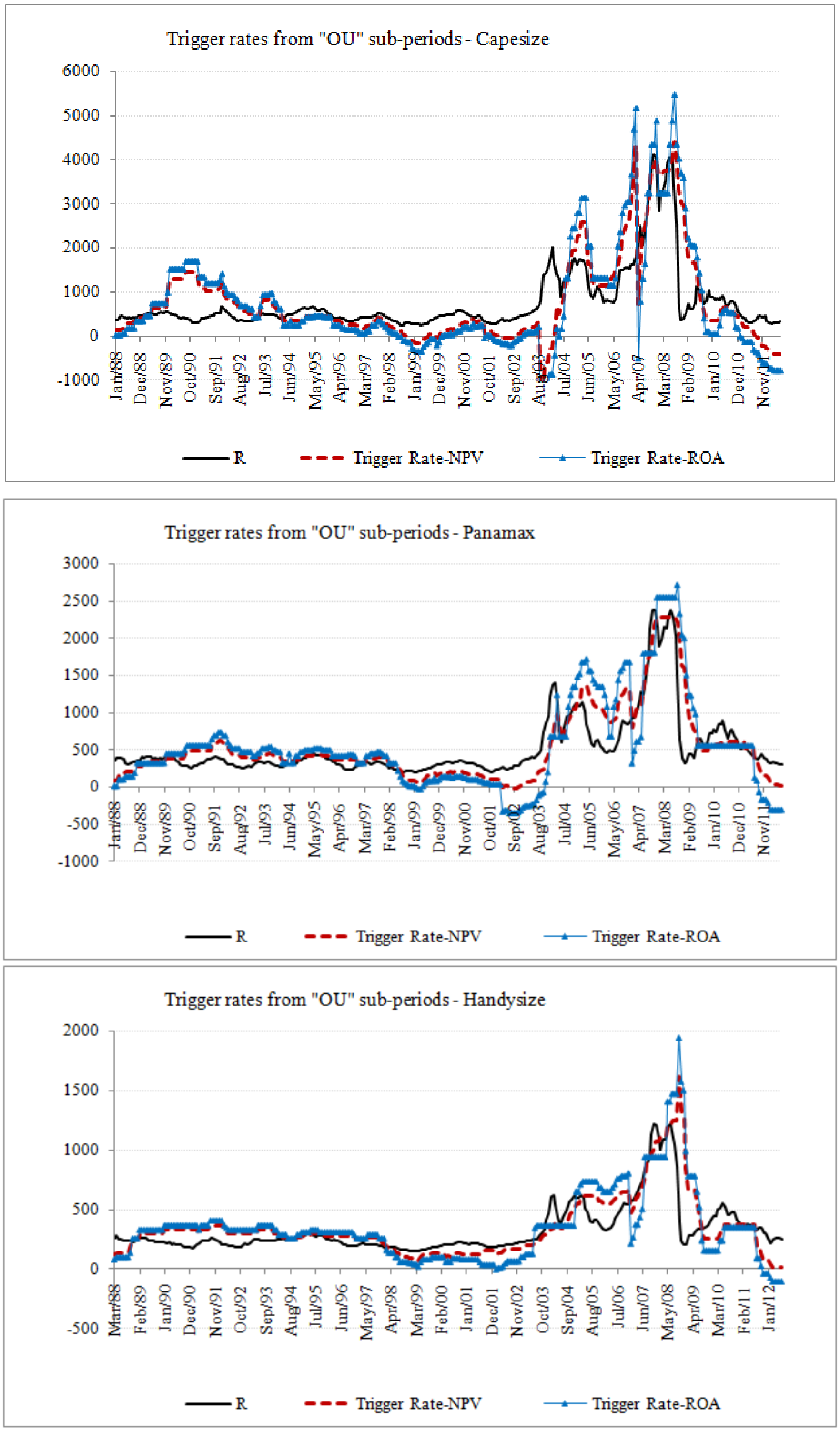
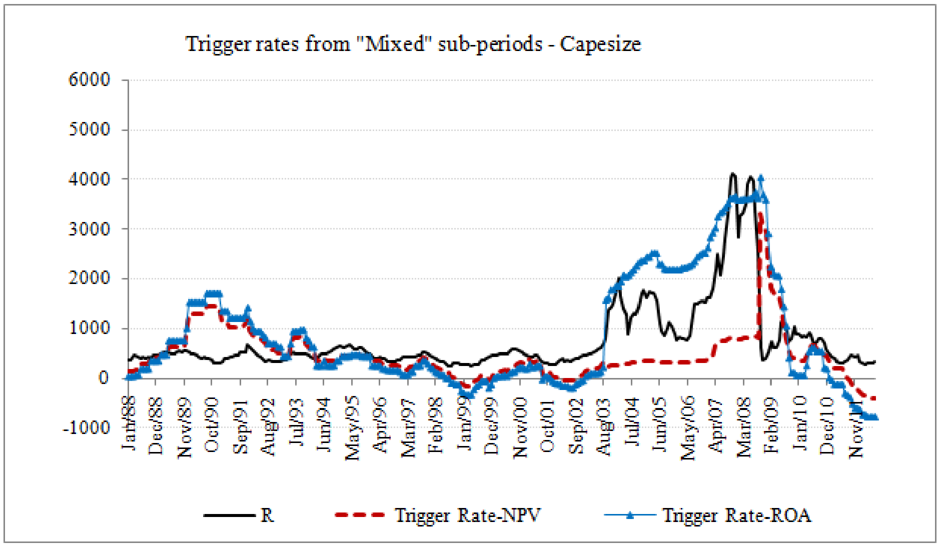
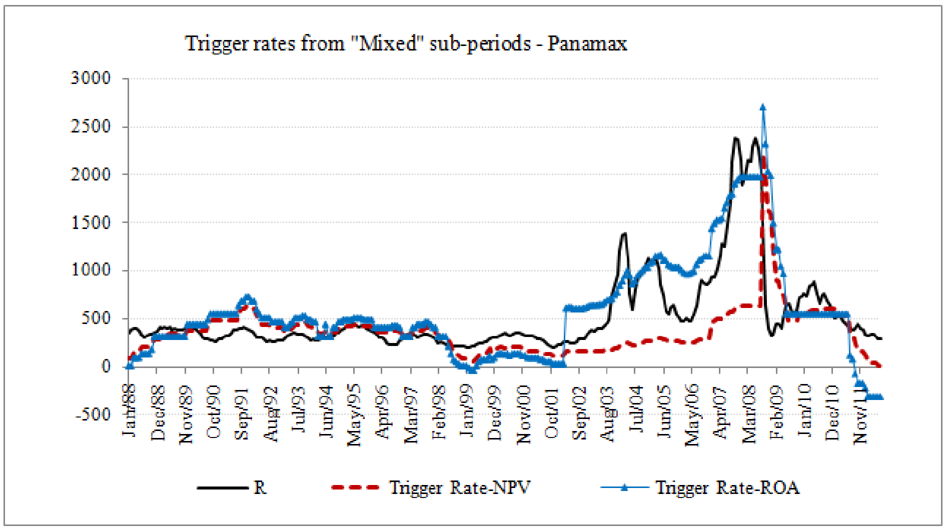


Figure 4-7: Trigger Rates from "Mixed" Sub-periods





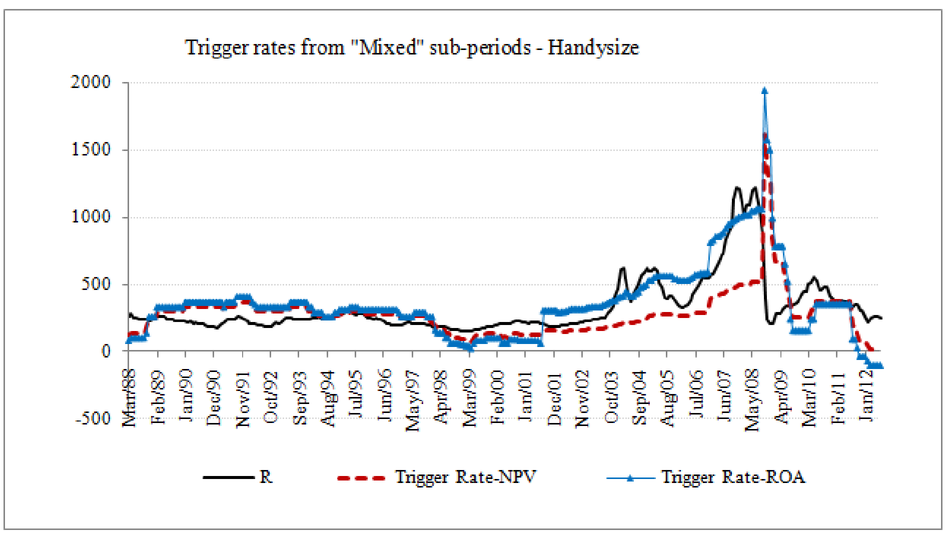


Figure 4-8: Expected Revenues from Immediate Investment and Postponement for the “OU” Sub-periods

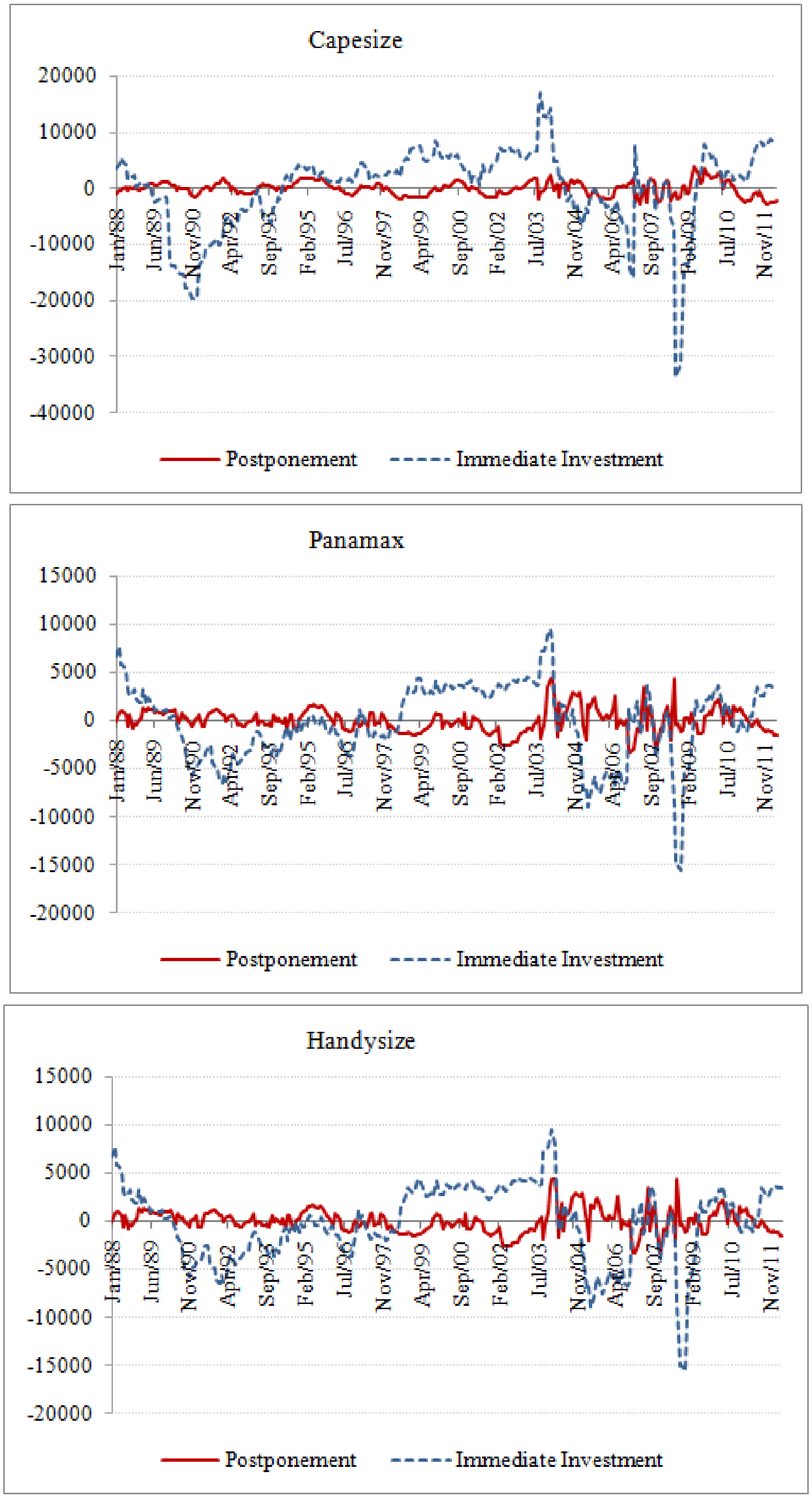
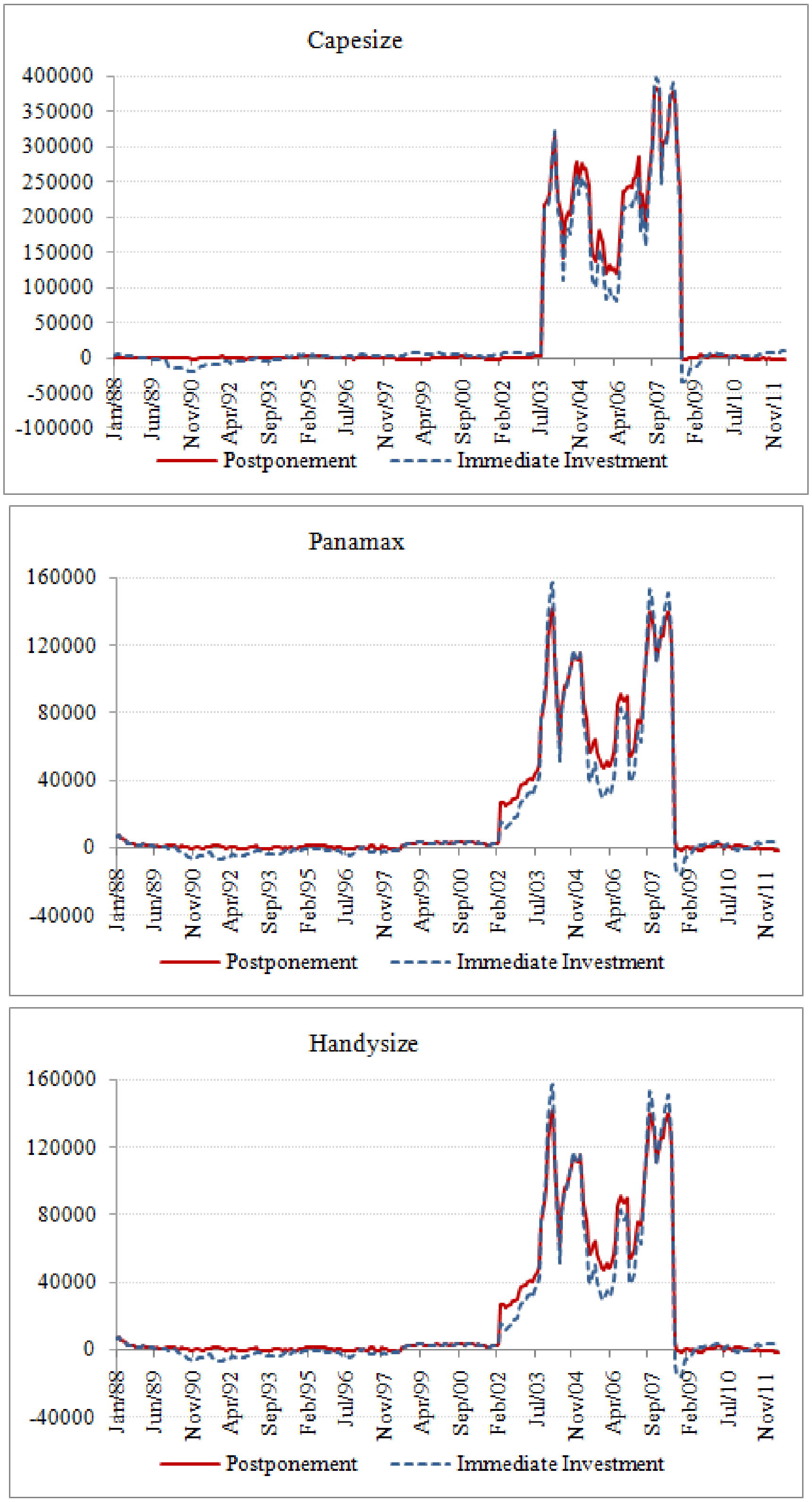


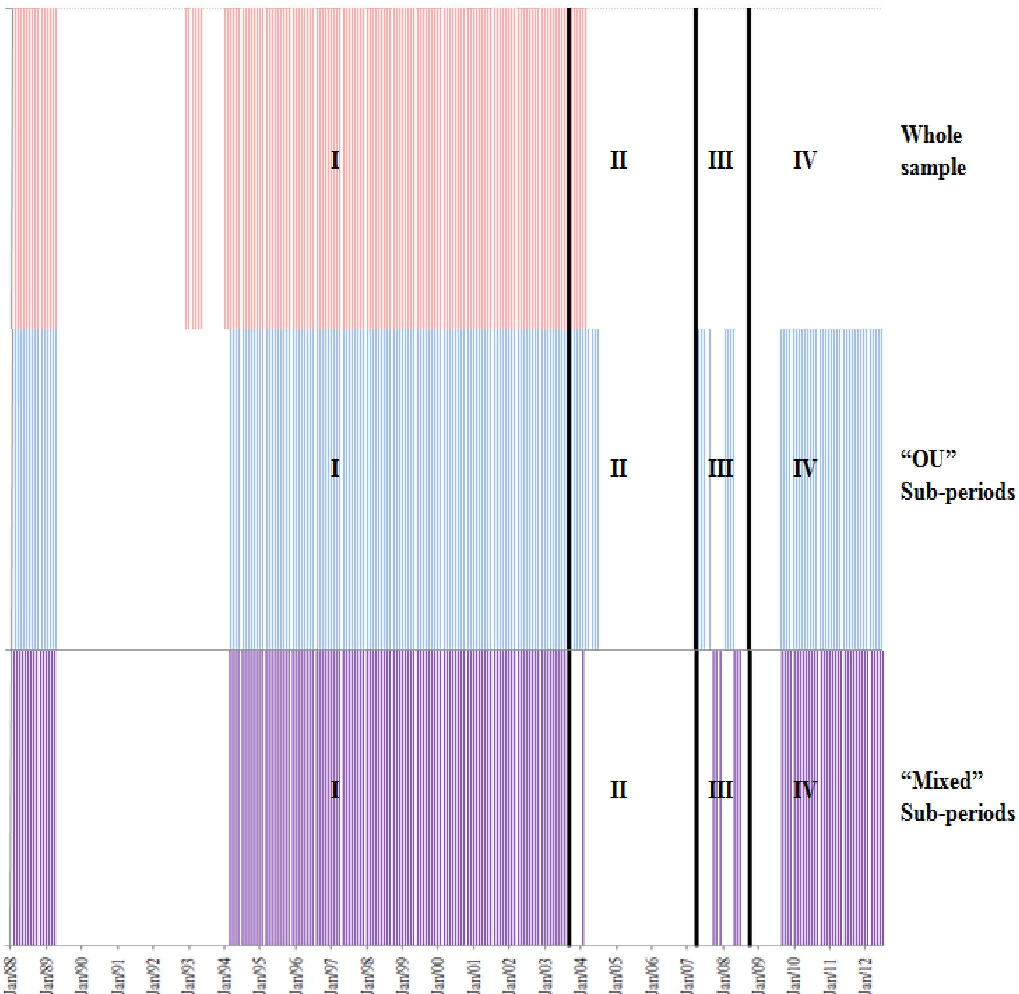
Figure 4-9: Expected Revenues from Immediate Investment and Postponement for the "Mixed" Sub-periods



4.3.4 Comparing results from the whole sample and two kinds of sub-periods

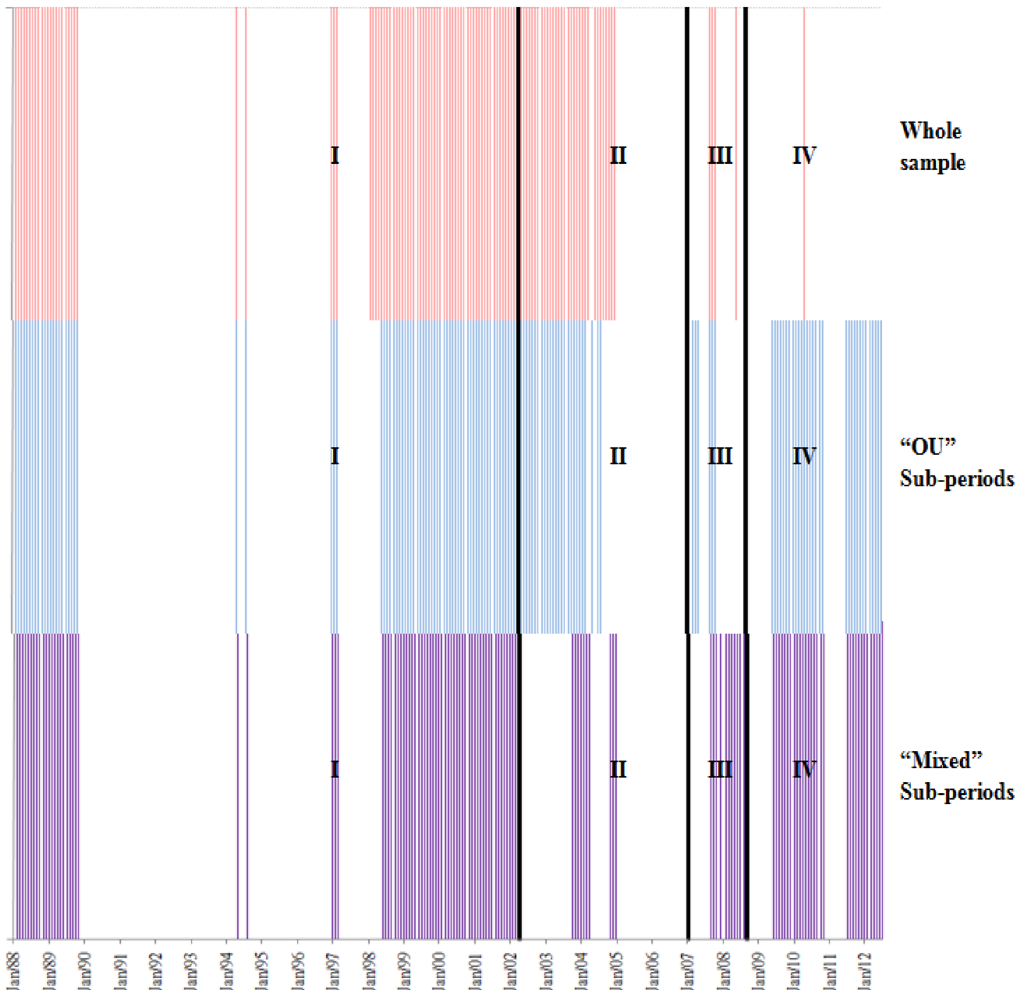
In this section, immediate investment results suggested by the whole sample and two kinds of sub-periods are compared. Figure 4-10 shows the results. The vertical lines indicate that immediate investment is recommended while period without them indicates immediate investment is not recommended. Clearly, the main difference between whole sample and "OU" sub-periods concentrates on sub-period IV. The results from the "OU" sub-periods encourage investment in recent times, while the results from the whole sample do not recommend investment. It is known from Table 4-7 that four parameters in sub-periods have been changed comparing with the base setting in the whole sample, i.e. m, u, σ, r. In addition, these parameters are all higher than the base settings except r for Capesize carriers in period IV. It is concluded in Section 4.3.2 that, except m, all the other parameters (i.e. u, σ, r) have positive effects on the trigger rate, and, among them, m and r are more sensitive than the others. Therefore, the trigger rates decrease with m and r significantly for Capesize carriers from the "OU" sub-periods. For Panamax and Handysize carriers, the increase in u, σ, r should push up the trigger rates. However, the trigger rates in fact decreases for both of these ship types, indicating that the mean level m has the most significant impact on the trigger rates. Differences between the “OU” sub-periods and “Mixed” sub-periods concentrate on sub-periods II and III since their assumptions are different. To examine which result is more fitted into the real investment behaviour in the market, a simple test is carried out next.

Figure 4-10: Immediate Investment Suggested by Three Divisions of Periods



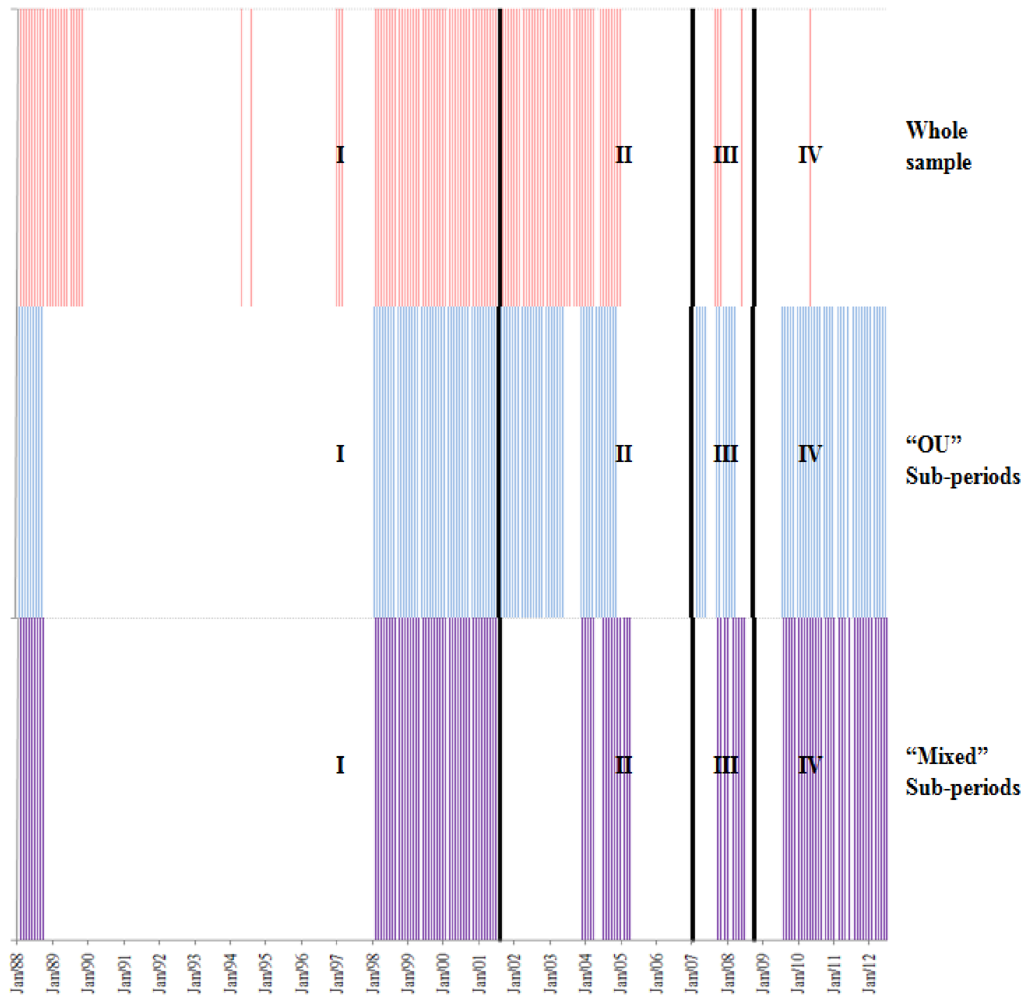
(a) Capesize carriers

Figure 4-10: Immediate Investment Suggested by Three Divisions of Periods (Continued)



(b) Panamax carriers

Figure 4-10: Immediate Investment Suggested by Three Divisions of Periods (Continued)



(c) Handysize carriers

Notes: The line in the figure means immediate investment.

Finally, a simple empirical test on the observed new-ship contracts for the three ship carrier types in the market is carried out. The dependent variable is $Order_t$, which is the total deadweight ton of the new orders at month t. Three factors, including the charter rate R_t, the new-building ship price P_t and the trigger rates from the ROA R^*_t are under investigation. The R^*_t's from the whole sample, the "OU" sub-periods and the "Mixed" sub-periods are tested respectively. The results are summarized in Table 4-8, which shows that the trigger rates R^*_t generally has a significantly negative impact on the new ship ordering, especially Capesize carriers in the "Mixed" sub-periods and Panamax and Handysize carriers in the "OU" sub-periods. New ship ordering is more motivated by the favourable freight market since time charter rate has the most significant impact on $Order_t$. The sub-periods result shows that new ship ordering is encouraged when the ship price is high, which indicates that ship price and freight rate have a close connection and a low investment cost is not the main concern for ship investment. Instead, the freight market plays a more important role on the investment decision. From the result of R^2, it is clear that the "OU" sub-period assumption is closer to the real investment behaviour for Panamax and Handysize carriers while the “Mixed” sub-periods assumption is more fitted to Capesize carriers. It is worth to note that the investment behaviour in the new-building ship market may not always be rational. New ships need to wait for its construction. Even the freight market is booming at the time of ordering, it may be a total different circumstances when the ships are delivered. Then it is possible that the real data of new ordering may not fit well into our model.

Table 4-8: Regression of Factors Impact on the New-ship Contracts

Regression model: $Order_t = \varphi_0+\varphi_1 R_t+\varphi_2 P_t+\varphi_3 R^*_t+\varepsilon_t$

	Capesize			Panamax			Handysize		
	Whole	OU sub-period	Mixed sub-period	Whole	OU sub-period	Mixed sub-period	Whole	OU sub-period	Mixed sub-period
φ_0	-2064338	-1902064	-2497908	2086032	-1828070	-782212	-2821638	-491614	-341867
φ_1	1533.3***	1579.9***	1769.2***	1090.9***	1034.9***	1017.7***	1070.1***	1080.5***	1118.1***
φ_2	47.3	42.3***	57.7***	-83.5	90.7***	51.5***	187.7	26.2**	15.8*
φ_3	-248.3	-288.5**	-643.5***	1265.6	-1085.1***	-711***	-3308.7	-245.7*	-81.2
R	0.6042	0.6149	0.6332	0.2896	0.3738	0.3203	0.5032	0.5081	0.4995

Notes: *, ** and *** denote the rejection of the null hypothesis at the 10%, 5% and 1% significance levels respectively.

4.4 Chapter conclusions

This chapter develops ship investment rules under uncertainty which successfully apply the real option approach. Different from past applications, the cash flow of the ship investment project starts with a lag due to the construction of a new ship, and this project has a finite time horizon because of the limited lifespan of a ship. Two kinds of stochastic process of freight rates are assumed - one is the GBM process which is the most common assumption, and the other is the OU process which seems more realistic. Based on these assumptions, payoffs from immediate investment and postponement are built up to develop the theoretical trigger rate level at which investors have no preference to immediate or suspended investment.

Empirically, the OU process is accepted for the whole data sample. However, if shipping cycles are taken into account, the OU process is only accepted in part of the sub-periods. The parameters determining freight rates are estimated dynamically and evolving, which shows a rare sudden jump-up or jump-down. The basic trigger rates generated from the whole sample show that investment is recommended during 1998-2004. The sensitivity analysis finds that the mean reverting speed, market uncertainty, discount rate and construction time have a positive impact on the trigger rate. Among all the factors, the long-term mean level is the most significant, followed by the discount rate. The results of the trigger rates from the sub-periods exhibit more dramatic fluctuations during the sub-period with high uncertainty. Different from the results from the whole sample, investment is recommended in recent times as suggested by the sub-period results. In addition, for Panamax and Handysize carriers, the OU process with sub-periods is closer to the observed new-ship contracts in the market, while the sub-periods mixed with the OU and GBM processes is more appropriate for Capesize carriers.

Chapter 5: A DUOPOLY GAME MODEL FOR SHIP INVESTMENT

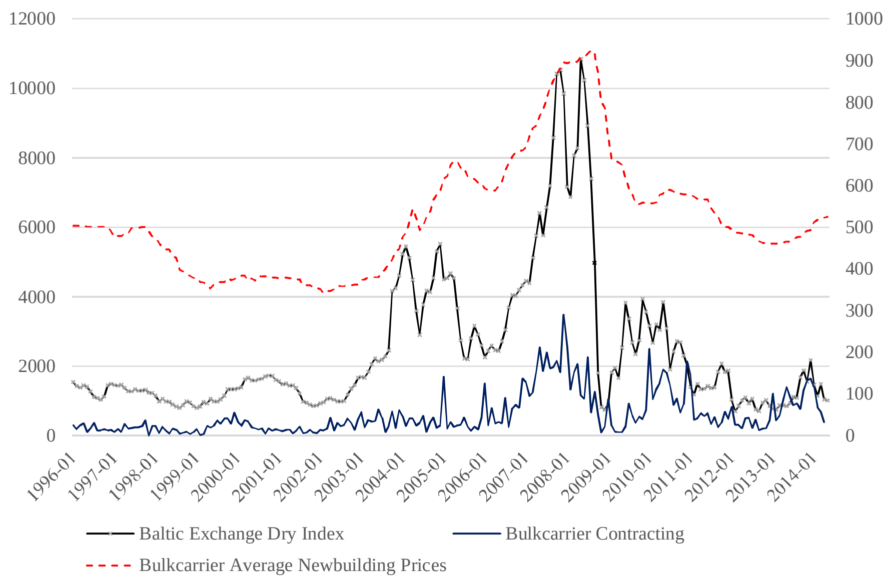
In this Chapter, a duopoly game-theory model is developed to study the impacts of ocean carriers' strategic behaviour in capacity expansion in a competitive market. It has been found that capacity expansion is a rational decision at both peak and trough shipping markets. The benefit of expansion is larger when the competitor also expands, which leads to chronicle oversupply and Prisoner's Dilemma. A numerical simulation is applied to confirm the analytical results. This research accounts for the persistent low freight rate in shipping, and points out possible strategies for stakeholders in the shipping industry to maintain a healthy global logistics system in maritime transportation.

5.1 Introduction

Maritime transport is the conveyer for global commodity trade. A stable freight rate in the world shipping market is essential to a healthy global logistics system. Since the 2008 global financial crisis, the world shipping market has remained sluggish, and the market freight rate is still showing no sign of recovery. The world layup capacity has reached its record high, and increasingly newer vessels are being demolition. The Baltic Exchange Dry Index (BDI), an indicator representing the average earning in the dry bulk sector, dropped precipitately from 11,000 to only one tenth (Figure 5-1), and remained at very low level most of the time. Shipping companies that had fast expansion before the crisis are facing series financial problems, and those on the verge of bankruptcy are praying for an early recovery of the market. However, there are still heavy new orders in this sluggish market. As shown in Figure 5-1, the number of new order contracts after the crisis is still high.

This not only happens in dry bulk sector, but also in the liner market. From January to October, 2013, the total new orders for container vessels amounted to US $19.2 billion with total capacity of 1.7 million TEU, which is about four times as much as that of the previous year (Clarkson PLC, 2014).

Figure 5-1: Dry Bulk Market Development from 1996 to 2014 (1996=100)



Thus, what are the motivations for these new orders facing an already over-crowded market? Shipping companies are competing in a global market where each has very little influence on the market freight rate, and the market share of a company is usually measured by its capacity, which is durable asset. To outperform its peers and to be successful in the market, the company has to select a best time to invest, so that its fleet can grow and its market share can expand. The new orders can be driven by high market demand, as well as by the expansion decision of the others, and by the low building prices when the market freight rate is low. This expansion behaviour in the shipping industry is optimal from the perspective of each individual shipping company, but can result in prolonged overcapacity in the market, which is destructive to the recovery of the market, and in return, reduces the profitability of every company in the market.

A review of the existing literature, as shown in the next section, reveals that little attention has been paid on modelling the strategic decisions in ship investment. From the individual company perspective, neglecting the strategic behaviour of competitors may overestimate the possible benefit of expansion. Unlike price and quantity competitions, the market share competition in the shipping industry has more significant long-term impacts on the market and the whole industry.

This study develops a game theory model to analyze the impacts of strategic capacity expansion on market supply in a competitive shipping market. As the market share in shipping is determined by its carrying capacity (Luo *et al*., 2014), for a given market freight rate and market demand, the two companies determine whether to expand its fleet according to the incremental profit of expansion. For given capacity, each company maximizes its profit by setting an optimal speed within a possible range. The condition for dominant strategy and the Nash Equilibrium (NE) in this duopoly game is identified, and the possibility of Prisoner's Dilemma is tested if expansion is a dominating strategy. A comparative static analysis of the investment strategy was conducted with respect to the bunker price, energy efficiency and freight rate. Theoretical results suggest that expansion is possible at both very high and very low freight rates, regardless the strategy of the competitor. The strategic capacity expansion will lead to a Prisoners' Dilemma and overcapacity in market supply. A numerical simulation is provided to support our analytical results.

The contributions of this paper to the literature are that it offers an analysis on the impacts of explanation reveals that expanding capacity is a rational decision for the individual shipping company, not just when the market is good, but also at sluggish market. This expansion often leads to excessive supply and chronicle low freight rate in shipping, which is usually attributed to the "short memory" of the ship-owners. This explains the current heavy new orders in the shipping industry even when everyone is praying for the coming of recovery. It points out that asking the industry to refrain from expansion is not useful. For a shipping company, it is better to recognize this inherent nature in the shipping market. For the public agency, this may be one possible chance to upgrade the world shipping fleet to become more energy efficient and cost effective.

After a review of the existing literature in ship investment, the theoretical model and results on the ship investment game are first presented. To demonstrate the theoretical results, numerical simulation is also provided, using the current data in bulk shipping as an example. Finally, a summary and conclusion is provided.

5.2 The Model

The objective of this research is to study the collective consequences of individual optimal behaviour in capacity expansion in a competitive market where the individual market share is based on its capacity. Hence, the cooperative behaviour is not considered. In addition, a number of assumptions are made to enable the theoretical analysis. A justification of these assumptions is given below.

First, it is assumed that there are only two competing companies in the market. Given that the shipping market is highly competitive, especially in the dry bulk sector, using a duopoly game is sufficient to obtain a lower bound on the impacts of capacity expansion. More competitors can only intensify the impact of capacity competition.

Second, the two companies are assumed to be identical. The reason of this assumption is that if there is a larger company and a smaller one, the competition between them is at a weak level. The competitors in shipping industry must have similar market power. If not, there may exhibit the leader-follower kind of game. That is not the scope of this study.

Third, the market freight rate and the market demand for each round trip are assumed given. This assumption is more close to the reality where market players individually have little influence on the freight rate and the demand is distributed by capacity. Even when the number of players in a specific route is small, the freight rate is determined by global market, not that on the specific route. This assumption allows us focus on the impact of individual capacity expansion without modelling the demand function. On the other hand, it still provides incentive for a shipping company to adjust the speed with different freight rate and the market demand. If the freight rate is high, a ship can sail faster to get more cargo in a year. Also, it is recognized that in practice there are many different kinds of charges that a carrier can collect from the shipper in addition to freight rate, such as fuel surcharges and terminal handling charges and freight rates may be very low on the backhaul of an imbalanced trade. To avoid the complications, the freight rate is assumed to be the overall charge for the whole round trip.

Fourth, the scale and energy efficiency of new ships are not considered. Again, this assumption is appropriate if the objective is to provide a lower bound. Additional benefits of expansion can only intensify the overcapacity due to expansion.

Above are the general assumptions on the setting of the duopoly model. There are other specific assumptions, which will be explained in the next section.

5.2.1 Basic model

In reality, capacity decisions are always made before determining ship speed. Using backward induction, the optimal speed of the vessel is first analyzed, then the capacity decision. Compared with the two-stage duopoly model on pricing and capacity expansion in Luo *et al.* (2012), the speed decision is not a competitive measure. It just helps to maintain the optimality of capacity expansion strategy.

To setup the optimal speed, it is assumed that there are two shipping companies carrying cargoes between port A and port B with round-trip distance l nautical miles. If the speed is s knots (nautical miles/hour) and the total working time in a year is γ hours, the number of round-trips that a ship can make in a year is $n=\gamma s/l$.

To allow for the analysis of the ship investment decision, a binary variable δ_i is used to denote company i's decision to order new ships - 0 for 'not order' (N) and 1 for 'order' (Y). Assuming that two shipping companies have identical initial number of ships k, the number of ships for company i will be $k+\delta_i\Delta k$, where Δk is the number of ships to order. Δk is not a decision variable, as the purpose of the model is just to analyze whether to expand, not the optimal number of ships to invest. The shipbuilding lag is neglected, based on the assumption that the market freight rate is given, no uncertainty is involved, and the investment decision is static, one-time game. Then the market share of a shipping company for any trip is $(k_i + \delta_i\Delta k)/K$ where $K=(k_i + k_j) + (\delta_i + \delta_j)\Delta k$. If the total market demand for shipping service is Q for every round-trip, the total quantity carried in each round-trip can be written as $q_i = (k_i + \delta_i\Delta k)Q/K$. For a given freight rate F (\$/tonne), the total revenue for company i is $Fnq_i=F\frac{\gamma s}{l}\frac{(k_i+\delta_i\Delta k)Q}{(k_i+k_j)+(\delta_i+\delta_j)\Delta k}$.

The costs of a ship are assumed to include two parts: voyage cost *VC* and operating cost *OC*. The voyage cost mainly consists of fuel cost. From Ronen (1982), fuel consumption per hour can be written as λs^{α} (α usually equals to 3), where s ($s_{\min} \leq s \leq s_{\max}$) is the actual vessel speed and λ is the fuel efficiency. A larger λ indicates lower energy efficiency. If the fuel cost is P_b, the total cost per year per ship can be written as ($\gamma \lambda P_b s^{\alpha} + OC$).

The profit facing by company i can be written as:

$$\max_{s_i} \pi_i(\delta_1, \delta_2) = \frac{F\gamma s_i(k+\delta_i \Delta k)Q}{l(2k+(\delta_1+\delta_2)\Delta k)} - (k+\delta_i \Delta k)\gamma\lambda P_b {s_i}^{\alpha} - (k+\delta_i \Delta k)OC - \delta_i \Delta k r P \quad \text{(5-1)}$$
$$s.t. \quad s_{\min} \leq s_i \leq s_{\max},$$

where r is the interest rate and P is the new building ship price. The last item is the annualized capital cost for investing Δk number of ships. This profit maximization under unequal constraints can be solved using Kuhn-Tucker method. The optimal speed can be written as:

$$s_i{}^* = \begin{cases} s_{\max} & (s_{\max} < v_{\delta_1\delta_2}) \\ v_{\delta_1\delta_2} & (s_{\min} \leq v_{\delta_1\delta_2} \leq s_{\max}) \\ s_{\min} & (s_{\min} > v_{\delta_1\delta_2}) \end{cases} \quad \text{(5-2)}$$

where $v_{\delta_1\delta_2} = (FQ/[\alpha l \lambda P_b(2k + (\delta_1 + \delta_2)\Delta k)])^{\frac{1}{\alpha-1}}$. Clearly, $v_{\delta_1\delta_2}$ follows $v_{11}<v_{10}=v_{01}<v_{00}$, i.e., the more the capacity invested, the lower the speed. Equation (5-2) shows that, within the range [$s_{\min}$, $s_{\max}$], the optimal speed increases with freight rate and average demand per ship, and decreases with energy efficiency, the shipping distance and bunker price.

Substituting the s_i^* into the profit function, the maximum profit function can be written as:

$$\pi_i(\delta_1, \delta_2)^* = \begin{cases} (k + \delta_i \Delta k)\left[\frac{G}{(2k+(\delta_1+\delta_2)\Delta k)^{\frac{\alpha}{\alpha-1}}} - OC\right] - \delta_i \Delta krP & if\ s_{\min} \le s^* \le s_{\max} \\ (k + \delta_i \Delta k)\left[\frac{F\gamma Q s_e}{l(2k+(\delta_1+\delta_2)\Delta k)} - \lambda P_b s^e - OC\right] - \delta_i \Delta krP & otherwise \end{cases} \quad (5\text{-}3)$$

where G=$G = \frac{(\alpha-1)\gamma}{(\lambda P_b)^{\frac{1}{\alpha-1}}}\left(\frac{FQ}{\alpha l}\right)^{\frac{\alpha}{\alpha-1}}$ and s_e=$s_{\max}$ or $s_{\min}$.

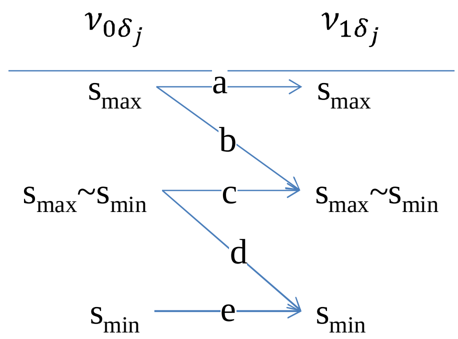
5.2.2 Analyzing Nash Equilibrium using a normal form game

From Equation (5-3), the payoff matrix for the normal form game can be constructed (Table 5-1). The analysis of Nash equilibrium is based on the incremental benefit of investment for one company regardless the strategy of the other, i.e., $\Delta\pi_i(\delta_j)=\pi_i^*(1,\delta_j)-\pi_i^*(0,\delta_j)$ [i=(1, 2) and j=(1, 2) and $i\neq j$]. Since the incremental benefit depends on the speed changes due to investment, the possible changes (Figure 5-2) are first listed, then the incremental benefits for these 5 paths are discussed.

Table 5-1: Payoff Matrix for Different Investment Decisions

		Company 2	
		N	*Y*
Company 1	*N*	$\pi_1^*(0,0)$, $\pi_2^*(0,0)$	$\pi_1^*(0,1)$, $\pi_2^*(0,1)$
	Y	$\pi_1^*(1,0)$, $\pi_2^*(1,0)$	$\pi_1^*(1,1)$, $\pi_2^*(1,1)$

Figure 5-2: Optimal Speed Change after Ship Investment



<u>The extreme case paths a and e</u>

Paths *a* and *e* in Figure 5-2 represent the situation that s^* equals to the boundary speed ($s_{\max}$ or $s_{\min}$) regardless of the investment decisions by any shipping company. The profit change equals to

$$\Delta\pi_i(\delta_j)^{ext} = \Delta k\left[\frac{F\gamma Q s_e}{2(2k+\Delta k)l} - \gamma\lambda P_b {s_e}^{\alpha} - (OC + rP)\right], \qquad (5\text{-}4)$$

This incremental profit is independent from δ_j, indicating that the investment decision of one company does not affect the other. Also, the first item in the bracket is the annual revenue increase of each ship due to expansion, while the second and third terms are the increase in voyage cost and fixed cost for each vessel. From this, it can be seen that in extreme market conditions, the decision of capacity expansion is determined by the freight market, bunker price and ship operation costs. It is irrelevant to the capacity expansion decision of the competitor. If all the ships in the company have to sail at full speed after investment, the demand must be very high, and the response of the competitors should not be a concern. When the speed is running at its minimum, the only reason for expansion is that the bunker price and capital cost are very low so that the incremental revenue can cover the additional costs.

The normal case path c

Define path c in Figure 5-2 as the normal case where ships sail at normal speed ($s_{\min} \leq v \leq s_{\max}$) after investment. The incremental benefit, $\Delta\pi_i(\delta_j)^c$ can be written as:

$$\Delta\pi_i(\delta_j)^c = G * N(\delta_j) - \Delta k(OC + rP) \tag{5-5}$$

where $N(\delta_j)=\frac{k+\Delta k}{(2k+(1+\delta_j)\Delta k)^{\frac{\alpha}{\alpha-1}}} - \frac{k}{(2k+\delta_j\Delta k)^{\frac{\alpha}{\alpha-1}}}$. From Appendix 5-A, it is clear that $N(1)>N(0)$. Therefore, $\Delta\pi_i(1)^c>\Delta\pi_i(0)^c$, the incremental benefit is larger if the competitor also expands. This result implies that if expansion is a good decision, the expansion decision of the competitor will not reduce the benefits of expansion. On the contrary, it enhances the benefits. From this, it is clear that the competition for market share in the shipping industry can easily lead to overcapacity.

The transfer case paths b and d

Paths b and d are the two cases where the speed transfers between the boundary speed and normal speed. Considering the differences between only one expands and both expand capacity, two cases exist for the payoff matrix for each path, which are summarized in Table 5-2.

Table 5-2: Payoff Matrix for Two Transfer Paths

Path $b1$: $\delta_i=\delta_j=1$, $s^*=v_{11}$; otherwise		
	N	Y
N	$\pi_1(0,0,s_{\max})$, $\pi_2(0,0,s_{\max})$	$\pi_1(0,1,s_{\max})$, $\pi_2(0,1,s_{\max})$
Y	$\pi_1(1,0,s_{\max})$, $\pi_2(1,0,s_{\max})$	$\pi_1(1,1,v_{11})$, $\pi_2(1,1,v_{11})$
	$\Delta\pi_i(0)^{b1}$	$\Delta\pi_i(1)^{b1}$

Path $b2$: $\delta_i=\delta_j=0$, $s^*=s_{\max}$; otherwise		
	N	Y
N	$\pi_1(0,0,s_{\max})$, $\pi_2(0,0,s_{\max})$	$\pi_1(0,1,v_{01})$, $\pi_2(0,1,v_{01})$
Y	$\pi_1(1,0,v_{10})$, $\pi_2(1,0,v_{10})$	$\pi_1(1,1,v_{11})$, $\pi_2(1,1,v_{11})$
	$\Delta\pi_i(0)^{b2}$	$\Delta\pi_i(1)^{b2}$

Path $d1$: $\delta_i=\delta_j=1$, $s^*=s_{\min}$; otherwise		
	N	Y
N	$\pi_1(0,0,v_{00})$, $\pi_2(0,0,v_{00})$	$\pi_1(0,1,v_{01})$, $\pi_2(0,1,v_{01})$
Y	$\pi_1(1,0,v_{10})$, $\pi_2(1,0,v_{10})$	$\pi_1(1,1,s_{\min})$, $\pi_2(1,1,s_{\min})$
	$\Delta\pi_i(0)^{d1}$	$\Delta\pi_i(1)^{d1}$

Path $d2$: $\delta_i=\delta_j=0$, $s^*=v_{00}$; otherwise		
	N	Y
N	$\pi_1(0,0,v_{00})$, $\pi_2(0,0,v_{00})$	$\pi_1(0,1,s_{\min})$, $\pi_2(0,1,s_{\min})$
Y	$\pi_1(1,0,s_{\min})$, $\pi_2(1,0,s_{\min})$	$\pi_1(1,1,s_{\min})$, $\pi_2(1,1,s_{\min})$
	$\Delta\pi_i(0)^{d2}$	$\Delta\pi_i(1)^{d2}$

The incremental benefits ($\Delta\pi_i(0)^{b1}$ for $b1$ and $\Delta\pi_i(1)^{d2}$ for $d2$) are the same as the extreme case, as the ships remain at the boundary speed after expansion. $\Delta\pi_i(1)^{b2}$ and $\Delta\pi_i(0)^{d1}$ are the same as the normal case because they do not involve boundary speed. For the other cases, the incremental profit of expansion can be written as:

$$\begin{cases} \Delta\pi_i(\delta_j)^b = G * A(\delta_j) - \frac{F\gamma Q s_{\max} k}{l(2k+\delta_j\Delta k)} + k\gamma\lambda P_b {s_{\max}}^{\alpha} - \Delta k(OC + rP) \\ \Delta\pi_i(\delta_j)^d = -G * B(\delta_j) + \frac{F\gamma Q s_{\min}(k+\Delta k)}{l(2k+(1+\delta_j)\Delta k)} - (k+\Delta k)\gamma\lambda P_b {s_{\min}}^{\alpha} - \Delta k(OC + rP) \end{cases}, \tag{5-6}$$

where $A(\delta_j)=\frac{k+\Delta k}{(2k+(1+\delta_j)\Delta k)^{\frac{\alpha}{\alpha-1}}}$, $B(\delta_j)=\frac{k}{(2k+\delta_j\Delta k)^{\frac{\alpha}{\alpha-1}}}$. Clearly $A(\delta_j)-B(\delta_j)=N(\delta_j)$.

For cases $b1$ and $d2$, it is straight forward that $\Delta\pi_i(0)^{b1}<\Delta\pi_i(1)^{b1}$ and $\Delta\pi_i(0)^{d2}<\Delta\pi_i(1)^{d2}$ from Table 5-2, because the constrained profit is always less than unconstrained one. For $b2$ and $d1$, by comparing with path c, it is clear that:

$$\Delta\pi_i(1)^{b2}=\Delta\pi_i(1)^c \text{ and } \Delta\pi_i(0)^{b2}>\Delta\pi_i(0)^c \tag{5-7a}$$

$$\Delta\pi_i(0)^{d1}=\Delta\pi_i(0)^c \text{ and } \Delta\pi_i(1)^{d1}<\Delta\pi_i(1)^c \tag{5-7b}$$

Appendix 5-B shows that $\Delta\pi_i(0)^{b2}<\Delta\pi_i(1)^{b2}$ and $\Delta\pi_i(0)^{d1}<\Delta\pi_i(1)^{d1}$ for both cases. Combining the result from the normal case, it is clear that when the shipping speed is decreasing after expansion, the incremental benefit of capacity expansion is larger when the competitor also expands.

From above analysis, it can be see that $\Delta\pi_i(1)>\Delta\pi_i(0)$ is valid for all the cases. Then the Nash equilibrium can be obtained under following cases:

a) $\Delta\pi_i(1)>0$ and $\Delta\pi_i(0)>0$: In this case, the Nash equilibrium is (Y, Y), i.e., both will expand.

b) $\Delta\pi_i(1)>0$ and $\Delta\pi_i(0)<0$: In this case, there are two equilibriums (Y, Y) and (N, N). However, (N, N) is not a stable equilibrium because $\Delta\pi_i(1)>\Delta\pi_i(0)$—expansion is a better decision for both.

c) $\Delta\pi_i(1)<0$ and $\Delta\pi_i(0)<0$: In this case, the Nash equilibrium is (N, N).

From this duopoly game, it is clear that when the players are competing for market share, the individual optimal behaviour may lead to overcapacity in the shipping market. Although capacity expansion in a good market does not lead to overcapacity, the competition for market share will not stop till both have negative incremental profits. Therefore, without considering the negative impact of capacity expansion on freight rate, it is evident that such a competition is detrimental to both players. When the demand is low, the low ship price can also lead to excessive capacity expansion, which may have significant long-term impacts on the shipping market. In a normal scenario, the strategic capacity expansion will lead to overcapacity because the incremental benefit is larger if both expand.

5.2.3 Possibility of Prisoners' dilemma

For symmetric game, if $\pi_1^*(1,0)>\pi_1^*(0,0)>\pi_1^*(1,1)>\pi_1^*(0,1)$, the game is a typical Prisoners' Dilemma. In our model, the extreme case will not fall into this situation because there is no strategic competition. However, it is possible in the other cases when capacity development is optimal, i.e., when $\pi_1^*(1,0)>\pi_1^*(0,0)$ and $\pi_1^*(1,1)>\pi_1^*(0,1)$. In this case, it is only necessary to check whether $\pi_1^*(0,0)>\pi_1^*(1,1)$.

From Equation (5-3) and Table 5-2, the profit difference between no one investing and both investing for normal case *c* and transfer case *b* and *d* can be written as:

$$\pi^c(0,0)-\pi^c(1,1)=\frac{G}{2^{\frac{\alpha}{\alpha-1}}}\left[\frac{1}{k^{\frac{1}{\alpha-1}}}-\frac{1}{(k+\Delta k)^{\frac{1}{\alpha-1}}}\right]+\Delta k(OC+rP) \tag{5-8a}$$

$$\pi^b(0,0)-\pi^b(1,1)=\frac{F\gamma Q s_{max}}{2l}-k\gamma\lambda P_b {s_{max}}^{\alpha}-G*A(1)+\Delta k(OC+rP) \tag{5-8b}$$

$$\pi^d(0,0)-\pi^d(1,1)=G*B(0)-\frac{F\gamma Q s_{min}}{2l}+(k+\Delta k)\gamma\lambda P_b {s_{min}}^{\alpha}+\Delta k(OC+rP) \tag{5-8c}$$

It is straight forward to see that $\pi^c(0,0)>\pi^c(1,1)$. Appendix 5-D shows that $\pi^b(0,0)>\pi^b(1,1)$ and $\pi^d(0,0)>\pi^d(1,1)$.

Having explored the possibility of overcapacity in the duopoly market when the players are competing for market share, and the existence of Prisoner Dilemma, comparative statics are used to analyze how the incremental benefit $\Delta\pi_i(\delta_j)$ changes with the market factors such as bunker price or the freight rate.

5.2.4 Comparative static analysis

Since it is straight forward to find the impacts of the price of new ships and the mortgage rate, this comparative static analysis is focused on the impact of market parameters including bunker price P_b, the fuel efficiency λ and freight rate F.

First, differentiate $\Delta\pi_i(\delta_j)$ in three cases *w.r.t.* bunker price P_b:

$$\frac{\partial \Delta\pi_i(\delta_j)^{ext}}{\partial P_b} = -\Delta k \gamma \lambda {s_e}^{\alpha} \tag{5-9a}$$

$$\frac{\partial \Delta\pi_i(\delta_j)^{c}}{\partial P_b} = G_{P_b} * N(\delta_j) \tag{5-9b}$$

$$\frac{\partial \Delta\pi_i(\delta_j)^{trs}}{\partial P_b} = \begin{cases} \frac{\partial \Delta\pi_i(\delta_j)^{b}}{\partial P_b} = G_{P_b} * A(\delta_j) + k\gamma\lambda {s_{max}}^{\alpha} \\ \frac{\partial \Delta\pi_i(\delta_j)^{d}}{\partial P_b} = -G_{P_b} * B(\delta_j) - (k + \Delta k)\gamma\lambda {s_{min}}^{\alpha} \end{cases}, \tag{5-9c}$$

where $G_{P_b} = \frac{\partial G}{G P_b} = -\frac{\gamma}{\lambda^{\frac{1}{\alpha-1}}}\left(\frac{FQ}{\alpha l P_b}\right)^{\frac{\alpha}{\alpha-1}} < 0$ and $N(\delta_j)>0$ as shown in Appendix 5-B. The signs for Equations (5-9a) and (5-9b) are obvious negative. Appendix 5-E.1 shows that Equation (5-9c) is also less than zero. Therefore, without taking into account that new ships can be more energy efficient, a higher bunker price reduces the incentive for making new order.

Differentiating $\Delta\pi_i(\delta_j)$ *w.r.t.* fuel efficiency parameter λ:

$$\frac{\partial \Delta\pi_i(\delta_j)^{ext}}{\partial \lambda} = -\Delta k \gamma P_b {s_e}^{\alpha} \tag{5-10a}$$

$$\frac{\partial \Delta\pi_i(\delta_j)^{c}}{\partial \lambda} = G_{\lambda} * N(\delta_j) \tag{5-10b}$$

$$\frac{\partial\Delta\pi_i(\delta_j)^{trs}}{\partial\lambda} = \begin{cases} \frac{\partial\Delta\pi_i(\delta_j)^b}{\partial\lambda} = G_\lambda * A(\delta_j) + k\gamma P_b s_{\max}{}^{\alpha} \\ \frac{\partial\Delta\pi_i(\delta_j)^d}{\partial\lambda} = -G_\lambda * B(\delta_j) - (k+\Delta k)\gamma P_b s_{\min}{}^{\alpha} \end{cases}, \tag{5-10c}$$

where $G_\lambda = \frac{\partial G}{\partial\lambda} = -\frac{\gamma}{(P_b)^{\frac{1}{\alpha-1}}}\left(\frac{FQ}{\alpha l\lambda}\right)^{\frac{\alpha}{\alpha-1}} < 0$. The signs for Equations (5-10a) and (5-10b) are obvious negative. Appendix 5-E.2 shows that Equation (5-10c) is also negative. These results show that increasing energy efficiency (reduce in the value of λ) can push up new orders.

Differentiating $\Delta\pi_i(\delta_j)$ *w.r.t.* the freight rate F:

$$\frac{\partial\Delta\pi_i(\delta_j)^{ext}}{\partial F} = \frac{\gamma Q s_e}{l}\frac{\Delta k}{2(2k+\Delta k)} - \Delta k r P_F{}' \tag{5-11a}$$

$$\frac{\partial\Delta\pi_i(\delta_j)^{c}}{\partial F} = G_F * N(\delta_j) - \Delta k r P_F{}' \tag{5-11b}$$

$$\frac{\partial\Delta\pi_i(\delta_j)^{trs}}{\partial F} = \begin{cases} \frac{\partial\Delta\pi_i(\delta_j)^b}{\partial P_b} = G_F * A(\delta_j) - \frac{\gamma Q}{l}\frac{k s_{max}}{(2k+\delta_j\Delta k)} - \Delta k r P_F{}' \\ \frac{\partial\Delta\pi_i(\delta_j)^d}{\partial P_b} = -G_F * B(\delta_j) + \frac{\gamma Q}{l}\frac{(k+\Delta k)s_{min}}{(2k+(1+\delta_j)\Delta k)} - \Delta k r P_F{}' \end{cases}, \tag{5-11c}$$

where $G_F = \frac{\partial G}{\partial F} = \gamma\left(\frac{F}{\alpha\lambda P_b}\right)^{\frac{1}{\alpha-1}}\left(\frac{Q}{l}\right)^{\frac{\alpha}{\alpha-1}} > 0$ and $P_F{}'$ is the sensitivity of new-building ship price to the freight rate change.

First, in Equation (5-11) if the change of new-building price due to freight rate is ignored (i.e., $-\Delta k r P_F{}' = 0$), then $\frac{\partial\Delta\pi_i(\delta_j)}{\partial F} > 0$ for all the three cases (The proof for Equation (5-11c) is shown in Appendix 5-E.3). This implies that if freight rate does affect new-building prices, higher freight rate always motivates making new order.

However, many existing studies found that new-building ship prices are positively correlated with the freight rate (Haralambides *et al*., 2004; Luo *et al*., 2009; Hawdon, 1978). For Equation (5-11a), if $\frac{\gamma Q s_e}{2l(2k+\Delta k)} > rP_F'$, the revenue increases faster than the annualized capital cost, then $\frac{\partial \Delta\pi_i(\delta_j)^{ext}}{\partial F}$>0: a higher freight rate increases the benefit of expansion; otherwise, if ship price decrease faster than the freight rate, then $\frac{\partial \Delta\pi_i(\delta_j)^{ext}}{\partial F}$<0: a low freight increases the benefit of expansion. From this, it can be seen that the motivation for investing in new ships not only comes from high freight rate, but also when the freight rate is low.

For Equation (5-11b), if $F > H\left(\Delta k / N(\delta_j)\right)^{\alpha-1}$ where $H = (\alpha\lambda P_b)(rP_F{}'/\gamma)^{\alpha-1}(l/Q)^{\alpha}$, then $\frac{\partial \Delta\pi_i(\delta_j)^{c}}{\partial F} > 0$, $\Delta\pi_i(\delta_j)^c$ increases with F (Appendix 5-E.3). It is better for ordering new ships when the freight rate is high enough. Otherwise, $\frac{\partial \Delta\pi_i(\delta_j)^{c}}{\partial F} < 0$, $\Delta\pi_i(\delta_j)^c$ increases when F is decreasing. For Equation (5-11c), if $> H\left(\Delta k / N(\delta_j)\right)^{\alpha-1}$, $\frac{\partial \Delta\pi_i(\delta_j)^{trs}}{\partial F}$>0 (Appendix 5-E.3), $\Delta\pi_i(\delta_j)^{trs}$ increases with F. On the other hand, if $F < H\big(2(2k + \Delta k)\big)^{\alpha-1}\big(2k + \delta_j \Delta k\big)$, then $\frac{\partial \Delta\pi_i(\delta_j)^{trs}}{\partial F}$<0 (Appendix 5-E.3) and $\Delta\pi_i(\delta_j)^{trs}$ increases when F is decreasing. These results show that expansion is a good strategy at both high and low freight rate.

The comparative static analysis shows that capacity expansion in shipping is a good strategy when the bunker price is low, the ship energy efficiency is high, or at both peak and low market freight rate. These results explain the high increase in new orders before 2008 when the ship price was high, as well as recently when the BDI is still very low but the new-building price is also very low.

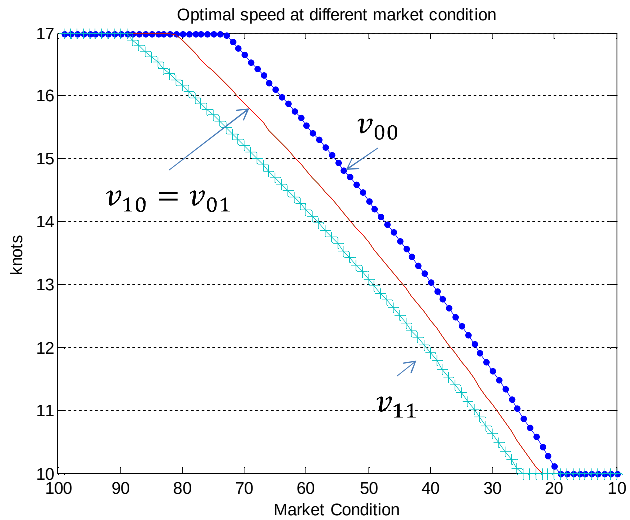
5.3 Numerical experiments

The purpose of this section is to show the profit and incremental benefits of capacity expansion. From that, the Nash equilibrium strategies for capacity expansion with different market conditions can be identified. In the numerical analysis, each company is assumed to have 10 identical Panamax bulk carriers (60000-80000 dwt). The round-trip distance is l=20,000 nm, and days at sea is 250 days (Gratsos *et al.*, 2010), or γ=6000 hours. Operating cost is 1.8×10^6 \$/year (Stopford, 2009: 224), and fuel efficiency is λ=0.0012 (Chang and Chang, 2013). The range of speed is around 12-15 knots (Alizadeh and Nomikos, 2009), and ±15% of the design speed 14.5 knots (Stopford, 2009: 593), which indicates that speed is around 12.3-16.7 knots. It is assumed that s_{min}=12 knots and s_{max}=17 knots, and that financing rate is r=2%.

Assume the market is changing from a very good market (F=\$100/tonne to only \$10/ton), and the quantity demanded for a round trip also decreases from 2.5 to 0.25 million tonnes. The change in shipping speed for each possible strategy combinations, their profits, as well as their incremental profits with the change of market conditions are simulated. Also, Δk=2 is assumed.

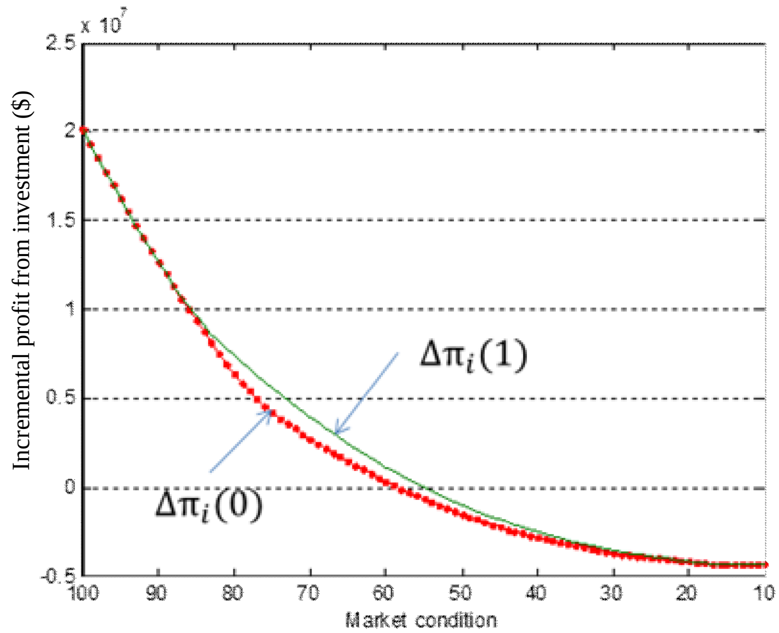
Figure 5-3 is the simulation result for the speed change at different market conditions. It shows that, if the market is really good (on the left side), the three lines overlay with each other, indicating expansion cannot decrease the shipping speed. Also, the speed at when no one invests (v_{00}) is larger than only one invests (v_{01} or v_{10}), which is again larger than both invest (v_{11}). If the market condition is really bad, they will all collapse to the minimum speed.

Figure 5-3: Optimal Speed Change with the Decrease of Market Freight Rate



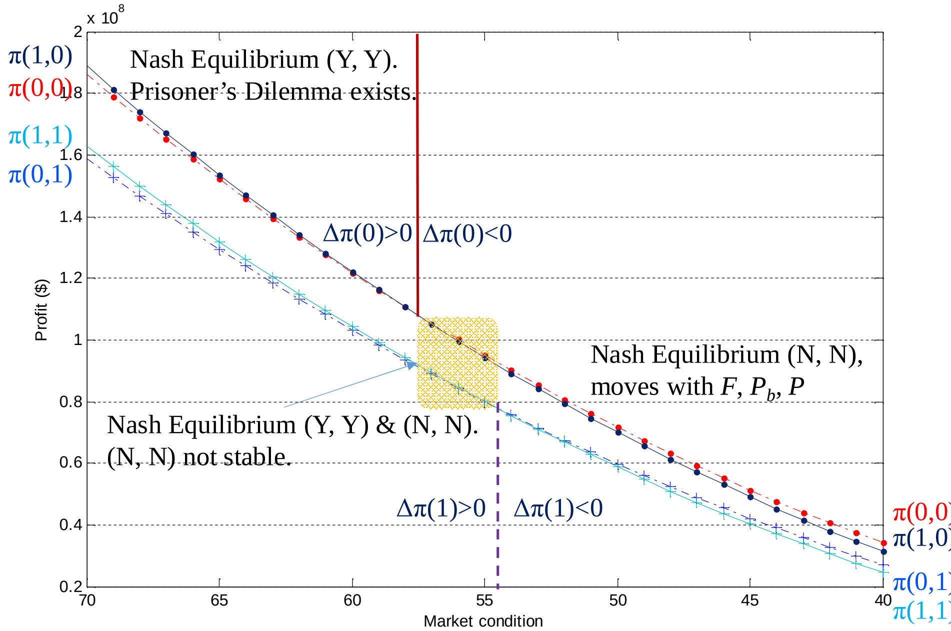
Second, the incremental benefit of capacity expansion for all possible strategies of the competitor is simulated, as shown in Figure 5-4. Firstly, the two lines decrease with the freight rate, indicating the incremental profit decreases when the market goes worse. Secondly, when the market is really good (on the left side) or really bad (on the right side), the two lines overlap with each other. This confirms that the investment decision of one player does not depend on the other. In the middle, $\Delta\pi_i(1)$ is higher than $\Delta\pi_i(0)$, meaning that the incremental profit is higher if the other also invests, which also confirms the theoretical result. If bottom fishing (order when the ship price is very low) is not considered, further decrease in the freight rate can drive the incremental benefit below zero. This indicates possible low orders in a sluggish market.

Figure 5-4: Change of Incremental Profits with the Possible Strategies of the Competitor



Finally, to check the possibility for Prisoner's Dilemma in capacity expansion, we plot the profits of one player for each possible strategy of the competitor where $\Delta\pi_i(1)>\Delta\pi_i(0)$, which is shown in Figure 5-5. The lines with dot markers (the upper two lines) are the profits when the other does not expand ($\pi(1,0)$ and $\pi(0,0)$), and lines with cross markers (the lower two lines) are the profits when the other expands its capacity ($\pi(1,1)$ and $\pi(0,1)$). It is clear that profits are higher if the other does not expand. The solid line indicates the profit from expansion, and the broken line is the profit from no expansion. Solid lines are higher than the broken line in the left. However this relationship is reversed in the right.

Figure 5-5: Profit Change for the Game Model when the Market Slows Down



Using this graph, it is straight forward to see that when $\Delta\pi(0)>0$, there is a unique Nash equilibrium (Y,Y) and Prisoner's Dilemma exists. This capacity expansion will further increase the market capacity and worsen the market condition.

In the middle block where $\Delta\pi(0)<0$ and $\Delta\pi(1)>0$, there are two Nash equilibriums (Y,Y) and (N,N). However, this (N,N) may not be stable because the incremental benefit is higher if both expand.

On the right part where $\Delta\pi(0)<0$ and $\Delta\pi(1)<0$, the market condition is worse than its middle point. Theoretically, no one should expand. Therefore, the Nash equilibrium is (N,N). However, in reality, If any player selects to expand, the other will also follow, as (*N*,*Y*) is not a possible equilibrium. In this case, not only will Prisoner's Dilemma occur, but also the excessive capacity will put the industry in a very bad situation.

5.4 Chapter conclusions

This paper develops a duopoly game theory model to analyze the consequences of uncoordinated individual optimal strategy in ship investment in a competitive environment. Two shipping companies are modelled, under a given market freight rate, competing for market share by expanding their respective fleet. The Nash equilibrium strategy in a normal form game is analyzed where the payoff of one player for each strategy (invest or not) dependents on the strategy of its competitor. For each shipping company, the incremental profit between investing in new ships and not investing for each given strategy of the competitor are compared, and the dominant strategies are identified. Results show that capacity expansion in shipping can happen in all market situations. However, the investment behaviour when the market is at its bottom has the most detrimental effect on the shipping industry. Also, the benefit of investment will not be reduced by the capacity expansion decision of the competitor. On the contrary, the incremental benefit is larger if the competitor also expands. This leads to the persistent overcapacity in shipping. It is also found that Prisoner's Dilemma exists whenever the capacity increase is beneficial to the individual company. This reveals the nature of the capacity investment in shipping: even in a duopoly market, the strategic behaviour of each individual company in capacity expansion can lead to mutually destructive effects.

A comparative static analysis of the incremental profit was carried out for the changes in bunker price, energy efficiency and freight rate. Results suggest that possibility of investment increases with decreasing bunker price or increasing energy efficiency. More importantly, investment is profitable at both market peak and trough. This theoretical result explains the heavy new orders when the freight rate is still at a very low level after the financial crisis. The low new-building price and the market share are the main driving forces for such behaviour. In addition, the possibility of Prisoner’s Dilemma increases with the increase of freight rate.

Chapter 6: CONTRIBUTIONS AND LIMITATIONS

6.1 Conclusions and contributions

6.1.1 Conclusions

This thesis analyzes ship investment decisions in three ways: the investment cost-revenue relationship, the investment allowing delay and the strategic investment behaviour. The first two issues are based on the decision facing by the individual shipping company, while the third issue incorporates the decision in competitive environment.

The entry point of the analysis on ship investment in this study is to address on the investment cost-revenue relationship, i.e. the ship price-freight rate relationship, taking into account structural change, both theoretically and empirically. Theoretically, the freight rate process is modelling with allowing a shifting mean with structural changes. The trend of the mean determines the long-term variation in the shipping cycle. Then the ship price–freight rate relationship is developed. Both theoretical and empirical results show that the sensitivity of ship prices to freight rate changes is found invariant to structural change. Empirically, the sensitivity is lower for larger ships and for new ships, the discount rate for second-hand ships is larger than that for new ships, implying that second-hand ship investors value short-term benefits more than new ship investors.

After obtaining the theoretical ship price-freight rate relationship, research moves to analyze the minimal market freight rate necessary for profitable ship investment, if shipping companies take into account the option value of delay the investment decision. Theoretically, trigger rates for ship investment are developed under two assumptions on the process of the freight rate - one is the GBM process which is the most common assumption, and the other is the OU process which seems more realistic. Empirically, the OU process is accepted for the whole data sample. However, if shipping cycles are taken into account, the OU process is only accepted in part of the sub-periods. It has been found that most of the previous investment behaviour can be explained by the trigger rates obtained using the real option approach, especially when cyclic nature is clear. The sensitivity analysis finds that the mean reverting speed, market uncertainty, discount rate and construction time have a positive impact on the trigger rate. Among all the factors, the long-term mean level is the most significant, followed by the discount rate.

Following that, strategic capacity expansion in a competitive shipping environment is considered. Two shipping companies, under a given market freight rate, competing for market share by expanding their respective fleet are modelled. A duopoly game-theory model is developed to study the Nash equilibrium strategy where the payoff of one player for each strategy (invest or not) dependents on the strategy of its competitor. Results show that capacity expansion is a rational decision at both peak and trough shipping markets. The benefit of expansion is larger when the competitor also expands, which leads to chronicle oversupply and Prisoner's Dilemma. A numerical simulation is applied to support analytical results.

6.1.2 Contributions

This study contributes on the investment decision theory in several ways. Firstly, studies on investment cost-revenue relationship suggests a way to anticipate the movement of ship price through modelling the ship price-freight rate relationship taking into account structural change, both theoretically and empirically. It contributes to the theory development in modelling the relationship between ship prices and the freight rate, considering both short- and long-term factors and their discrete effect on the formation of the cyclic shipping market. The mean-reverting process is useful in modelling the short-term continuous fluctuation of the freight rate, while the movements of the means can be seen as a long-term trend in the shipping cycle. Although these changes are continuous, incorporating the effects of structural change allows the modelling of a more realistic ship price–freight rate relationship. This part of study also reveals different behaviour between investors in new and second-hand ships, in different ship sizes and in different periods. In practical terms, the results of ship price-freight rate relationship should help shipping companies and ship-owners to better understand any change in the freight rate and its effect on ship prices. If there is no structural change, our model provides a way to estimate future freight rate changes from the expected trend of the mean, which can lead to a change in ship prices. If there is structural change, our model result shows that the sensitivity of ship prices to the freight rate will not be affected. Any change in the level of ship prices will not be related to the freight rate, but this level can be calculated using the estimated parameters of the expected change in the mean of the freight rate.

Secondly, studies on option value of ship investment provide a flexible thinking on ship investment decisions. Unlike the traditional NPV rule, the method in this part incorporate high uncertainty in the market and produces more accurate results. Theoretically, this part contributes to the application of the real option approach in shipping economics, and makes the first attempt to suggest clear rules of the timing of investment in new ships. The proposed model can be also applied to second-hand ship investment decisions with the assumption of no construction lag and a shorter lifespan. In practical terms, this study provides an in-depth detection of the freight rate process and its effect on ship investment rules. The results remind ship investors to concentrate on shipping cycle properties, and also help investors, shipping companies and decision makers to understand the flexible thinking on ship investment.

Thirdly, studies on strategic investment behaviour contributes to the literature by analyzing strategic capacity expansion in shipping and its impact on market oversupply. It is the first attempt that addresses the collective consequences of individual optimal strategy in ship investment. It reveals that overcapacity is a natural result in a competitive market when they are competing for capacity. The results can help ship-owners to understand ship investment behaviour so as to make better decisions regarding fleet expansion. Due to the chronically overcapacity, in a long run, the market freight rate will keep oscillating around its long term mean. Theoretically, it is a rational decision for a shipping company to make new orders even when the freight rate is low, because low freight rate also lead to low ship prices. However, such optimal decision at individual level can create over capacity in shipping supply, which may lead to the early retirement of the old or inefficient vessels. From the public point of view, it can help to improve the efficiency of the world shipping fleet, and phase out un-productive ships. For example, it is a good time to put the new ship-building technologies into new ships to replace the old, inefficient ships for fuel and emission reduction. This can help to achieve the goal of reducing CO_2 emission from international shipping.

In summary, this study can help different players in the shipping industry to better understand the relationship between shipbuilding market and freight market, understand different investment strategies, as well as better recognize the role of individual shipping company's capacity expansion decision.

6.2 Limitations and future studies

First, this research only uses the real option theory to develop the investment rules on new ship ordering facing by the individual shipping company but not include the second-hand buying rules. Extensions can be made to apply the theoretical relationship between the second-hand ship price and freight rate to the second-hand buying project.

Second, the study of ship investment rules using real option theory only considers the situation facing by an individual shipping company. The environment of the whole industry is ignored. For future studies, the responds of market demand and supply could be included in the model.

Finally, research on strategic investment behaviour has many assumptions, which can be relaxed for different objectives. For example, by taking into account the shipbuilding lag and the negative impact of market capacity on future market freight rate, it is possible to extend this model to study the relationship between the cyclical freight rate and capacity expansion decision for given market demand. Also, it is very interesting to study the Nash equilibrium on the individual optimal expansion quantity by relaxing the assumption that the incremental capacity is fixed and change the duopoly to n-oligopoly. It is also interesting to see the possibility of cooperation among few players in a specific route in a globally competitive market. This can be very useful to study the behaviour of the liner alliances, such as the existing G6 alliance and the proposed P3.

APPENDICES

Appendix for Stochastic Process

This research involves two kinds of continuous-time stochastic processes; one is the geometric Brownian motion (GBM), the other is the OU process. These two processes both represent the evolution of a variable over time and are used to describe the movement of the freight rate process in this thesis.

A. Geometric Brownian motion

The GBM is the most widely used process for modelling the random variables in the past. It describes a process in which the drift of a variable grows geometrically over time. Mathematically, a variable R followed the GBM process can be written as:

$$\frac{dR_t}{R_t} = \alpha dt + \nu dz \tag{A. 1}$$

where α is the expected rate of growth constant drift of the process, v is the amount of random variations in the trend, and dz is the increment of a Wiener process with $dz = \varepsilon_t \sqrt{dt}$ where $\varepsilon_t \sim N(0,1)$. Then the expectation and variation of dz are $E(dz)=0$ and $Var(dz)=dt$. From Equation (3-1), the percentage growth in R is normally distributed with mean α and variance v^2 in one unit of time.

According to Dixit and Pindyck (1994), the mean and the variance of R_t are:

$$\begin{aligned} E(R_t) &= R_0 e^{\alpha t} \\ var(R_t) &= {R_0}^2 e^{2\alpha t}\left(e^{\nu^2 t} - 1\right) \end{aligned} \tag{A. 2}$$

Equation (A. 1) shows that the GBM is a Markov process, indicating that the logarithm of the ratio between R in subsequent periods should not depend on the values of prior periods. The following regression can be performed to test the GBM process (Høegh, 1998):

$$ln\frac{R_t}{R_{t-1}} = \beta_1 + \beta_2 ln\frac{R_{t-1}}{R_{t-2}} + e_t \qquad \text{(A. 3)}$$

where β_1 and β_2 are parameters waiting to be determined. In this test, the null hypothesis is that β_2 is equal to zero, which indicates that the data does not depend on its past value, then the series follow the GBM process.

According to Damiano *et al.* (2009), the parameters of the GBM process can be estimated using the past data. First, R is converted into its logarithm value, denoting it as $G_t=\ln R_t$. In using Ito's lemma, G_t follows the GBM process:

$$dG_t = \left(\alpha - \frac{1}{2}v^2\right)dt + vdz \qquad \text{(A. 4)}$$

The discrete time counterpart of Equation (A. 4) can be written as:

$$\Delta G_t = c + e_t \qquad \text{(A. 5)}$$

where $c = \left(\alpha - \frac{1}{2}v^2\right)\Delta t$ and $e_t = v\varepsilon_t\sqrt{\Delta t}$ where $\varepsilon_t \sim N(0,1)$.

Running the regression of Equation (A. 5), estimated parameters of α and v can be obtained:

$$\hat{v} = \frac{S}{\sqrt{\Delta t}}$$
$$\hat{\alpha} = \frac{\hat{v}^2}{2} + \frac{c}{\Delta t} \qquad (A.\ 6)$$

where S is the standard error of Equation (A. 5).

B. Mean-reverting motion

An alternative stochastic process is the mean-reverting process. Different with the GBM process, a variable follows OU process fluctuates around a long-term equilibrium mean level and will not drift too far away from it. Mathematically, if R follows the OU process, it can be written as:

$$dR = u(m - R)dt + \sigma dz \qquad (B.\ 1)$$

where m is the long-term equilibrium level of the variable R; u is the mean-reverting speed, describing the speed for R reverting to m; σ is a standard deviation measuring the volatility of this process and dz is the increment of a Wiener process.

The expectation and variance of R_t given in the work by Dixit and Pindyck (1994) are:

$$E(R_t) = m + (R_0 - m)e^{-ut}$$
$$var(R_t) = \frac{\sigma^2}{2u}(1 - e^{-2ut}) \qquad (B.\ 2)$$

As suggested in past studies (for example Dixit & Pindyck (1994)), if a time series follows the OU process, it is an AR(1) process. Then ADF test can be applied to check whether OU process is an appropriate assumption of R. The null hypothesis is that the original series is non-stationary (has a unit root). If the absolute values are larger than the reported critical values, the null hypothesis of a unit root is rejected. The tested series then can be viewed as an OU process.

The parameters of the OU process in Equation (B. 1) can also be estimated. In following Dixit and Pindyck (1994), the discrete-time counterpart of the OU process for R can be written as:

$$R_t=a+bR_{t-1}+\varepsilon_t \tag{B. 3}$$

where a and b are constants and $\varepsilon_t \sim N(0,S^2)$, where S is the standard deviation. The relationship between the parameters of the discrete-time model in Equation (B. 3) and the continuous-time version in Equation (B. 1) are given by

$$u = -\frac{\ln\hat{b}}{\Delta t},\ m = \frac{\hat{a}}{1-\hat{b}}\ and\ \sigma = S\sqrt{\frac{2\ln\hat{b}}{(\hat{b}^2-1)\Delta t}} \tag{B. 4}$$

where Δt is the time interval between the observations.

Appendix for Chapter 4

4-A. Trigger rate under real option rule - GBM process

From the analysis in chapter 4, the trigger rate $R^*_{\mathrm{G-ROA}}$ can lead to the following equation:

$$F_0(R) = e^{-rdt}E_0[F_{dt}(R)] \tag{4-A. 1}$$

Since $(1+x)^{\frac{1}{x}} \approx e$ when $x \to 0$, assuming that $x=rdt$. With $dt \to 0$, it can be got:

$$e^{-rdt} \approx \frac{1}{1+rdt} \qquad (4\text{-A. }1)$$

Substituting Equation (4-A. 1) into Equation (4-A. 1):

$$F_0(R) = \frac{1}{1+rdt} E_0[F_{dt}(R)] \qquad (4\text{-A. }2)$$

Equation (4-A. 2) can be simplified as:

$$rF_0(R)dt = E_0[dF(R)] \qquad (4\text{-A. }3)$$

where $dF(R)$=$F_{dt}(R) - F_0(R)$. The left-hand side is the capital increment for the optimal investment at time *t*, and the right-hand side is the expected return if the investment is postponed.

Using Ito's Lemma to expand $dF(R)$ in Equation (4-A. 3) and ignore the terms of order higher than two in dt:

$$dF(R) = F_R dR + \frac{1}{2} F_{RR}(dR)^2 \qquad (4\text{-A. }4)$$

where F_R=dF/dR, F_{RR}=d^2F/dR^2.

Since dR follows the GBM process, substitute Equation (A. 1) into Equation (4-A. 4):

$$dF(R) = \left(\alpha R F_R + \frac{v^2R^2}{2} F_{RR}\right) dt + vRF_R dz \qquad (4\text{-A. }5)$$

Substituting Equation (4-A. 3) into Equation (4-A. 5):

$$\frac{v^2R^2}{2}F_{RR} + \alpha RF_R - rF = 0 \qquad \text{(4-A. 6)}$$

The first boundary condition of $F(R)$ is $F(0)=0$ since when $R=0$, the project will generate no profits. This condition leads a general solution to $F(R)$ in Equation (4-A. 6) (i.e. $F(R) = AR^{\lambda}$, where $\lambda>1$). Substituting $F(R) = AR^{\lambda}$ into Equation (4-A. 6):

$$\frac{v^2}{2}\lambda^2 + \left(\alpha - \frac{v^2}{2}\right)\lambda - r = 0 \qquad \text{(4-A. 7)}$$

with solutions $\lambda_1 = \left(\frac{1}{2} - \frac{\alpha}{v^2}\right) + \sqrt{\left(\frac{1}{2} - \frac{\alpha}{v^2}\right)^2 + \frac{2r}{v^2}}>1$.

Another boundary condition is that investment will be made as soon as the charter rate reaches the trigger rate $R^*_{\mathrm{G-ROA}}$:

$$F_0(R^*_{\mathrm{G-ROA}}) = A(R^*_{\mathrm{G-ROA}})^{\lambda_1} = R^*_{\mathrm{G-ROA}}K_{\delta} - P_0 \qquad \text{(4-A. 8)}$$

The third boundary condition is called the first-order "smooth pasting" condition of Equation (4-A. 8):

$$\lambda_1 A(R^*_{\mathrm{G-ROA}})^{\lambda_1 - 1} = K_{\delta} \qquad \text{(4-A. 9)}$$

Solving Equation (4-A. 8) and Equation (4-A. 9), we can get the trigger rate $R^*_{\mathrm{G-ROA}}$:

$$R^*_{\mathrm{G-ROA}} = \frac{\lambda_1 P_0}{(\lambda_1 - 1)K_{\delta}} \qquad \text{(4-A. 10)}$$

The present expected return at time 0, $F_0(R_t)$, based on the real option rule is:

$$F_0(R_t) = \begin{cases} R_0K_\delta - P_0 & R_0 \geq R^*_{\mathrm{G-ROA}} \text{ (immediate investment)} \\ \frac{R_0K_\delta}{\lambda_1} & R_0 < R^*_{\mathrm{G-ROA}} \text{ (postpone investment)} \end{cases} \quad (4\text{-A. } 11)$$

4-B. Trigger rate under option rule - OU process

If dR in Equation (4-A. 4) follows an OU process, substitute Equation (B. 1) in Appendix B into Equation (4-A. 4):

$$dF(R_t) = \left(u(m-R)F_R + \frac{1}{2}\sigma^2 F_{RR}\right)dt + \sigma F_R dz \quad (4\text{-B. } 1)$$

Substituting Equation (4-A. 3) into Equation (4-B. 1):

$$\frac{1}{2}\sigma^2 F_{RR} + u(m-R)F_R - rF = 0 \quad (4\text{-B. } 2)$$

Define a variable $y = \frac{u(m-R)^2}{\sigma^2}$. Then,

$$y_R = -\frac{2u(m-R)}{\sigma^2} \text{ and } y_{RR} = \frac{2u}{\sigma^2} \quad (4\text{-B. } 3)$$

where $y_R = dy/dR$, $y_{RR} = d^2y/dR^2$.

Let $F(R)=f(y)$. It has:

$$F_R = f_y y_R = -\frac{2u(m-R)}{\sigma^2} f_y \text{ and } F_{RR} = \frac{4u}{\sigma^2} y f_{yy} + \frac{2u}{\sigma^2} f_y \quad (4\text{-B. } 4)$$

where $f_y = df/dy$, $f_{yy} = d^2f/dy^2$.

Insert Equation (4-B. 4) into Equation (4-B. 2) and then divide $2u$ on both sides:

$$yf_{yy} + (b - y)f_y - \gamma f = 0 \tag{4-B. 5}$$

where b=1/2 and γ=r/2μ.

Equation (4-B. 5) is the Kummer equation whose solution is:

$$f(y) = A_0 H(\gamma, b, y) + B_0 y^{1-b} H(\gamma - b + 1, 2 - b, y) \tag{4-B. 6}$$

where A_0 and B_0 are constants, and $H(\cdot)$ is the confluent hypergeometric function or Kummer function, given by the following series representation (Slater, 1960):

$$\begin{aligned} &H(\gamma, b, y) = 1 + \frac{\gamma}{b} y + \frac{\gamma(\gamma+1)}{b(b+1)} y^2 + \frac{\gamma(\gamma+1)(\gamma+2)}{b(b+1)(b+2)} y^3 + \cdots \\ &\lim_{y\to\infty} H(\gamma, b, y) = \frac{\Gamma(b)}{\Gamma(\gamma)} e^y y^{\gamma-b} \end{aligned} \tag{4-B. 7}$$

where $\Gamma()$ is the Gamma function.

The two constants must be related in a way which forces f→0 as R→-∞, implying

$$B_0 = -KA_0 \tag{4-B. 8}$$

where $K = \frac{\Gamma(b)\Gamma(\gamma-b+1)}{\Gamma(2-b)\Gamma(\gamma)}$.

Then Equation (4-B. 6) can be simplified as:

$$F(R) = f(y) = A_0(H_1 - Ky^{1-b}H_2) \tag{4-B. 9}$$

where $H_1 = H(\gamma, b, y)$ and $H_2 = H(\gamma - b + 1, 2 - b, y)$.

Let $X(R) = H_1 - Ky^{1-b}H_2$, then we have:

$$X(R) = H\left(\frac{r}{2u}, \frac{1}{2}, \frac{u(m-R)^2}{\sigma^2}\right) - \frac{\Gamma(b)\Gamma(\gamma-b+1)}{\Gamma(2-b)\Gamma(\gamma)} \frac{u^{1-b}(m-R)^{2-2b}}{\sigma^{2-2b}} \left(\frac{r}{2u} + \frac{1}{2}, \frac{3}{2}, \frac{u(m-R)^2}{\sigma^2}\right) \quad \text{(4-B. 10)}$$

For the trigger rate $R^*_{\mathrm{OU-ROA}}$, it will lead to:

$$\begin{cases} A_0 X(R^*_{\mathrm{OU-ROA}}) = R^*_{\mathrm{OU-OP}} K_\rho + m(K_r - K_\rho) - P_0 \\ A_0 X'(R^*_{\mathrm{OU-ROA}}) = K_\rho \end{cases} \quad \text{(4-B. 11)}$$

Eliminating A_0 in Equation (4-B. 11), the trigger rate satisfies:

$$K_\rho X(R^*_{\mathrm{OU-ROA}}) - [R^*_{\mathrm{OU-ROA}} K_\rho + m(K_r - K_\rho) - P_0] X'(R^*_{\mathrm{OU-ROA}}) = 0 \quad \text{(4-B. 12)}$$

The present expected return at time 0, $F_0(R_t)$, based on the real option rule is:

$$F_0(R_t) = \begin{cases} R_0 K_\rho + m(K_r - K_\rho) - P_0 & R_0 \geq R^*_{\mathrm{OU-ROA}} \text{ (immediate investment)} \\ \frac{K_\rho X(R_0)}{X'(R_0)} & R_0 < R^*_{\mathrm{OU-ROA}} \text{ (postpone investment)} \end{cases} \quad \text{(4-B. 13)}$$

Appendix for Chapter 5

5-A. Optimization for Equation (5-1)

The optimization problem described in Equation (5-1) can be solved using the Kuhn–Tucker method. First, the Lagrangian function is

$L(s_i, \lambda_1, \lambda_2) = \frac{F\gamma s_i(k+\delta_i \Delta k)Q}{l(2k+(\delta_1+\delta_2)\Delta k)} - (k + \delta_i \Delta k)\gamma\lambda P_b {s_i}^{\alpha} - (k + \delta_i \Delta k)OC - \delta_i \Delta krP - \lambda_1(s_i - s_{\max}) - \lambda_2(-s_i + s_{\min})$ (5-A. 1)

Application of Kuhn-Tucker condition gives:

$$\frac{\partial L}{\partial s_i} = \frac{F\gamma(k+\delta_i \Delta k)Q}{l(2k+(\delta_1+\delta_2)\Delta k)} - (k + \delta_i \Delta k)\gamma\lambda P_b {s_i}^{\alpha-1} + \lambda_1 - \lambda_2 = 0 \qquad \text{(5-A. 2a)}$$

$$\frac{\partial L}{\partial \lambda_1} = -s_i + s_{\max} \geq 0 \qquad \text{(5-A. 2b)}$$

$$\frac{\partial L}{\partial \lambda_2} = s_i - s_{\min} \leq 0 \qquad \text{(5-A. 2c)}$$

$$\lambda_1 \frac{\partial L}{\partial \lambda_1} = \lambda_1(-s_i + s_{\max}) = 0 \qquad \text{(5-A. 2d)}$$

$$\lambda_2 \frac{\partial L}{\partial \lambda_2} = \lambda_2(s_i - s_{\min}) = 0 \qquad \text{(5-A. 2e)}$$

$$\lambda_1 \geq 0, \lambda_2 \geq 0 \qquad \text{(5-A. 2f)}$$

If $\lambda_1>0$, $\lambda_2=0$, from Equation (5-A. 2d) and (5-A. 2a), $s_i=s_{\max}$, $s_{\max}<\left(\frac{FQ}{\alpha\lambda P_b l(2k+(\delta_1+\delta_2)\Delta k)}\right)^{\frac{1}{\alpha-1}}$. If $\lambda_1=0$, $\lambda_2=0$, from Equation (5-A. 2a), (5-A. 2b) and (5-A. 2c), $s_i=\left(\frac{FQ}{\alpha\lambda P_b l(2k+(\delta_1+\delta_2)\Delta k)}\right)^{\frac{1}{\alpha-1}}$, $s_{\min} \leq s_i \leq s_{\max}$. If $\lambda_1=0$, $\lambda_2>0$, from Equation (5-A. 2e) and (5-A. 2a), $s_i=s_{\min}$, $s_{\min}>\left(\frac{FQ}{\alpha\lambda P_b l(2k+(\delta_1+\delta_2)\Delta k)}\right)^{\frac{1}{\alpha-1}}$.

In summary, assuming $v_{\delta_1\delta_2} = \left(\frac{FQ}{\alpha\lambda P_b l(2k+(\delta_1+\delta_2)\Delta k)}\right)^{\frac{1}{\alpha-1}}$, the optimal speed is:

$$s_i = \begin{cases} s_{\max} & (s_{\max} < v_{\delta_1\delta_2}) \\ v_{\delta_1\delta_2} & (s_{\min} \leq v_{\delta_1\delta_2} \leq s_{\max}) \\ s_{\min} & (s_{\min} > v_{\delta_1\delta_2}) \end{cases} \qquad \text{(5-A. 3)}$$

The maximized profit equals to:

$$\pi_i(\delta_1,\delta_2)^* = \begin{cases}(k+\delta_i\Delta k)\left[\frac{G}{(2k+(\delta_1+\delta_2)\Delta k)^{\frac{\alpha}{\alpha-1}}} - OC\right] - \delta_i \Delta k r P & if\ s_{\min} \le s^* \le s_{\max} \\ (k+\delta_i\Delta k)\left[\frac{F\gamma Q s_e}{l(2k+(\delta_1+\delta_2)\Delta k)} - \lambda P_b s^e - OC\right] - \delta_i \Delta k r P & otherwise\end{cases} \quad (5\text{-A. }4)$$

5-B. Properties of the term $N(\delta_j)$

5-B.1 Comparison between N(1) and N(0)

In order to comparing $N(1)$ and $N(0)$, we make a difference between them:

$$N(1) - N(0) = \frac{k+\Delta k}{(2k+2\Delta k)^{\frac{\alpha}{\alpha-1}}} - \frac{2k+\Delta k}{(2k+\Delta k)^{\frac{\alpha}{\alpha-1}}} + \frac{k}{(2k)^{\frac{\alpha}{\alpha-1}}} \quad (5\text{-B. }1)$$

Equation (5-B. 1) equals to when α=3:

$$\frac{1}{2}\left[\left(\frac{1}{\sqrt{2k}} - \frac{1}{\sqrt{2k+\Delta k}}\right) - \left(\frac{1}{\sqrt{2k+\Delta k}} - \frac{1}{\sqrt{2k+2\Delta k}}\right)\right] \quad (5\text{-B. }2)$$

Let $f(x)=\frac{1}{\sqrt{x}} = x^{-0.5}$ and substitute $f(x)$ into Equation (5-B. 2):

$$\frac{1}{2}[(f(2k) - f(2k+\Delta k)) - (f(2k+\Delta k) - f(2k+2\Delta k))] \quad (5\text{-B. }3)$$

Since $f'(x) < 0$ and $f''(x) > 0$, it is straight forward to see that $f(2k+\Delta k)<f(2k)$, $f(2k+2\Delta k)<f(2k+\Delta k)$, and $f(2k)-f(2k+\Delta k)>f(2k+\Delta k)-f(2k+2\Delta k)$. Therefore, $N(1)>N(0)$.

5-B.2 The sign of $N(\delta_j)$

The expression of $N(\delta_j)$ is from Equation (5-5). First, we assume that $k>\Delta k>0$, i.e., new orders are less than the existing fleet size, and they are both positive. Second, we use α=3 in this discussion. To discuss whether $N(\delta_j)>0$, it equivalent to discuss whether $\frac{k+\Delta k}{k} - \left(\frac{2k+(1+\delta_j)\Delta k}{2k+\delta_j\Delta k}\right)^{1.5} > 0$, or $1 + \frac{\Delta k}{k} > \left(1 + \frac{\Delta k}{2k+\delta_j\Delta k}\right)^{1.5}$.

The Left Hand Side (LHS) is the increasing proportion in investor's own capacity k, while the Right Hand Side (RHS) is the proportional increase in the total market capacity $2k+\delta_j\Delta k$.

The Left-Hand Side (LHS) is the increasing proportion in investor's own capacity k, while the Right-Hand Side (RHS) is the proportional increase in the total market capacity $2k+\delta_j\Delta k$.

Let $m=\Delta k/(2k+\delta_2\Delta k)$ and expand the RHS using a Taylor series approximation:

$$(1+m)^{1.5} \approx 1 + 1.5m + \frac{1}{2}1.5 * 0.5 * m^2 - \frac{1}{6}1.5 * 0.5 * 0.5 * m^3 - \cdots \quad \text{(5-B. 4)}$$

Since the terms that have the negative sign only reduce the value of the RHS of Equation (5-B. 4) and terms that have the positive sign are very small, it is sufficient to check if:

$$\frac{\Delta k}{k} > 1.5m + \frac{1}{4}1.5m^2 \quad \text{(5-B. 5)}$$

Now, because $\Delta k/k$ is at least twice as much as m, substitute m in the RHS of Equation (5-B. 5) with $\Delta k/(2k)$:

$$1.5\frac{\Delta k}{2k} + \frac{1}{4}1.5\left(\frac{\Delta k}{2k}\right)^2 = 1.5\frac{\Delta k}{2k}\left(1 + \frac{\Delta k}{8k}\right) \quad \text{(5-B. 6)}$$

From Equation (5-B. 6), as long as $\Delta k < \frac{8}{3}k$, i.e., the expansion capacity is not larger 2.66 times of its original capacity, the LHS is always larger than the RHS. In other words, the $N(\delta_j)>0$.

5-C. Relationship between $\Delta\pi_i(0)$ and $\Delta\pi_i(1)$ for case *b*2 and *d*1

We construct a reference value $X=\pi_i(1,0,v_{10})-\pi_i(0,0,v_{10})$ for path $b2$ and $Y=\pi_i(1,1,v_{01})-\pi_i(0,1,v_{01})$ for path $d1$. The second term in X, $\pi_i(0,0,v_{10})$, and the first term in Y, $\pi_i(1,1,v_{01})$, can be obtained by substituting the value v_{10} into $\pi_i(0,0)$ and v_{01} into $\pi_i(1,1)$ in Equation (5-1). $\pi_i(0,0,v_{10})$ and $\pi_i(1,1,v_{01})$ equal to:

$$\pi_i(0,0,v_{10}) = G\frac{2(\alpha-1)k+\alpha\Delta k}{2(\alpha-1)(2k+\Delta k)^{\frac{\alpha}{\alpha-1}}} - kOC \quad \text{(5-C. 1a)}$$

$$\pi_i(1,1,v_{01}) = G\frac{2(\alpha-1)k+(\alpha-2)\Delta k}{2(\alpha-1)(2k+\Delta k)^{\frac{\alpha}{\alpha-1}}} - (k+\Delta k)OC - \Delta krP \quad \text{(5-C. 1b)}$$

Substituting $\pi_i(1,0,v_{10})$ and $\pi_i(0,1,v_{01})$ from Equation (5-3) and $\pi_i(1,1,v_{01})$ and $\pi_i(0,0,v_{10})$ from Equation (5-C) into X and Y, we can get:

$$X = G\frac{(\alpha-2)\Delta k}{2(\alpha-1)(2k+\Delta k)^{\frac{\alpha}{\alpha-1}}} - \Delta k(OC+rP) \quad \text{(5-C. 2a)}$$

$$Y = G\frac{(\alpha-2)\Delta k}{2(\alpha-1)(2k+\Delta k)^{\frac{\alpha}{\alpha-1}}} - \Delta k(OC+rP) \quad \text{(5-C. 2b)}$$

The differences between $\Delta\pi_i(1)^{b2}$ and X and between $\Delta\pi_i(0)^{d1}$ and Y equal to:

$$\Delta\pi_i(1)^{b2} - X = G * \left[\frac{k+\Delta k}{(2k+2\Delta k)^{\frac{\alpha}{\alpha-1}}} - \frac{k+\frac{(\alpha-2)}{2(\alpha-1)}\Delta k}{(2k+\Delta k)^{\frac{\alpha}{\alpha-1}}}\right] \quad \text{(5-C. 3a)}$$

$$\Delta\pi_i(0)^{d1} - Y = G * \left[\frac{k+\frac{\alpha}{(2\alpha-2)}\Delta k}{(2k+\Delta k)^{\frac{\alpha}{\alpha-1}}} - \frac{k}{(2k)^{\frac{\alpha}{\alpha-1}}}\right] \quad \text{(5-C. 3b)}$$

The term $\frac{k+\Delta k}{(2k+2\Delta k)^{\frac{\alpha}{\alpha-1}}} - \frac{k+\frac{(\alpha-2)}{2(\alpha-1)}\Delta k}{(2k+\Delta k)^{\frac{\alpha}{\alpha-1}}}$ in Equation (5-C. 3a) can be re-written as comparing $1 + \frac{\frac{\alpha}{2\alpha-2}\Delta k}{k+\frac{(\alpha-2)}{(2\alpha-2)}\Delta k}$ and $\left(1 + \frac{\Delta k}{2k+\Delta k}\right)^{\frac{\alpha}{\alpha-1}}$. Similarly, the term $\frac{k+\frac{\alpha}{(2\alpha-2)}\Delta k}{(2k+\Delta k)^{\frac{\alpha}{\alpha-1}}} - \frac{k}{(2k)^{\frac{\alpha}{\alpha-1}}}$ in Equation (5-C. 3b) can be rewritten as comparing $1 + \frac{\alpha\Delta k}{2\alpha-2k}$ and $\left(1 + \frac{\Delta k}{2k}\right)^{\frac{\alpha}{\alpha-1}}$. When α=3, the difference between the square of these two terms for Equation (5-C. 3a) and Equation (5-C. 3b) is:

$$\left(1 + \frac{\frac{3}{4}\Delta k}{k+\frac{1}{4}\Delta k}\right)^2 - \left(1 + \frac{\Delta k}{2k+\Delta k}\right)^3 = \frac{8(k+\Delta k)^2\Delta k^2(3k+\Delta k)}{(4k+\Delta k)^2(2k+\Delta k)^3} \quad \text{(5-C. 4a)}$$

$$\left(1 + \frac{3\Delta k}{4k}\right)^2 - \left(1 + \frac{\Delta k}{2k}\right)^3 = -\frac{\Delta k^2(3k+2\Delta k)}{16k^3} \quad \text{(5-C. 4b)}$$

Therefore, Equation (5-C. 4a)>0, and Equation (5-C. 4b)<0. Then, we have the following relationship:

$$\Delta\pi_i(1)^{b2} > X \quad \text{(5-C. 5a)}$$

$$\Delta\pi_i(0)^{d1} < Y \quad \text{(5-C. 5b)}$$

As $s_{max} > v_{10}$ for path $b2$ and $v_{11} < s_{min}$ for path $d1$, we have:

$$\pi_i(0,0,s_{max}) > \pi_i(0,0,v_{10}) \quad \text{(5-C. 6a)}$$

$$\pi_i(1,1,v_{11}) > \pi_i(1,1,s_{min}) \quad \text{(5-C. 6b)}$$

Subtracting Equation (5-C. 6a) from $\pi_i(1,0,v_{10})$, and subtract $\pi_i(0,1,v_{01})$ from

Equation (5-C. 6b), we get:

$$\pi_i(1,0,v_{10})-\pi_i(0,0,s_{\max})<\pi_i(1,0,v_{10})-\pi_i(0,0,v_{10}) \quad \text{(5-C. 7a)}$$

$$\pi_i(1,1,v_{11})-\pi_i(0,1,v_{01})>\pi_i(1,1,s_{\min})-\pi_i(0,1,v_{01}) \quad \text{(5-C. 7b)}$$

Equation (5-C. 7) is equivalent to:

$$\Delta\pi_i(0)^{b2}<X \quad \text{(5-C. 8a)}$$

$$Y>\Delta\pi_i(1)^{d1} \quad \text{(5-C. 8b)}$$

From Equation (5-C. 5) and (5-C. 8), $\Delta\pi_i(0)^{b2}<X<\Delta\pi_i(1)^{b2}$ and $\Delta\pi_i(0)^{d1}<Y<\Delta\pi_i(1)^{d1}$, showing that $\Delta\pi_i(0)^{b2}<\Delta\pi_i(1)^{b2}$ and $\Delta\pi_i(0)^{d1}<\Delta\pi_i(1)^{d1}$ in both cases.

5-D. Prisoners' Dilemma (transfer case)

For the transfer case, we know the ranges for $s_{\max}$ and $s_{\min}$ satisfy:

$$\begin{cases} \left(\frac{FQ}{\alpha l\lambda P_b\left(2k+(1+\delta_j)\Delta k\right)}\right)^{\frac{1}{\alpha-1}} < s_{\max} < \left(\frac{FQ}{\alpha l\lambda P_b\left(2k+\delta_j\Delta k\right)}\right)^{\frac{1}{\alpha-1}} \\ \left(\frac{FQ}{\alpha l\lambda P_b\left(2k+(1+\delta_j)\Delta k\right)}\right)^{\frac{1}{\alpha-1}} < s_{\min} < \left(\frac{FQ}{\alpha l\lambda P_b\left(2k+\delta_j\Delta k\right)}\right)^{\frac{1}{\alpha-1}} \end{cases} \quad \text{(5-D. 1)}$$

As expanding the capacity of company i would lead to speed reduction to or from the boundary speed, from Equation (5-D. 1), we can get:

$$\frac{F\gamma Q}{2l}s_{\max} > \frac{\alpha G}{2\alpha-2}\frac{1}{\left(2k+(1+\delta_j)\Delta k\right)^{\frac{1}{\alpha-1}}} \quad \text{and} \quad -k\gamma\lambda P_b {s_{\max}}^{\alpha} > -\frac{G}{\alpha-1}\frac{k}{\left(2k+\delta_j\Delta k\right)^{\frac{\alpha}{\alpha-1}}} \quad \text{(5-D. 2a)}$$

$$-\frac{F\gamma Q s_{\min}}{2l} > -\frac{\alpha G}{2\alpha-2}\frac{1}{\left(2k+\delta_j\Delta k\right)^{\frac{1}{\alpha-1}}} \quad \text{and} \quad (k+\Delta k)\gamma\lambda P_b {s_{\min}}^{\alpha} > \frac{G}{\alpha-1}\frac{k+\Delta k}{\left(2k+(1+\delta_j)\Delta k\right)^{\frac{\alpha}{\alpha-1}}} \quad \text{(5-D. 2b)}$$

Substituting Equation (5-D. 2a) and (5-D. 2b) into Equation (5-8b) and (5-8c) respectively, we have:

$$\pi^b(0,0) - \pi^b(1,1) > \frac{G}{\alpha-1}\left(\frac{1.5}{(2k+(1+\delta_j)\Delta k)^{\frac{1}{\alpha-1}}} - \frac{k}{(2k+\delta_j\Delta k)^{\frac{\alpha}{\alpha-1}}} - \frac{1}{(2k+2\Delta k)^{\frac{1}{\alpha-1}}}\right) + \Delta k(OC + rP) \quad \text{(5-D. 3a)}$$

$$\pi^d(0,0) - \pi^d(1,1) > \frac{G}{\alpha-1}\left(\frac{1}{(2k)^{\frac{1}{\alpha-1}}} - \frac{1.5}{(2k+\delta_j\Delta k)^{\frac{1}{\alpha-1}}} + \frac{k+\Delta k}{(2k+(1+\delta_j)\Delta k)^{\frac{\alpha}{\alpha-1}}}\right) + \Delta k(OC + rP) \quad \text{(5-D. 3b)}$$

The RHS of Equation (5-D. 3a) can be written as:

$$\begin{cases} \frac{G}{\alpha-1}N(1) + \Delta k(OC + rP) > 0 & \text{when } \delta_j = 1 \\ \frac{G}{\alpha-1} * J + \Delta k(OC + rP) & \text{when } \delta_j = 0 \end{cases} \quad \text{(5-D. 4)}$$

where $J = \frac{1.5}{(2k+\Delta k)^{\frac{1}{\alpha-1}}} - \frac{1}{(2k+2\Delta k)^{\frac{1}{\alpha-1}}} - \frac{0.5}{(2k)^{\frac{1}{\alpha-1}}}$.

Differentiate J *w.r.t.* k, we can get:

$$\frac{\partial J}{\partial k} = \frac{1}{2}\left[\frac{1}{(2k)^{1.5}} - \frac{1}{(2k+\Delta k)^{1.5}}\right] - \left[\frac{1}{(2k+\Delta k)^{1.5}} - \frac{1}{(2k+2\Delta k)^{1.5}}\right] > 0 \quad \text{(5-D. 5)}$$

Equation (5-D. 5) indicates that, with the increase of k, J will increase. If $k=\Delta k$, it is straight forward to see that $J>0$. Then it is clear that $J>0$ for $k>\Delta k$.

Thus, the RHS of Equation (5-D. 3a) is larger than 0, i.e. $\pi^b(0,0)-\pi^b(1,1)>0$.

Similar, the RHS of Equation (5-D. 3b) equals to:

$$\begin{cases} \frac{G}{\alpha-1}\left[N(1) - N(0) + \frac{1}{2}\left(\frac{1}{(2k)^{\frac{1}{\alpha-1}}} - \frac{1}{(2k+\Delta k)^{\frac{1}{\alpha-1}}}\right)\right] + \Delta k(OC + rP) > 0 & \text{when } \delta_j = 1 \\ \frac{G}{\alpha-1} * N(0) + \Delta k(OC + rP) > 0 & \text{when } \delta_j = 0 \end{cases} \quad \text{(5-D. 6)}$$

Since $N(1)>N(0)$ from Appendix 5-B, the RHS of Equation (5-D. 3b) is positive, then $\pi^d(0,0)-\pi^d(1,1)>0$.

5-E. Comparative static analysis

5-E.1 Comparative static analysis *w.r.t.* P_b

Equation (5-9c) is for the transfer case, from the RHS of the first equation and LHS of the second equation in Equation (5-D. 1), we have:

$$\begin{cases} k\gamma\lambda {s_{max}}^{\alpha} < -G_{P_b} * B(\delta_j) \\ -(k+\Delta k)\gamma\lambda {s_{min}}^{\alpha} < G_{P_b} * A(\delta_j) \end{cases} \tag{5-E. 1}$$

where $G_{P_b} = -\frac{\gamma}{\lambda^{\frac{1}{\alpha-1}}}\left(\frac{FQ}{\alpha l P_b}\right)^{\frac{\alpha}{\alpha-1}}$.

Substitute Equation (5-E. 1) into Equation (5-9c):

$$\frac{\partial \Delta\pi_i(\delta_j)^{trs}}{\partial P_b} = \begin{cases} \frac{\partial \Delta\pi_i(\delta_j)^{b}}{\partial P_b} < G_{P_b} * N(\delta_j) \\ \frac{\partial \Delta\pi_i(\delta_j)^{d}}{\partial P_b} < G_{P_b} * N(\delta_j) \end{cases} \tag{5-E. 2}$$

In Equation (5-E. 2), $G_{P_b}<0$ and $N(\delta_j)>0$, then we have $\frac{\partial \Delta\pi_i(\delta_j)^{trs}}{\partial P_b} < 0$.

5-E.2 Comparative static analysis *w.r.t.* λ

From Equation (5-D. 1), we have the following inequality:

$$\begin{cases} k\gamma P_b {s_{max}}^{\alpha} < -G_\lambda * B(\delta_j) \\ -(k+\Delta k)\gamma P_b {s_{min}}^{\alpha} < G_\lambda * A(\delta_j) \end{cases} \tag{5-E. 3}$$

Substitute Equation (5-E. 3) into Equation (5-10c):

$$\frac{\partial \Delta\Pi_i(\delta_j)^{trs}}{\partial\lambda} = \begin{cases} \frac{\partial \Delta\pi_i(\delta_j)^b}{\partial\lambda} < G_\lambda * N(\delta_j) \\ \frac{\partial \Delta\pi_i(\delta_j)^d}{\partial\lambda} < G_\lambda * N(\delta_j) \end{cases} \tag{5-E. 4}$$

In Equation (5-E. 4), G_λ<0 and $N(\delta_j)$>0, then we have $\frac{\partial \Delta\pi_i(\delta_j)^{trs}}{\partial\lambda} < 0$ for all the four cases.

5-E.3 Comparative static analysis *w.r.t. F*

From Equation (5-D. 1), we have the following inequality:

$$\begin{cases} -G_F * B(\delta_j) < -\frac{\gamma Qk}{l(2k+\delta_j\Delta k)} s_{\max} < -\frac{G_F k}{(2k+\delta_j\Delta k)(2k+(1+\delta_j)\Delta k)^{\frac{1}{\alpha-1}}} \\ G_F * A(\delta_j) < \frac{\gamma Q(k+\Delta k)}{l(2k+(1+\delta_j)\Delta k)} s_{\min} < \frac{G_F(k+\Delta k)}{(2k+(1+\delta_j)\Delta k)(2k+(1+\delta_j)\Delta k)^{\frac{1}{\alpha-1}}} \end{cases} \tag{5-E. 5}$$

Substitute the LHS of Equation (5-E. 5) into Equation (5-11c):

$$\frac{\partial \Delta\pi_i(\delta_j)^{trs}}{\partial F} = \begin{cases} \frac{\partial \Delta\pi_i(\delta_j)^b}{\partial F} > G_F * N(\delta_j) - \Delta kr{P_F}' = \frac{\partial \Delta\pi(\delta_j)^c}{\partial F} \\ \frac{\partial \Delta\pi_i(\delta_j)^d}{\partial F} > G_F * N(\delta_j) - \Delta kr{P_F}' \frac{\partial \Delta\pi(\delta_j)^c}{\partial F} \end{cases} \tag{5-E. 6}$$

where $G_F = \frac{\partial G}{\partial F} = \gamma\left(\frac{F}{\alpha\lambda P_b}\right)^{\frac{1}{\alpha-1}}\left(\frac{Q}{l}\right)^{\frac{\alpha}{\alpha-1}} > 0$.

Equation (5-E. 6) shows that if $\frac{\Delta k G_F}{2(2k+\Delta k)} \frac{1}{(2k+(1+\delta_j)\Delta k)^{\frac{1}{\alpha-1}}} - \Delta k r P_F{}' < 0$, $\frac{\partial \Delta\pi_i(\delta_j)^b}{\partial F} < 0$; if $\frac{\Delta k G_F}{2(2k+\Delta k)} \frac{1}{(2k+\delta_j\Delta k)^{\frac{1}{\alpha-1}}} - \Delta k r P_F{}' < 0$, $\frac{\partial \Delta\pi_i(\delta_j)^d}{\partial F} < 0$. Since $\frac{1}{(2k+(1+\delta_j)\Delta k)^{\frac{1}{\alpha-1}}} \leq \frac{1}{(2k+\delta_j\Delta k)^{\frac{1}{\alpha-1}}}$, when $\frac{\partial \Delta\pi_i(\delta_j)^d}{\partial F} < 0$, it must be true that $\frac{\partial \Delta\pi_i(\delta_j)^b}{\partial F} < 0$. Therefore, the condition for $\frac{\partial \Delta\pi_i(\delta_j)^{trs}}{\partial F} < 0$ is:

$$F < H\big(2(2k + \Delta k)\big)^{\alpha-1}\big(2k + \delta_j \Delta k\big) \tag{5-E. 7}$$

where $H = (\alpha\lambda P_b)\left(\frac{r P_F{}'}{\gamma}\right)^{\alpha-1}\left(\frac{l}{Q}\right)^{\alpha}$.

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