Managerial Rules for Recovering from a Disruption Event in Liner Shipping

A thesis submitted for the degree of Doctor of Philosophy

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Abstract

The aim of this study is to propose managerial rules for recovering from a disruption event in liner shipping. A critical realism philosophy is adopted in the design of the research. Optimisation and an experimental methodology which follows the critical realism paradigm is used as a framework. Particle swarm optimisation (PSO) is an optimisation model in which various rules are implemented to search for the optimal option to recover from a disruption problem. Solution representations for two options, speeding up and skipping, have been designed. A case study of a trans-Pacific route is used to generate novelty in the model under various configurations of degrees of disruption, maximum speeds, fuel prices, time windows and skipping penalties. The results show that the skipping option performs better than the speeding up option when there is a large amount of delay. The port skipping option is more valuable when the maximum speed limit of a vessel is low. The option of port skipping saves more total cost than the option of speeding up when fuel prices increase. Particularly, a vessel which applies the skipping option can save more total cost than one which applies the speeding option when there are high fuel prices and high degrees of disruption. In other words, speeding up is recommended in the case of low fuel prices and low degrees of disruption. The speeding option is recommended when a vessel faces a short delay and has a long time window. In contrast, the skipping option is more valuable when there is a long delay and a short time window. The higher the skipping delay penalties, the more valuable the speeding option is.

Keywords: Liner shipping, disruption, meta-heuristics, PSO

Chapter 1. Introduction

Chapter 1 presents an overview of the research. The research background is described followed by the research aim and objectives. The research scope bounding the study is demonstrated. The research methodology which addresses the research question is provided. Finally, the thesis structure is presented as a guide to the remaining chapters.

1.1 Research Background and Motivation

Marine transport is a major mode of international trade that links transport networks to support supply chains. Over a few decades, there has been a significant increase in international seaborne trade volume. From 1980 to 2015 the United Nations Conference on Trade and Development (UNCTAD) states that it has increased from 3,704 million tons to 10,048 million tons (UNCTAD, 2016). Given this growth, the world marine fleet shows the same increasing trend to cover its market. UNCTAD (2016) report that the world fleet rose from 1,745,922 to 1,806,650 thousand deadweight tons from 2015 to 2016. The highest percentage increase was for container shipping.

Liner shipping is a marine transport mode in which vessels sail according to a preannounced schedule. To pursue operational excellence, an appropriate interrelated network usually needs to be planned. In practice, when a vessel starts a journey it may not be able to follow the planned schedule because of delay. For example, a ship liner may not be able to access a port, because of the low availability of tug boats or tidal windows, or it may not be able to depart the port on time due to congestion or low productivity at the port (Notteboom, 2006). Unexpected situations may arise, such as labour strikes or severe weather conditions.

The obvious negative impacts of such uncertainties and disruptive events affect supply chains (Vernimmen et al., 2007). Terminal operators may need to reorganise berthing time slots for vessels. Other operations, such as yard planning, and inland transport, such as truck and rail, may also have to be rescheduled. Additionally, shippers who are the owners of cargo may need to increase inventory levels to ensure enough cargo is sent to manufacturers. Most importantly, the shipping line itself is faced with an increase in operating costs, including capital, crewing, bunkers, etc.

A popular approach to handling disruption is the speed-up option, which aims to increase speed to recover delay due to disruption. According to prior studies, there can be speed optimisation problems if a vessel tries to speed up to avoid uncertainties or disruption events (Fagerholt et al., 2010; Qi and Song, 2012). In recent literature, Aydin et al. (2017) recommend speeding up a vessel to recover from uncertainty.

Apart from the speeding up strategy, Notteboom (2006) suggests many other options. The first option is accelerating port turnaround time. This can be done in a port that has high productivity in order to catch up with a preannounced schedule. The second option is skipping unimportant ports of call and using another feeder to transport the containers to the skipped ports later. Third, a vessel can skip unimportant ports of call first but return to the skipped ports later. A fourth option is cut-and-run. This option means a vessel leaves the port before finishing the planed unloading and loading of containers to avoid delay from a low tide situation. Finally, a shipping line may insert an idle vessel to recover delay.

In spite of the existence of various strategies, we do not know which strategy needs to be used in which circumstance. Few scholars have compared the ability of each strategy to handle disruption.

Brouer et al. (2013) suggest speeding up or slowing down a vessel to avoid disruption events in the network design. Also, one vessel in the fleet may be able to skip some ports and charter another to ship containers to the skipped port (called the skipping option in this thesis). Another option is for a vessel to skip some ports but return to the skipped port later to deliver the containers itself (called the swapping option in this thesis).

Li et al. (2015) recommend the same options as Brouer et al. (2013), speeding up or slowing down vessels, skipping and swapping. However, they model the problem differently. Li et al. (2015) use nonlinear programming (NLP) to model the speed optimisation problem of a single vessel without a specified time window. In other words, a vessel should arrive to the exact predefined schedule without any allowable time window. The skipping option is defined by adding the unloading and loading time of the skipped containers at the port to which they are shipped. However, it does not include the time spent chartering another vessel to transport containers back to their destination, but this can be done by booking the slot for the misconnected containers from the same ship liner company. The operational definition of the swapping option is the same as Brouer et al. (2013). The experiment is conducted with various configurations of sailing distances, degrees of delay, delay penalty functions, maximum speed limits, and fuel prices.

Li et al. (2016) consider regular uncertainty and disruption events with and without time windows in a multi-stage stochastic model. The difference in this model from the study mentioned above is that a disruption event can occur at any port during the voyage and a vessel can learn where there is a disruption event at any waypoint at sea and be able to avoid it by appropriate vessel speed and port turnaround time options. Two operational rules at each port of call, first come first served (without a time window) and service agreed within predefined time (with a time window), are set. The skipping option is also experimented with to see whether it can provide lower costs and be able to meet predefined port arrival times. A trans-Pacific route is used as a case study.

However, such comparisons have the following limitations. First, the contribution of Brouer et al. (2013) proposes a mixed integer programming (MIP) model to solve disruption problems for multiple vessels, but lacks a summary of the prescription of which options should apply to which condition of vessels in the fleet. Second, Li et al. (2015) provide prescriptive rules on how to recover from the disruption in each configuration, but there are limitations in terms of time window constraints and skipping penalties. Third, Li et al. (2016) aim to avoid recovering regular uncertainty and disruption events. Even though disruption event is uncertain and unpredictable in nature, reactive actions that focus on decisions after disruption events is not necessary to consider the model to be stochastic one. Given the limitations mentioned, this study focuses on the comparison between the speeding up and skipping options to recover from disruption event with various configurations of degrees of disruption event, maximum speed limits, fuel prices, time windows and skipping penalties, using the deterministic model.

1.2 Research Aim and Objectives

The aim of this research is to provide operational rules to recover a vessel when a disruption happens at a particular location during the voyage. In particular, this study compares two popular disruption handling strategies, speeding up and port skipping. The possible approaches are speeding up or slowing down a vessel and port skipping in various design configurations. In order to achieve the aim, the following objectives must be accomplished.

1. Understand the existing body of knowledge by conducting a comprehensive literature review. The main focus of the review is on the topic of liner shipping. Related problems in strategic, tactical planning and operational levels are reviewed. The second key literature category is disruption problems. Similar disruption problems, in air transportation, are reviewed.
2. Develop an optimisation model for a single vessel when disruption happens during a journey and how to cope with such a disruption by speeding up or skipping, as recommended by the existing literature.
3. Implement the optimisation model in a C# software package.
4. Verify and validate the model against the existing theory in the literature.
5. Conduct an experiment to propose a prescriptive theoretical framework for handling a disruption event that can contribute to the body of knowledge.

1.3 Research Scope

The main theory framing this research is in the disciplines of operational research (OR), management science (MS) and optimisation theory, to which the disruption problem of liner shipping belongs. The territory of the literature is therefore in the context of liner shipping, the disruption problem in many forms of transportation and managerial rules for suggesting options to deal with disruption in liner shipping. Normally, there are two principle aims of this field: first, formulating an optimisation model to represent the actual operating system and propose a better algorithm than the benchmark to solve such a problem, which makes a contribution to the methodological literature by improving the efficiency and effectiveness of the algorithm; and second, providing a prescriptive framework for application to the specific problem. The scope of this research is to make a theoretical contribution to disruption in liner shipping in the OR and MS literature.

The study focuses on comparison between the speed-up and skipping strategies. Among the strategies not included are speeding up port calls, swapping, cut-and-run, and insertion of idle vessels. The reason for this is that these options need to be evaluated on a case by case basis (Dirksen, 2011; Li et al., 2015; Li et al., 2016). First, for speeding up port calls, ship lines and ports need close contact. Second, even though Li et al. (2015) and Dirksen (2011) include port swapping option in their studies, they state that the rules cannot be generalisable but are made on a case by case basis. Third, the model does not include the accessibility of ports, or cut-and-run options, which do not have practical use. Finally, it is rare for an operational manager to use an idle vessel to recover a disruption event because of the high cost of vessels.

The optimisation model is based on the deterministic model of Li et al. (2015) due to the drawbacks of the stochastic model which is time-consuming and does not provide significantly different results in terms of solution quality. Even though they present structural rules for degrees of disruption event, maximum speed limits and fuel prices, the experiment of Li et al. (2015) lacks configurations of time windows and skipping penalties. We therefore include time windows and skipping penalties in addition to degrees of disruption event, maximum speed limits and fuel prices to compare the speeding up and skipping options.

1.4 Research Methodology

The majority of management studies research follows the inductive or deductive approach. The concept of the inductive approach is to formulate theory from case studies or ground theory, while the deductive approach tests the existing theory and generalises to a boarder population. Descriptive models particularly identify factors for policy makers.

The aim of this study is to formulate a prescriptive framework to deal with a disruption event in liner shipping. The study of OR or MS disciplines which always apply optimisation (or simulation) methodology is suggested for this research. The advantages of this methodology is that it combines both deductive and inductive characteristics (Harrison et al., 2007). The process first derives an optimisation model from existing theories and assumptions deductively, then generates new findings from experiments to establish new theories inductively. Therefore, the managerial rules for recovering a disruption event from when a vessel embarks until it completes a journey is recommended with various design configurations of degrees of disruption event, maximum speeds, fuel prices, time windows and skipping penalties.

1.5 Thesis Structure

The document is structured as follows:

Chapter 1: Introduction

This chapter presents the background and motivation for the research. It outlines the research aim and objectives. The research territory and research methodology that shape the study are highlighted.

Chapter 2: Literature Review

The literature review is in 2 main sections. The first relates to the liner shipping context and describes strategic, tactical and operational planning relevant to disruption in various types of transportation, both air and marine. The similarities and differences of each type are compared and contrasted to investigate why disruption problems in liner shipping are essential to study. The second section presents the recovery rules for disruption problems in liner shipping literature in order to suggest appropriate options to handle such disruption.

Chapter 3: Methodology

Optimisation and simulation in management studies are described and a roadmap of how to conduct experimental studies is presented.

Chapter 4: Model Formulation

The mathematical formulation of disruption in liner shipping is demonstrated.

Chapter 5: Experiment and Results

The experimental design and model validation are presented in this section.

Chapter 6: Discussion

This section presents the discussion, theoretical contribution and practical implications.

Chapter 7: Conclusion, Limitations and Future Research

The conclusion, limitations and future research are given in the final section.

Chapter 2. Literature Review

In this chapter, it is divided into 4 main sections. The first section relates to mode of transportation. The second section focuses on the liner shipping context and describes strategic, tactical and operational planning. The third section explains the disruption problem in various types of transportation, both air and marine. The similarities and differences of each type are compared and contrasted to investigate why disruption problems in liner shipping are essential to study. The final section presents the limitations of previous literature related to recovery rules for disruption problems in liner shipping literature in order to suggest appropriate options to handle such disruption.

2.1 Modes of Transportation

Transportation plays a crucial role in moving objects such as people or goods from one place to another. Important modes of transport are water, air and road which each have an industry, that operate under different conditions (Lee and Song, 2017; Christiansen et al., 2007). Vessels and aircraft typically carry cargo across the sea in order to fulfil international trade, while trucks receive products from vessels or aircraft to move to door-to-door destinations. One similarity between vessel and aircraft operation is that both have to pay port fees to cross national borders whereas trucks do not. The bills received from airlines are electronic, while maritime bills are still paper-based. Another important similarity between ship and plane transport is that both face higher uncertainty than truck transport because of weather conditions which are difficult to predict.

Turning to the differences between marine and air transportation, the majority of aircraft carry passengers, whereas vessels carry cargo across the ocean. Marine transportation takes many days or weeks due to its lower speed. In contrast, aircraft can fly at high speed, taking just hours or days to arrive at destinations. Passengers do not always care to travel overnight, while it does not matter for cargo. Therefore, we rarely see airlines operating around the clock, but ships do. On the other hand, even though trucks carry cargo, they transport cargo within a region. Hence, they do not need to operate around the clock. Vessels have larger capacities than aircraft, but aircraft move faster than vessels, therefore aircraft attract high-value low-volume cargoes.

Most aircraft carry similar amounts of cargo or passengers, while there are various sizes of cargo carried by ship. This means there is a large variety of fleet designs. There is also a constraint in the compatibility between ports and vessels, unlike other modes, because of tides and sizes. In addition to variations in physics in marine transport, economic aspects also fluctuate in the ship market. The cost structures of two vessels which are almost identical may be quite different. Service differentiation is more important for airlines than maritime transport, because the freight of the air industry is human, while for the marine industry it is cargo. Low service differentiation emphasises cost-based rather than revenue-based strategy to compete. Therefore, the marine sector usually makes alliances with other companies. A summary of the similarities and differences is presented in Table 2.1.

Table 2.1: Comparison of different types of transportation (Lee and Song, 2017; Christiansen et al., 2007)

Operational configuration	Mode of Transportation		
	Maritime	Airline	Road
Trade type	International	International	Regional
Port fee	Yes	Yes	No
Type of bill	Electronic	Paper	NA
Operational uncertainty	High	High	Low
Voyage length	Days or weeks	Hours or days	Hours or days
Engine speed	Low	High	NA
Majority types of shipment	Cargo	Passenger	Cargo
Operating around the clock	Always	Rarely	Rarely
Capacity carried	Large	Medium	Small
Value of cargo	Low	High	NA

Multiple types of shipment	Yes	No	Yes
Fleet variety in terms of physics and economics	High	Low	Low
Compatibility of vessel and port	Yes	Rarely	No
Service differentiation	Low	High	NA

Due to these differences, there is a need to investigate various types of transportation differently. According to Christiansen et al. (2007), the vast majority of literature studies truck and airline transport. This study therefore focuses on marine transport, particularly liner shipping, as described in the next section.

2.2 Liner Shipping

The world population growth, the demand for a high standard of living and competition for local resources increase the requirement for international trade. Maritime transportation has therefore seen a rapid growth over the last few decades. Even though there is a high necessity for real world shipping operation, research in this area falls behind the reality.

Ronen (1983) and Christiansen et al. (2007) suggest reasons for the lack of attention to maritime transport in literature; firstly, the low visibility of ships. Most companies normally transport cargo by truck due to the advantage of indoor accessibility. Research organisations sponsor research on road, rail and air transportation. People in most regions see trucks, aircraft and trains but do not see ships. The second reason is that it is difficult to customise decision support systems because of the wide variety of operating systems and problem structures. Thirdly, there is high uncertainty in maritime operation. Sometimes, vessels are delayed by weather conditions, machine breakdown or labour strikes. Sometimes, they are delayed by high congestion or low productivity at the port. In the planning stage, given the high cost of planning a lot of buffer time, vessels are often rescheduled instead. Most importantly, the shipping industry has a long history going back thousands of years. Shipping companies are therefore not willing to share data or concerns with researchers.

However, due to the recent advancement of computer technology, there is an awareness of the importance of decision support systems, which can help liner shipping companies operate more efficiently and effectively, Maersk Line, the world leading liner company, has begun to collaborate with academic researchers to develop a decision support system that can solve practical problems on a large scale (Meng et al., 2014). The increased volume of world seaborne trade, of various types, from 30,823 to 54,800 billons of ton-miles between 2000 and 2016 is shown in Table 2.2. This has caught the attention of the research community.

Table 2.2: World seaborne trade, by type of cargo, from 2000 to 2016 (billons of ton-miles) (UNCTAD, 2016)

Type of cargo (billions of ton-mile)/ year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Chemicals	552	552	593	606	625	651	689	724	736	765	824	864	889	908	914	953	998
Gas	576	591	611	662	719	736	833	913	956	958	1,147	1,344	1,346	1,347	1,392	1,467	1,561
Oil	9,631	9,352	8,971	9,698	10,393	10,729	11,036	11,011	11,200	10,621	11,237	11,417	11,890	11,779	11,717	12,059	12,410
Containers	3,170	3,271	3,601	4,216	4,785	5,269	5,757	6,422	6,734	6,030	6,833	7,469	7,673	8,076	8,237	8,428	8,757
Other (minor bulk commodities and other dry cargo)	9,998	10,023	10,167	10,275	10,729	10,782	11,330	11,186	11,272	10,325	11,504	11,927	12,375	12,952	14,707	14,892	15,156
Main bulk commodities	6896	7,158	7,331	7,852	8,527	9,107	9,745	10,503	11,028	11,400	12,824	13,596	14,691	15,312	15,768	15,790	15,918
Total	30,823	30,947	31,274	33,309	35,778	37,274	39,390	40,759	41,926	40,099	44,369	46,617	48,864	50,374	52,735	53,589	54,800

Davarzani et al. (2016) review the literature related to green port and maritime logistics. A systematic literature (bibliometric and network) analysis tool is used to identify the key literature and provide fundamental knowledge on concept, theory, tools and technique, as well as identify the key investigators, collaboration patterns, research clusters, interrelationships and seminal research areas.

Song et al. (2016) study modelling port competition from a transport chain perspective. They take an analytical approach and use a non-cooperative game model in the study. A novel port competition problem involving both hinterland shipments and transhipment cargoes is analysed from a transport chain cost perspective, taking into account port handling charges, deep sea transport costs, hinterland transport costs, and feeder service costs. Case studies of Southampton and Liverpool ports are presented for their managerial implications.

Generally, there are three types of marine transportation, industrial, tramp and liner, that match the needs of various cargos (Lawrence, 1972). Industrial shippers usually carry raw materials or processed materials in their own vessels to destinations with the aim of operating cost minimisation. Tramp operators typically do not own their cargos, but pick up containers and bulk commodities at ports according to shipper’s demands, in order to maximise revenue. In other words, operations of this type are similar to taxicabs. In contrast to tramp ships, liners usually transport final manufactured goods in containers according to a fixed published schedule. In other words, this type of ship operates similar to a bus service. In order for the liner to meet its published departure dates, three decision-making levels are given in the literature. Table 2.3 summarises the terms used in this study.

Table 2.3: Nomenclature

Word	Definition
Liner shipping network design problem	This problem aims to determine the ports, and the sequence of ports, container vessels should visit, and the frequency and speed of vessels.
Fleet size and mix problem	This problem aims to determine the number and type of vessels to serve demand. It consists of 2 stages of decision-making, firstly which ships to operate, and secondly which route each ship should

	sail and the number of voyages along each route. The first is a strategic problem and the second is a fleet deployment problem, used to find the best solution for fleet size and mix. If demand changes, the second problem can be resolved when there is available fleet size.
Fleet deployment problem	This problem aims to assign a number and type of ships to predefined routes to meet demand.
Planned earliest arrival time	The earliest pre-defined time which liner shipping and ports of call agree to start loading and unloading. If vessels arrive before this time, they have to wait.
Planned latest arrival time	The latest pre-defined time which liner shipping and ports of call agree to start loading and unloading. If vessels arrive later than this time, they are penalised.
Time window	The planned earliest and latest arrival time of a vessel at a port of call.
Transit time	The time window for containers
Sea contingency time	Buffer time for uncertainty at sea. It depends on the distance between each leg. If it is a long voyage, the sea contingency time is high, because of the high uncertainty.
Vessel route	The sequence of ports that a vessel has to visit.
Vessel schedule or service	The pre-announced time or time window for each port of call that a vessel has to follow on its route.
Bunker consumption	The fuel consumption of the main engine. The specific type of fuel is IFO380.
Main engine	The engine which vessels activate at sea.
Auxiliary	The engine which vessels activate in the mooring period (Du et al.,

engine	2011).
IFO 380 fuel price	The price of the specific type of fuel consumed by the main engine. This type of fuel is cheaper than marine gas oil (MGO) fuel.
MGO fuel price	The price of distillates from the refinery process with much lower viscosity and sulphur content below 0.1% (Panagakos, Stamatopoulou and Psaraftis, 2014; Notteboom and Vernimmen, 2009).
Time charter rate	The market rate of a vessel including the cost of chartering a container vessel in the fleet or chartering out an owned vessel to another carrier (Brouer et al., 2014a).
long-haul liner service route	Large containerships operating across continents calling at hub ports (Meng and Wang, 2011b).
feeder liner service routes	Small containerships operating within a region calling at spoke ports (Meng and Wang, 2011b).

2.2.1 Strategic Planning

For long-term planning (around 20-30 years), key decisions include alliance strategies, fleet size and mix, network design and ship design.

Agarwal and Ergun (2010) utilise concepts from mathematical programming and game theory to design a mechanism to guide carriers in an alliance to pursue an optimal collaborative strategy. The mechanism provides side payments to the carriers, as an added incentive, to motivate them to act in the best interest of the alliance while maximising their own profits. They suggest a mechanism to help carriers form sustainable alliances.

In addition to alliances, in the long run, appropriate size and a proper number of vessels should be planned to reduce seasonally uncertain demand. An optimal fleet depends on how long the trade route is (port time and sailing time) and how often services run. For example, Ng (2015) tries to find how many and what types of ship should be deployed, considering how liner shipping can obtain such vessels. In other words, the vessels can be chartered from other ship owners or from the liner itself. To make decisions that minimise total costs, container shipping demands, which are random on each leg, are taken into account. Meng and Wang (2010) handle uncertain demand by assuming demand between each port, with normal distribution.

Fleet expansion and ship size need to be planned in the long term. Tran and Haasis (2015) make an empirical study of the effects of fleet capacity and ship size as well as slot utilisation level, market freight rate and oil price on revenue and cost of shipping lines over the period 1997–2012. The findings show the relationship between ship size and financial indicators. There is a positive influence of slot utilisation level and market freight rate, and a negative influence of oil price, on the financial results of liner carriers.

One important strategy in planning liner shipping is good network design, which means finding the sequence of ports a vessel should visit to minimise total cost and prevent, as far as possible given typical uncertainties, delay at all ports of call. There are many studies in this area which deal with regular uncertainties in deterministic ways, since the network design problem itself is an NP-hard problem. If considered in a stochastic way, it is more difficult to find solutions. Therefore, many papers use deterministic, rather than stochastic ways of designing networks to save computational time. Liner network design can be classified into four categories (Meng et al., 2014).

The first type is a feeder network (Fagerholt, 1999; Sambracos et al., 2004). The characteristic of this type of network is that it consists of a main hub port, which is the origin or destination of the containers, and several small ports. The second type is the liner network design without transhipment ports (Chuang et al., 2010; Shintani et al., 2007). This type aims to cover long term uncertain demands by designing a few liner service routes without operation at transhipment ports. The third type of network is a hub and spoke network (Baird, 2006; Gelareh, Nickel and Pisinger, 2010). The main characteristic of this type is that a vessel can transport containers from hub ports to other hub ports to tranship them to spoke ports in the same region. Finally, the most complicated type is a general liner shipping network composed of more ports and transhipment operations (Meng and Wang, 2011a).

Karsten et al. (2015) include time constraints in liner shipping network design. Direct transportation between each port of call provides low transit time. This catches the attention of the shipper but at the expense of high operational cost because there is not enough container demand to fill the vessel or the high speed required to catch up with the low transit time constraint. An improvement heuristic is proposed to compare the effectiveness of the algorithm with the benchmark problem from Brouer et al. (2014a), using LINER-LIB data.

Brouer et al. (2014a) propose a set of benchmarks for a liner shipping company, using real-life data from Maersk Line and other liner shipping companies. Liner shipping network design, which has the characteristic of transhipment on butterfly routes, is presented by an integer programming model. The data objects include port lists, fleet lists, cargo demand lists, and graph and distance lists. The attribution of port lists consists of Unicode of port, port name, country in which the port is located, the territory which a vessel can operate in within a region, the region of port location, latitude, longitude, draft, move, cost of a full transfer for transhipment, fixed port call cost, and variable cost which is a function of capacity. The attribution of fleet lists consists of the category of vessel, its capacity, design draft, minimum and maximum speed, design speed, daily bunker consumption, number of vessels in the fleet, Suez Canal fee and Panama Canal fee. Distance class consists of origin and destination port, distance between each port, draft limit, Suez traversal and Panama traversal. Demand class comprises origin and destination port, quantity, freight rate and maximum transit time.

Brouer et al. (2014b) propose a meta-heuristic algorithm for the liner network design problem. Constructive heuristics are designed by transforming the problem into an instance of the multiple quadratic knapsack problem. An improvement heuristic uses mixed integer programming to select a set of port insertions and removals on each service. The comparison of solution quality and computational results are made against the benchmark problem from Brouer et al. (2014a), using LINER-LIB data.

Bell et al. (2011) study a container assignment model for the liner network design problem and propose a frequency-based maritime container assignment model using an analytical model and Excel solver.

Liu et al. (2014) present a global intermodal liner network design problem. Gate port allocation is modelled by integer programming (IP) or integer linear programming (ILP) and solved IP by CPLEX software. The network evaluation model is a MIP model solved by CPLEX. For the large scale problem, a simulation based framework is implemented to propose converting inland origin–destination demand from another model of transportation to the port-to-port demand model. Finally, a heuristic algorithm is used to solve the problem.

Mulder and Dekker (2014) demonstrate a linear programming (LP) model for the liner network design problem. The paper combines the fleet design problem, scheduling problem and cargo routing problem. The aim of the study is to compare the composite solution approach with a reference network (Mulder and Dekker, 2013). The problem is tested on the Asia–Europe trade lane of Maersk.

Noshokaty (2013) optimises voyage gross profit, subject to deterministic or stochastic cargo demand. The sensitivity is decided based on the effect of cargo quantity or freight, cargo handling rate or charges, and ship speed or fuel consumption. In a competitive environment with old ships, shipping optimisation systems (SOS) optimally allocate new ships to lines in order to figure out their prospective gross profit, and appraise their worthiness.

Wang and Meng (2014) design a liner network design problem with a deadline. A sequence of ports of call and ships are determined for each itinerary. So as to maximise total profit, the model determines how to transport containers with the deployed ships. The model is formulated by mixed-integer non-linear non-convex programming and proposes a column generation based heuristic method to solve the problem. An experiment using an Asia–Europe trade lane shows that the proposed algorithm provides a good quality solution.

Wang et al. (2014) study a cargo allocation, ship routing and scheduling problem. Mixed-integer nonlinear programming (MINLP), and CPLEX and GUROBI software are applied to MIP by linearising non-linear terms. Managerial implications are presented via a case study of an Asia-Europe trade lane.

Wang et al. (2015) study a container assignment model for a liner network design problem. MINLP, an analytical approach, and MATLAB and CPLEX 12.1 software

are used to solve linear optimisation models and mixed-integer linear optimisation models. The model extends the container assignment model from Bell et al. (2011) to maximise profit. A tactical level profit-based container assignment problem with known demand from historical data is first modelled to improve the liner network. Then, an operational level profit-based container assignment which aims to maximise profit is designed. A case study of an Asia–Europe–Oceania network is presented for managerial rules.

In strategic planning, ship design is another important problem. Lai et al. (2013) apply a quantitative study to green practices for compliance in shipping design. The findings show a positive relationship between shipping design for compliance (SDC) and service performance and no relationship between SDC and financial performance.

The summary of literature in strategic liner shipping is shown in Table 2.4.

Table 2.4 Summary of Literature in Strategic Liner Shipping

Reference	Problem and major consideration	Approach
Agarwal and Ergun (2010)	Alliance	Game theory
Ng (2015)	Fleet deployment	Stochastic dependency
Meng and Wang (2010)	Fleet size	CPLEX
Tran and Haasis (2015)	Fleet size	Multiple regression
Fagerholt (1999)	Network design	Set partitioning problem
Sambracos et al. (2004)	Network design	Heuristics
Chuang et al. (2010)	Network design	Fuzzy genetic approach
Shintani et al. (2007)	Network design	Genetic algorithm
Baird (2006)	Network design	Quantitative
Gelareh, Nickel and Pisinger (2010)	Network design	Lagrangian method combined with a primal heuristics
Meng and Wang (2011a)	Network design	Exact branch-and-bound based e-optimal algorithm

Karsten et al. (2015)	Network design	Heuristics
Brouer et al. (2014a)	Network design	Base integer programing
Brouer et al. (2014b)	Network design	Meta-heuristics
Bell et al. (2011)	Network design	Excel solver
Liu et al. (2014)	Network design	CPLEX; Heuristics
Mulder and Dekker (2014)	Network design	Composite solution approach
Noshokaty (2013)	Network design	Chance-constrained model
Wang and Meng (2014)	Network design	Column generation based heuristic method
Wang et al. (2014)	Cargo allocation	CPLEX; GUROBI
Wang et al. (2015)	Cargo allocation	MATLAB; CPLEX
Lai et al. (2013)	Ship design	Quantitative

2.2.2 Tactical Planning

For medium term planning (around a few months to a year), fleet deployment is one of the most important problems. This type of problem requires the assignment of vessels to shipping routes in order to maximise profits or minimise costs. Perakis and Jaramillo (1991) are pioneers who studied this problem, using a LP model and fixing both the service frequencies of the different routes and the speeds of the ships.

Meng and Wang (2010) propose a short-term fleet planning problem with cargo shipment demand uncertainty for a single vessel. An ILP model with chance constrained programming is efficiently solved by CPLEX. The impact of chance constraints and cargo demand is investigated in a numerical study.

Wang and Meng (2012a) propose fleet deployment with container transhipment operations. Container transhipment can be operated at any port, any number of times. MIP is formulated and solved by CPLEX. An Asia–Europe–Oceania shipping network is used as a case study for the managerial implications.

Wang et al. (2013c) apply a MIP and joint chance constrained programming model and the sample average approximation method. The problem is solved by CPLEX (v12.1). Their study extends a liner ship fleet deployment problem from Meng and

Wang (2010) aiming to minimise the total cost while maintaining a service level under uncertain container demand. They also propose a sample average approximation method and validate the effectiveness of the solution with a real case study.

Wang et al. (2013a) combine fleet deployment and ship route design in their study. A LP and ε-optimal global optimisation algorithm are designed for the study. Maximum and minimum liner ship route capacity utilisation problems are proposed. Managerial implication is provided by a case study on an Asia-Europe route.

Herrera et al. (2016) propose a prescriptive model to handle a fleet deployment problem relating to an expansion of the Panama Canal, expanding on the study of Wang and Meng (2012a). A MIP model is implemented. Their results demonstrate that there are positive effects on total costs from fleet redeployment of larger vessels to canal-crossing routes. The results show lowered vessel costs and higher utilisation rates.

Dong and Song (2009) combine fleet deployment with empty container repositioning. The system is modelled by event-driven simulation-based optimisation. They focus on a type of parameterised rule-based empty container, repositioning policies to simultaneously optimise fleet deployment, minimising the expected total costs. A case study is conducted.

Dong and Song (2012) extend the fleet deployment problem of Dong and Song (2009) by considering how inland transport times and uncertain demand affect container fleet sizing. A simulation-based optimisation is used. A Trans-Pacific lane and Europe–Asia lane are used to compare cases in which inland transport time is deterministic or stochastic. The results provide useful implications for the problem.

Meng and Wang (2011b) determine service frequency, containership fleet deployment plan, and sailing speed for a long-haul liner service route. MINLP is developed for a given service frequency and ship type. Two linearisation techniques are subsequently presented to approximate this model with a mixed-integer linear program, where the branch-and-bound approach controls the approximation error below a specified tolerance. This paper demonstrates that the branch-and-bound based e-optimal algorithm obtains a globally optimal solution with a predetermined relative optimality tolerance, e, in a finite number of iterations.

Andersson et al. (2015) propose an integrated model of fleet deployment with speed optimisation to compare with a separated one. A rolling horizon heuristic is used to solve the problem. A real case study for deployment and routing problem in RoRo-shipping is used in this study. The results demonstrate that the solution quality is better when fleet deployment is combined with speed optimisation.

Cheaitou and Cariou (2012) study fleet deployment combined with speed optimisation. They propose a slow streaming strategy (increasing the number of vessels but reducing speed) model for perishable products (which need reefer containers, for which the fuel consumption design is different from dry containers and tends to consume more auxiliary bunker) in a Northern Europe–South America trade case study.

Song and Dong (2013) combine fleet deployment, long-haul and empty container repositioning in order to minimise total costs including ship costs, fuel consumption costs, port costs, and laden and empty container costs. Three-stage optimisation (stage 1: number of ships; stage 2: their capacity; stage 3: sailing speeds) is modelled to suggest practical implications for a case study.

Song et al. (2015) propose the combination of a fleet deployment problem with a speed optimisation model, considering uncertain port time in order to simultaneously optimise expected costs, service level and CO2 emissions. A simulation-based non-dominated sorting genetic algorithm is used to solve the problem. A case study is implemented for managerial purposes.

Song and Yue (2016) study fleet deployment by applying a genetic algorithm (GA) to minimise total cost and reduce capacity waste in order to evaluate the efficiency and practicability of real case studies.

Song et al. (2017) study ship deployment, planned sailing speed, and service scheduling of a liner shipping route with both sea and port uncertainties taking multiple objectives from various perspectives, extending from Song et al. (2015) There are 3 objectives of the study: (i) to define key performance indicators (KPIs) in liner shipping service design from various perspectives; (ii) to investigate the relationships between the KPIs and their impact on optimal solutions; and (iii) to evaluate the impact of various speed options on the KPIs and optimal solutions.

Zacharioudakis et al. (2011) combine cost modelling with fleet deployment optimisation. A generic cost model is demonstrated. GA is used in the experimental study with what-if analysis. The model depicts how the initial design of a liner system can be optimised by modifying system attributes to dynamically meet new requirements.

For other fleet deployment problems, we refer to Wang and Meng (2017) for a systematic literature review.

Another element of medium term planning is scheduling design to reduce regular uncertainties. The scheduling problem in liner shipping is planning for the expected arrival time and expected departure time at each port of call on the route. It can reduce the overall costs of a liner company and also increase credibility due to on-time delivery. For example, Dulebenets and Ozguven (2017) propose MINLP for perishable assets, linearised using a set of piecewise linear secant approximations to minimise the total route service cost and the asset decay cost for French Asia Line.

Since it is more useful to consider uncertain factors in shorter term planning, there is literature focusing on uncertain timings both at ports and at sea (Wang and Meng, 2012b). Notteboom (2006), on the other hand, argue that 93.6 percent of delay originates from uncertainties during port operations. Qi and Song (2012) therefore propose a nonlinear stochastic port time model in order to identify the speed of a vessel that can optimise fuel emission. However, since it is very difficult to solve such a model analytically due to nonlinear stochastic constraint, they apply simulation-based stochastic approximation methods to find the near optimal speed that can balance fuel emission and service level.

Wang and Meng (2012c) schedule uncertain wait times, due to port congestion, and uncertain container handling times by MINLP and solve it by a sample average approximation method, linearisation techniques and a decomposition scheme using CPLEX-12.1 in a case study of a Asia–America–Europe route.

Zhang and Li (2016) demonstrate joint optimisation of a scheduling and routing problem. A simulation-based method is used to conduct an experiment on the impact of transit time on winning a competition. Sensitivity analysis is undertaken on the impact of speed, port time, maximum transit time and inventory routing on total costs.

Lee et al. (2015) apply an analytical model to unpredictable shipping delay, bunker cost and delivery reliability. Their results suggest a simple and implementable policy with controlled cost and guaranteed delivery reliability.

In addition to the scheduling problem, for medium term planning, speed optimisation is another important problem. When a vessel's speed increases by a few knots, it leads to a sharp increase in fuel consumption (Notteboom and Vernimmen, 2009). This can make up more than 75% of the total operating costs (Ronen, 2011). A vessel's speed affects all levels of decision making. Higher speeds result in fewer ships being required to keep weekly services at a strategic level. At a tactical level, sailing speed is a crucial decision in fleet deployment when there is flexibility in delivery timescales. Weather and currents influence speed at an operational level (Lee et al., 2017). The following studies relate to the speed optimisation problem.

Notteboom and Vernimmen (2009) study the trade-off between speed, number of vessels and round trip time, in order to minimise total costs on line bundling services. They use an analytical approach on a case study of Europe–Asia trade. The results show that high bunker inventory leads to low speed, and more vessels being deployed can lead to higher service integrity because of additional buffer allowance.

Fagerholt et al. (2010) compare a NLP solver with a shortest path heuristic algorithm. Hvattum et al. (2013) propose an exact algorithm to solve a speed optimisation problem. Qi and Song (2012) propose a model which considers uncertain port times to minimise fuel consumption and summarise structural properties for managerial application affected by uncertain port time.

Psaraftis and Kontovas (2014) apply a simulation model to investigate how important configurations affect cost in a speed optimisation problem. The experiment is conducted on fuel price, the state of the market, the dependency of fuel consumption on payload and the inventory cost of cargo.

Wang and Meng (2012d) study speed optimisation in a network design problem. A MINLP model is proposed and applied to solve a real case study. The main contribution is calibrating the bunker consumption from historical data as a function of speed. Then, an investigation is made the optimal sailing speed for each leg of the liner network design problem.

Wang (2016) investigates fundamental properties for a network containership sailing for speed optimisation. A higher speed implies higher bunker consumption (higher bunker costs), shorter transit time (lower inventory costs), and larger shipping capacity per ship per year (lower ship costs) to minimise costs. Analytical solutions and a simple bi-section search method are used in the study. They propose a pseudo-polynomial-time solution algorithm that can efficiently obtain an epsilon-optimal solution for the sailing speed of containerships.

He et al. (2017) present a NLP model and apply an analytical approach to a speed optimisation problem. Heterogeneous convex costs and heterogeneous speed limits across arcs and service time-window constraints are implemented. The results show that the proposed algorithm is faster than a general convex optimisation solver (MATLAB) on test instances, and requires much less memory. The findings provide some insight for ship planners on how to balance operating costs and service quality.

Since speed optimisation problems affect several levels of decision making, many studies combine them with other configurations. One interesting configuration is combining with a bunkering problem. Aydin et al. (2017) compare dynamic programming with a deterministic model and heuristic algorithm on uncertain port time and bunkering location for a real case study.

Yao et al. (2012) propose a bunker consumption function as a function of speed for different vessel sizes, and suggest there are managerial implications when the effects of port arrival time windows, bunker fuel prices, ship bunker fuel capacities and skipping port options are considered on the bunker fuel management problem in a real case study.

Sheng et al. (2014) study refuelling and speed optimisation problems to compare a stochastic model with a stationary model (Yao et al., 2012). They focus on a single vessel and consider bunker price, and use consumption as a stochastic variable. A multi-stage dynamic model and modified rolling horizon method are used to represent the model and find the solution to the problem.

Sheng et al. (2015) continue the study of Sheng et al. (2014) of a refuelling and speed optimisation problem. MINLP, a multi-stage dynamic model and a progressive hedging algorithm are applied in the study. A CPLEX solver for a stationary model is compared with a dynamic model (progressive hedging algorithm) when uncertain bunker price and uncertain bunker consumption are considered. If the ship bunker inventory drops below s, bunker fuel is filled to the level S.

Wang et al. (2014) propose a hybrid fuzzy-Delphi–TOPSIS based methodology to handle uncertain information in an environment of refuelling problem. They develop a benchmarking framework in order to better understand the complex relationships in a case study of East Asia.

Wang and Meng (2015) study robust bunker management for liner shipping networks (refuelling and speed optimisation for network design problems). MINLP is modelled to minimise total costs, consisting of ship costs, bunker costs and inventory costs, under the worst-case bunker consumption scenario. Then, a linearised technique is used to transform a non-linear to a linear function. Managerial insight is given by a case study of an Asia–Europe–Oceania network.

Zhen et al. (2017) propose dynamic programming to set a threshold for a solution of a refuelling problem. Fuel price and fuel consumption are stochastic when the decision variable is an amount of fuel added at a port without considering fuel consumption as a function of speed. A case study in the Mediterranean Sea of Maersk Line is applied in the study.

A speed optimisation problem can be considered in addition to the refuelling problem with speed optimisation, combined with weather effects. Du et al. (2015) propose mixed-integer linear programming (MILP) and apply robust optimisation techniques to minimise fuel consumption under severe weather conditions and high fuel prices in a Asia–Europe case study of Singapore.

Lee et al. (2017) present weather effects on a speed optimisation problem by using the NLP model and consider archive weather data to estimate a real fuel consumption function, in a case study of the Mediterranean and Black Sea, and use multi objective particle swarm optimisation (MOPSO) as a decision support system to solve such a case study.

Environmental factors are other parameters which the speed optimisation problem is combined with. Corbett et al. (2009) explore the effect of tax policy on speed reduction leading to a reduction of CO2 emissions. Two scenarios, container loading or good packaging and additional ships to maintain the same amount of cargo transported to the destination, should be implemented.

Kontovas and Psaraftis (2011) include environmental factors to provide an operational model and a policy for a vessels and ports to reduce emissions. A vessel should sail at slow speed to reduce CO2 emissions, leading to an increase in sailing times. Therefore, port time should be reduced so that the time schedule can be met.

Kontovas (2014) studies the intervention of green ship routing with a scheduling problem. A conceptual approach is proposed in a routing and scheduling problem in liner shipping, and the parallel body of knowledge in vehicle routing, with emissions being taken into consideration.

Psaraftis and Kontovas (2010) present a conceptual paper that investigates the trade-off between economic and environmental performance. The results show three main ways to reduce CO2 emissions, improving ship design, imposing tax and speed optimisation.

Emission control is another area in which sailing speed is affected. Fagerholt et al. (2015) trade off the route and the speed when a vessel sails inside or outside the emission control area in order to minimise cost. The aim of the study is to propose a model and apply it to a real case study.

Dulebenets (2016) demonstrates MINLP and applies a linearisation technique and dynamic secant approximation to compare the existing International Maritime Organization (IMO) regulations with an alternative policy, using French Asia Line 3 route. The findings show that the introduction of emission restrictions within emission control areas (ECAs) can significantly reduce pollution levels but may incur increased route service costs for the liner shipping company. They can reduce the quantity of sulphur-dioxide emissions produced by 40.4 percent. At the same time, emission restrictions require the liner shipping company to decrease the vessel sailing speed not only on voyage legs within ECAs but also during adjacent voyage legs, which increases the total vessel turnaround time and in turn increases the total route service cost by 7.8 percent.

Berth scheduling is an interesting problem which affects vessel speed. Reinhardt et al. (2016) propose that speed optimisation of an existing liner shipping network can be solved by adjusting the port berth times to minimise fuel consumption. Maersk Line is used as a case study.

Dadashi et al. (2017) study a berthing problem with a tidal window. Particularly, they emphasise a continuous berth scheduling model at multiple marine container terminals with tidal considerations, using MIP and CPLEX. A case study at the port of Bandar Abbas (Iran) is used to examine the managerial implications.

Venturini et al. (2017) integrate a multi-port berth allocation problem with speed optimisation. The problem is similar to the multiple depot vehicle routing problem with time windows. Collaboration between port terminals and shipping liners can lead to cost savings (berth allocation problem). Optimisation of operations and sailing times leads to reductions in bunker consumption and, thus, to fuel cost and air emission reductions.

The cargo allocation problem is another problem that exists in the literature. Guericke and Tierney (2015) study the joint of cargo allocation problem with speed optimisation in a liner shipping problem. The trade off of transit time requirements and speed optimisation is set. A model is proposed, and realistic data from LINER-LIB (Brouer et al., 2014a) is used to conduct an experimental study.

Xia et al. (2015) present joint planning of fleet deployment, speed optimisation, and a cargo allocation problem. MILP is modelled and an iterative search algorithm is used to maximise total profits at the strategic level. A fuel consumption function that depends on speed and load is demonstrated. Finally, managerial insights are obtained by testing the model in various scenarios.

The summary of literature in tactical liner shipping is shown in Table 2.5.

Table 2.5 Summary of Literature in Tactical Liner Shipping

Reference	Problem and major	Approach

	consideration	
Perakis and Jaramillo (1991)	Fleet deployment	Dependent approach
Meng and Wang (2010)	Fleet deployment	CPLEX
Wang and Meng (2012a)	Fleet deployment	CPLEX
Wang et al. (2013c)	Fleet deployment	CPLEX
Wang et al. (2013a)	Fleet deployment	ε-optimal global optimisation
Herrera et al. (2016)	Fleet deployment	MIP
Dong and Song (2009)	Fleet deployment; Empty container repositioning	Simulation
Dong and Song (2012)	Fleet deployment	Simulation
Meng and Wang (2011b)	Fleet deployment	Branch-and-bound approach
Andersson et al. (2015)	Fleet deployment; Speed optimisation	Rolling horizon heuristics
Cheaitou and Cariou (2012)	Fleet deployment; Speed optimisation	Quantitative
Song and Dong (2013)	Fleet deployment; Empty container repositioning	Three stage optimisation
Song et al. (2015)	Fleet deployment; Speed optimisation	Genetic algorithm
Song and Yue (2016)	Fleet deployment	Genetic algorithm
Song et al. (2017)	Fleet deployment; Speed optimization; Scheduling	Genetic algorithm
Zacharioudakis et al. (2011)	Fleet deployment	Genetic algorithm
Dulebenets and Ozguven (2017)	Scheduling	Piecewise linear secant approximations
Wang and Meng (2012b)	Uncertain time; Scheduling	Exact cutting-plane based solution algorithm
Notteboom (2006)	Uncertain time; Scheduling	Quantitative

Qi and Song (2012)	Uncertain time; Scheduling	Simulation-based stochastic approximation
Wang and Meng (2012c)	Uncertain time; Scheduling	Sample average approximation method; linearisation techniques; decomposition scheme; CPLEX
Zhang and Li (2016)	Scheduling; routing	Simulation
Lee et al. (2015)	Scheduling; bunker	Analytical
Notteboom and Vernimmen (2009)	Speed optimisation	Analytical
Fagerholt et al. (2010)	Speed optimisation	Shortest path heuristic
Psaraftis and Kontovas (2014)	Speed optimisation	Simulation
Wang and Meng (2012d)	Speed optimisation	MINLP model
Wang (2016)	Speed optimisation	Simple bi-section search
He et al. (2017)	Speed optimisation	Analytical
Aydin et al. (2017)	Speed optimization; bunker	Dynamic programming
Yao et al. (2012)	Speed optimization; bunker	CPLEX
Sheng et al. (2014)	Speed optimization; bunker	Modified rolling horizon
Sheng et al. (2015)	Speed optimization; bunker	Progressive hedging algorithm
Wang et al. (2014)	Bunker	Hybrid fuzzy-Delphi–TOPSIS
Wang and Meng (2015)	Speed optimization; bunker	Linearised technique
Zhen et al. (2017)	Bunker	Dynamic programming

Du et al. (2015)	Speed optimization; bunker; weather effect	robust optimisation
Lee et al. (2017)	Speed optimization; weather efffect	Particle swarm optimisation
Kontovas and Psaraftis (2011)	Speed optimization; environmental effect	Quantitative
Kontovas (2014)	Green ship routing; scheduling	Piecewise-linear functions
Psaraftis and Kontovas (2010)	Speed optimization; environmental	Quantitative
Fagerholt et al. (2015)	Emission control area	N/A
Dulebenets (2016)	Emission control area	Dynamic secant approximation
Reinhardt et al. (2016)	Berth scheduling	Piecewise linear function
Dadashi et al. (2017)	Berth scheduling	CPLEX
Venturini et al. (2017)	Berth scheduling; speed optimisation	CPLEX
Xia et al. (2015)	Fleet deployment; speed optimization; cargo allocation	Iterative search algorithm

2.2.3 Operational Planning

As explained previously, although at a strategic and tactical level a planner tries to minimise regular uncertainties, there are still irregular uncertainties that happen daily. Many researchers have tried to cope with these uncertainties by creating decision support systems (DSSs) for planners to see situations and make decisions in real time. Balmat et al. (2011) study how to minimise risk of accidents at sea that happen due to ship speed and position. In other words, if a vessel drives very fast or drives to dangerous locations, there is a high tendency for accidents to happen. Therefore, a DSS is created to raise the alarm in real time when a ship is in such a risk zone.

Balmat et al. (2009) try to identify factors resulting in risk that may cause a ship to collapse or an environmental crisis. They put a percentage figure on the degree to which the ship may be in danger. The factors the research considers are both static and dynamic. The static components include flag, year of construction, gross tonnage, numbers of companies, duration of detention and ship type. The dynamic elements include, sea state, wind speed, visibility and night or day. These factors are included to assess risk in real time. The fuzzy logic approach is used to find the percentage risk, so that suitable vessels, in terms of design, are operated for safety purposes. We refer to the review of the literature on fundamental issues of risk management of Goerlandt and Montewka (2015).

In addition to risk minimisation problems, there are many pieces of literature which apply DSS to real time scheduling problems, in order to minimise costs and arrive at ports of call in time. Kim and Lee (1997) are pioneers of using optimisation-based DSS for scheduling bulk cargoes by assigning them to a schedule in tramp shipping. LINDO optimiser software is used as a tool in the scheduling process in order to maximise the profit obtained from the transportation revenue of cargoes when the operating costs of vessels have already been reduced.

A similar scheduling of bulk problem in tramp shipping is proposed by Bausch et al. (1998). The authors assign cargoes to the scheduling process so that all loads are transported at a minimum cost and satisfy all limitations such as time window and compatibility between port and vessel. The output of this optimisation process is presented as a schedule on a spreadsheet for users to track.

Fagerholt (2004) initialises a DSS called TurboRouter to consider many of the limitations of the scheduling process. Fagerholt and Lindstad (2007) continue developing TurboRouter to meet all the requirements of the vessel scheduling problem in industrial and tramp shipping. The researchers extend the DSS developed by the Norwegian Marine Technology Research Institute. Time windows, vessel capacities, compatibility between ports and vessels, bunker consumption rates, and bunkering port calls are taken into account in planning for vessels to arrive at port within specific time periods and with the maximum profit. As a result, decision makers can easily see the schedule through a user interface. TurboRouter receives satellite positions from ships in real time and computes the estimated arrival times at given ports.

Apart from industrial and tramp shipping, Lam (2010) focuses on designing DSS for a scheduling of liner shipping problem. Lam (2010) takes an integrated approach to selecting the location of ports and schedules vessels to arrive at ports within a given time window. Finally, financial factors are analysed. In the scheduling process, a planner can add, delete, insert, edit or move the port manually, and the distance and time window of every port are updated automatically. Finally, the optimal schedule is provided for a decision maker to minimise all related costs.

Moreover, Ballou et al. (2008) present a DSS called Voyage and Vessel Optimization Solutions (VVOS) in order to schedule vessels to reach ports of call with minimum CO_2 emissions within a given time window when facing uncertain ocean conditions such as wind, waves and currents. VVOS is considered user friendly as it is flexible enough for the user to choose whether they would like to use an optimisation module. Similarly, Windeck and Stadtler (2011) focus on developing DSS for a routing and scheduling problem in order to minimise costs and CO_2 emissions by considering weather factors.

Another type of operational planning problem in liner shipping is fleet repositioning. Tierney et al. (2017) present a multi-objective mixed integer programming model and propose a multi-objective simulated annealing heuristic to balance profit making with cost-savings and environmental sustainability. Asia-CA3 route is used as a case study. Zheng et al. (2016) propose a two-stage optimisation model to trade off container leasing price, the use of foldable containers and empty container repositioning in a liner shipping network design problem. An Asia-Europe-Oceania route is used to evaluate the effectiveness of the algorithm.

Container routing is another operational problem covered in the liner shipping literature. Wang et al. (2013) study container routing by proposing container network routing which incorporates transit time and maritime carbonate.

Wong et al. (2010) use MATLAB to propose a multi-objective immunity-based evolutionary algorithm verified with benchmarking functions and compared with four optimisation algorithms to assess its diversity and spread.

Xing and Zhong (2017) demonstrate container flow recovery in a hub and spoke network. ILP is modelled and other shipping companies' services and other modes of transport (roadway, railway and airline) are studied, as alternative candidates to transport miss-connected containers.

For the revenue management problem, Wang et al. (2015) demonstrate seasonal shipping revenue management. They model this by MINLP, and branch and bound is used in the algorithm to compare the model with the exiting algorithm. Then, a managerial rule is presented.

For a review of the other literature, we refer to Panayides and Cullinane (2002) for competitive advantage in liner shipping. A theory of competitive advantage from the strategic management literature is presented. Porter's competitive strategy framework emphasises low cost, unique product or service and a focus on specific groups of customers. It also focuses on industry structure which affects the sustainability of firms, while positioning reflects firms' abilities over their rivals. Resource-based theory, which focuses on firms' unique resources and capabilities, is also demonstrated.

We refer to Brouer et al. (2017) for optimisation in liner shipping, a model of liner shipping network design, container routing and speed optimisation, empty container repositioning and stowage planning, disruption management, bunker purchasing and benchmark instances in LINER-LIB data.

Psaraftis and Kontovas (2013) review papers on speed optimisation and present a taxonomy of the models in which speed is a decision variable.

Christiansen et al. (2013) present a systematic literature review on the routing and scheduling problem. They focus on prescriptive models rather than descriptive models from 2002 to 2012. The paper does not include berth scheduling, container stowage, container management, container yard management, cargo allocation or non-commercial vessels (e.g. naval vessels).

Meng et al. (2014) review the literature on container routing and scheduling in liner shipping. The focus of the study is on model formulations, assumptions and algorithm design over 30 years of OR methods. They study containership fleet size and mix, alliance strategy and network design (at the strategic level); frequency determination, fleet deployment, speed optimisation and schedule design (at the tactical level); and container booking and routing and ship rescheduling (at the operational level).

Mansouri, Lee and Aluko (2015) review multi-objective decision support systems on sustainable maritime transport using a systematic literature review. The focus of the study is on multi-objective optimisation, decision support systems and environmental factors in maritime transport.

Steenken, Voß and Stahlbock (2005) review container terminal operation. They show the increasing trend for container operation and present terminal structure and handling equipment. For handling equipment, types of cranes, such as quay cranes and stacking cranes, are summarised; for horizontal transport means, automated guided vehicles and straddle carriers are presented; for assisting systems, communication and positioning systems are explained; for container terminal systems, a great variety of container terminals, depending on which type of handling equipment is combined to form the terminal system, are illustrated; terminal logistics and optimisation methods are given; for the ship planning process, the berth planning, stowage planning and crane split are demonstrated. Storage and stacking logistics are other topics in the study. Transport optimisation, such as quayside transport, landside transport and crane transport, are explained in the study. Finally, simulation systems are presented in the review.

Stahlbock and Voß (2008) present a literature review on the topic of container terminals.

Wang et al. (2016) review cruise shipping, which is sailing about in an area without a precise destination, especially for pleasure.

The summary of literature in operatonal liner shipping is shown in Table 2.6.

Table 2.6 Summary of Literature in Operational Liner Shipping

Reference	Problem and major consideration	Approach
Balmat et al. (2011)	Risk of accidents	Fuzzy
Balmat et al. (2009)	Risk of accidents	Fuzzy
Kim and Lee (1997)	Scheduling of tramp shipping	LINDO
Bausch et al. (1998)	Scheduling of tramp shipping	Spreadsheet
Fagerholt (2004)	Scheduling of tramp shipping	Optimisation algorithm
Fagerholt and Lindstad (2007)	Scheduling of tramp shipping	Optimisation algorithm
Lam (2010)	Scheduling of liner shipping	Integrated approach
Ballou et al. (2008)	Emission; Weather condition	Voyage and Vessel Optimization Solutions
Windeck and Stadtler (2011)	Routing and scheduling	Variable neighborhood
Tierney et al. (2017)	Environmental	Multi-objective mixed integer programming; simulated annealing
Zheng et al. (2016)	Liner shipping network design	Two-stage optimisation
Wang et al. (2013)	Container routing	N/A
Wong et al. (2010)	Repositioning	multi-objective immunity-based evolutionary algorithm
Xing and Zhong (2017)	Container recovery	Real-time DSS
Wang et al. (2015)	Revenue management	Branch and bound

2.3 Disruption Event

There are three planning levels; strategic planning level, tactical planning level and operational planning level. Strategic and tactical planning helps a decision maker prevent uncertain and disruption in long and medium term level while disruption event can still happen daily. Reactive action that handles a disruption event after it happens is therefore categorised into operational level.

2.3.1 Similarities and Differences between Airline and Liner Recovery

In Section 2.2.1, a comparison of transportation characteristic between air, road and water is presented. Both aircraft and vessels aim to carry cargo or passengers across the ocean, while trucks carry cargo to destinations within a region. Liners and airlines, which are large companies, usually operate through hub and spoke networks. There are many other characteristics that marine transport has in common with air transport. Both face high uncertainty due to adverse weather conditions which upset pre-specified schedules. Disruption frequently leads to late arrival or departure at following ports or airports. This section explains in more detail how to deal with disruption events in both cases (Brouer et al., 2013; Lee and Song, 2017; Qi, 2015).

Three factors have to be recovered after an aircraft faces a disruption event, the crew, the aircraft itself and the passengers. Crew recovery management is a crucial issue in air transportation, and must take into account working hours, training and leave. It aims to reschedule the disrupted rota to ensure that all flights have enough crew to operate during the disruption event and allow the airline to recover normal operation as soon as possible. In contrast, since liner shipping operates continuously around the clock, crew rescheduling after a disruption event is less necessarily. We therefore focus on how to recover aircraft and passengers, which resemble vessels and cargo.

Traditionally, there are four main ways to recover from a disruption event in the air industry, delays, cancelations, swaps and speed changes. Delay means an aircraft waits for a period to let the delay propagate to its following flight. Practically, most aircraft do not operate overnight. The initial delay therefore disappears. For liner shipping operation, it is not possible to allow a delay to recover a vessel itself due to the fact that there is no slack time. This can be explained by the operational process of a ship liner which operates continuously around the clock.

Another option is cancelation of flights. This option usually applies when an airline experiences large delays or runway capacity is reduced. This allows it to resume its flight schedule because aircraft are flexible and can swap to another flight. This method is not directly appropriate for ship liners due to the interruption of operation. However, a possible operational process can be to cancel or omit some ports of call instead. Containers which have to go to the skipped port can be unloaded at a nearby port and wait for another vessel to ship them to their destinations.

A third option is swapping flights to reduce the negative effects of delay propagation to the remaining flights. This option is similar to the previous one in recovery of aircraft. Swapping from one aircraft to another is always possible, since an aircraft becomes idle after each flight. However, this option is not usable for a ship liner because it is never empty. If a ship liner has to move cargo from one vessel to another, it is extremely costly and time consuming. Even though this process seems not to be applicable to liner shipping, the swapping option can be applied to the sequence of ports of call particularly ports located in the same region.

A fourth option is changing speed. Physically, it is difficult for an aircraft to speed up to recover from disruption. Normally, it can increase approximately 8–10% from the original plan. This can be explained by the fact that flight schedules are designed to have high speeds, leaving little room to speed up. By contrast, liner shipping always applies slow stream speed, approximately 16-18 knots. Thus there is an option to speed up to 22-24 knots, which is around a 40% increase. This option is even more powerful for long inter-continental legs, where there is more flexibility for a vessel to adjust its speed.

Even though the vast majority of disruption problems have been studied in the airline industry, because of the huge potential loss associated with them (Mu et al., 2011), for the reasons given above it is necessary to develop a model to describe the disruption problem in liner shipping and an algorithm to deal with it.

2.3.2 Disruption Problem in Liner Shipping

The negative impact of airline disruption usually takes a maximum of around 48 hours to recover, while liner shipping may take days or weeks to recover. This is due to the fact that if there is disruption, airlines have many aircraft which can accommodate passengers from the disrupted flight within hours. However, if containers face misconnection problems, transferring them to another vessel may take up to a week because ship liners normally operate weekly. We can therefore see that severe disruption delays liner shipping. This section investigates in detail how to deal with disruptions in liner shipping.

Notteboom (2006) suggests five approaches to dealing with disruption events on an Asia-Europe route. First, a vessel reschedules the order of ports of call to handle more important cargoes which have to be shipped to those ports. This benefits only important cargoes, while less crucial ones are penalised. Second, a vessel decides to skip less important ports of call in order to arrive at the more important ones on time. Cargoes which have to be shipped to the omitted ports may be transported by other vessels or other modes of transport. Third, a vessel abruptly stops unloading or loading even if the process is not complete. This option is usually recommended to solve disruption in the case of a tidal window. The remaining cargoes are transhipped to the next port of call to wait for other vessels to transport them to the destination. Fourth, the turnaround time of the next ports of call are speeded up to recover the delay. The turnaround time can be saved if a vessel goes to a high productivity port. Finally, a vessel can speed up to recover its schedule. These methods are recommended narratively in a case study of an Asia-Europe route without any quantitative method.

Li et al. (2015) propose a quantitative disruption recovery plan for closed-loop liner shipping for a single vessel. Speeding up, port skipping, port swapping, allowing a vessel to sail at higher maximum velocity and increasing buffer time are investigated for different degrees of disruption and route distances. The routes considered are Asia-Europe (long cross ocean leg) and trans-Pacific (more ports nearby before crossing the ocean). They consider the case of longer port times when a vessel has to wait for the next available berthing slot due to missing a planned schedule. Another significant condition taken into account in the study is fuel price.

In case of speeding up, the results demonstrate that a vessel tends to speed up faster after disruption than in the following legs, regardless of the degree of disruption, distance in each leg or delay penalty function. It should be noted that all segments use the same fuel consumption function. The port skipping approach is helpful when a vessel has a low maximum speed. It is useful for reducing fuel costs leading to a reduction in total operating costs when ports of call are located near one another or there are high fuel prices. The patterns of rules are similar in the case of applying the port swapping method. The difference is that port swapping can save more operating costs when a vessel has a high maximum speed, because it allows vessels to arrive at all ports of call in a region. Port skipping can reduce operating costs more than port swapping in the case of extra delay. This is because port skipping can reduce the delay while port swapping decreases the delay in important ports but increases the delay in less important ones. Finally, the result proves the common sense conclusion that adding buffer time can recover delay. From investigating buffer time added in various leg patterns, the experimental results confirm that buffer time should be added to the shorter legs due to there being less flexibility (Qi and Song, 2012; Wang and Meng, 2012c).

Since Li et al. (2015) consider only a deterministic model without time window constraint to suggest the above rules for recovering a vessel, Li et al. (2016) extend the model a multi-stage stochastic model with and without time windows. A single voyage is assumed to be a planned stage. Regular uncertainties are normally handled by probabilistic historical data. However, disruption is an unexpected event happening dynamically during the journey. In reality, 93.6 percent of such uncertainty and disruptions occur in port (Notteboom, 2006). Li et al. (2016) thus consider uncertainties and disruptions that happen in port. Ship liners can normally learn the location of disruption at any point in a sea leg before arriving at port or during the stay in that place. Both regular uncertainties and disruption events can, therefore, be managed simultaneously.

The approaches which the model considers are speeding up and increasing productivity in port in order to balance delay costs, fuel costs and accelerating costs in port. A trans-Pacific route is an example route experimented on in the study. The experiment compares 3 main criteria. The first is the patterns of vessel speeding up, port speeding up, dynamic control policy and port skipping policies to handle different degrees of delay from regular uncertainties to both regular uncertainties and disruption events. The second is evaluated with and without time window constraints. The third is assessed based on how fast the liner can learn of the disruption before it arrives.

The results in the case of only regular uncertainties demonstrate that vessel and port operations are likely to speed up when the delay is larger, no matter whether the case is with or without a time window. Another interesting result is that even if there is no delay on a given waypoint in the leg, a vessel is still able to speed up to deal with future uncertainties. The speeding up option not only depends on the degree of delay but also the vessel position. The results illustrate that a vessel should speed up when it is at a later waypoint rather than an earlier one. This can be explained as there being less hurry, because there is more time left at the earlier waypoint.

The second case is that of both regular uncertainties and disruption events simultaneously. The experimental results show that a vessel does not speed up when delay increases all the time. This is because there is a disruption event which is a particular phenomenon constituting extra delay. This situation can result in speeding up sharply so that a vessel can arrive at a port of call before the disruption happens. On the other hand, it can also slow down a vessel so that the disruption has already finished at the port. This is one significant difference between considering only regular uncertainties and regular uncertainties plus disruption events. For the other criteria, the results show no difference from the case of only considering regular uncertainties.

The third numerical study compares static with dynamic policies in handling regular uncertainties. The observation suggests that real-time policy can capture the deviation of uncertain port time better than static policy, resulting in more cost saving for the case without a time window. There is a slight difference in the case with a time window. The results show the same pattern, that dynamic policy can reduce costs more than static policy when the degrees of delay increase. Nonetheless, cost savings do not change significantly when a vessel is ahead of schedule. The study result is also robust for other port time distributions.

Fourth, valuable results are also obtained when applying real-time policy to coping with both regular uncertainties and disruption simultaneously. The experiment in this case is divided into two types. The first experiment assumes that an incoming disruption is known in advance, while the other is dynamically updated during the journey. In the first case, the relative saving cost after applying a real-time control policy can derive either from speeding up to finish the operation at a port of call before disruption happens, or from slowing down to arrive at the port after the disruption has ended. The more severe the disruption, the more cost savings can be obtained from real-time policy. In the second case, the disruption information is invisible at the beginning of the journey but becomes more accurate over time. More accurate disruption information provides more cost savings.

Fifth, port skipping is valuable to save operating costs. In the cases with and without earliest handling time, two possible solution patterns are recommended. Port skipping leads to a reduction in cost by saving delay penalty costs at the following ports of call in a voyage, even though there is a slight penalty at the skipped port. However, in some situations, port skipping can bring about higher skipping costs and extra handling time at the following ports of call. Consequently, the delay penalty grows larger and mitigates the value of port skipping.

Although Li et al. (2015) and Li et al. (2016) propose different approaches to recovering a disrupted vessel, the container is another entity which has to be rescheduled. Brouer et al. (2013) propose mixed integer programming (MIP) combined with a time-space network to recover both vessels and containers in a hub and spoke network design. In the proposed model, the vessel speeding up, port skipping and port swapping approaches are embedded to reschedule multiple vessels. The speeding up option can be illustrated on a time-space network by discretising the speed on a given leg. The model includes the availability of berthing slot constraints. This constraint forces only one vessel to berth at a time, in the berthing slot. Disrupted containers can be recovered by hiring other vessels to transport them to their destinations. If containers cannot arrive at a port destination on time, they are penalised. The objective is to minimise both sailing and container misconnections as well as delay penalty costs.

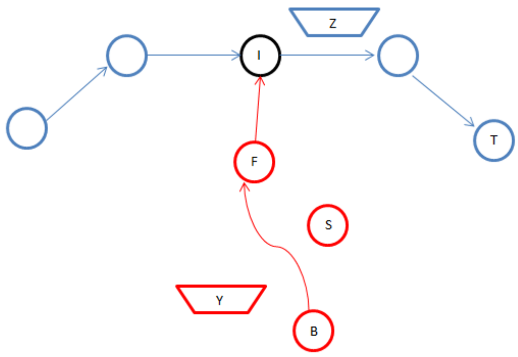

Figure 2.1: Container recovery schedule

Since we have already explained in detail how to recover vessels (Li et al., 2015), we focus on how to recover disrupted containers (Brouer et al., 2013). Containers can be delayed by two situations, delay resulting from misconnection of containers at skipped ports or transhipment ports, and delay at port destinations. As shown in

Figure 2.1, misconnection of containers can happen at port *S* or port *I* which are considered skipping and transhipment ports when the origin of container *C* is at port *B* and the destination is at port *T*. According to the container routes, we can see that containers have to be transported by two vessels. In the first route, vessel *Y* carrying container *C* sails at a certain speed on the red route. It tries to tranship container *C* at port *I* to vessel *Z*. The container is misconnected if vessel *Y* cannot arrive at port *I* before vessel *Z* departs. As a result, container *C* is penalised as a misconnected and delayed container. Another misconnection is the case where vessel *Y* skips port *S* and heads to port *F*. Container *C*, which has to be unloaded at port *S*, is therefore considered a misconnected container. This misconnection is also considered a delayed container and is penalised as a misconnection and a delayed container.

The computational study experiments with the approaches to take when disruption happens at various locations in both legs and at sea. Four real life delay cases are used as examples in the experiment. In the first, multiple vessels are delayed at sea due to bad weather, and in the remaining three, vessels in the network are delayed at port due to port closure, berth prioritisation and expected congestion.

In the first case, the result of the model suggests skipping a port of call, while in real life this situation is dealt with by speeding up. The solution in the model is shown to be a lower cost choice. The result in the second case shows that the solutions obtained from real life are not comparable with those obtained from the model. This is because containers are reflowed to deal with disruption, but this option is not included in the model. In the third case, vessels compete to arrive within the berth time slot. Only a single vessel can berth at any given time. The solution shows no difference between the real life and optimal solution from the model. In the fourth case, the test instance is the situation where a vessel learns of expected congestion at the next port of call. The real life solution is to skip that port, while the model suggests speeding up to arrive at the port before the expected congestion happens. In this case, the solution from the model is better than the real life implementation.

Even though Brouer et al. (2013) take both vessels and containers into account, their model includes only berthing slot constraints. Kjeldsen (2012) proposes more detailed recovery operations taking vessel capacity, port productivity, vessels and port compatibility and container routes into consideration. The problem is modelled by MIP and time-space network in order to minimise sailing costs on the selected route, the operating costs at the ports of call, berthing costs, cargo delay costs from the original plan and costs of the cargo transhipment process when disruption happens.

There are many vessel routes in a network. One vessel route contains a set of ports of call. A vessel has the capacity to carry several types of cargo. Each cargo has its own origin and destination, and can be carried by many vessels on different routes because of the transhipment process. If transhipment occurs, there is an associated cost. There are three types of port, cargo origin, transhipment and cargo destination, each with its own productivity rate. During operation, one important constraint is vessel and port compatibility. There are two kinds of incompatibility, permanent and temporary. An example of permanent incompatibility is a vessel being larger than the berthing slot. Temporary incompatibility can be due to tides which drastically reduce draft, meaning the vessel cannot enter port for some period.

Since MIP makes the problem complicated, the author deals with this situation by using linear programming (LP) to reroute the cargo only, because vessel routes are well-developed in the strategic planning phase. This is solved by CPLEX. Another way to cope with this complexity that the author applies, is large neighbourhood search to recover both vessels and cargoes given different degrees of disruption. The algorithm is divided into two phases, construction and repair. The first phase is constructing a feasible schedule for vessels considering disruption. The second phase is cargo repair which cannot be handled in the construction phase. A detailed explanation of the construction and repair phases follows.

In the construction phase, disruption can be related to either a vessel or a port. If the disruption is relevant to a vessel, the following actions are implemented according to the disruption period. If a vessel is disrupted for the entire time of a port call, this port is skipped. There are three cases where a vessel is not disrupted for the entire period of a port call. First, if a vessel expects to arrive at a port before or during the disruption, the vessel should speed up, or the loading and unloading process should operate faster, or the waiting time should be decreased to avoid the disruption. If such actions cannot reduce the length of the port call, the vessel should skip that port. Second, if a vessel is between ports when the disruption happens, it has to speed up to recover the disrupted time; otherwise the next port call is cancelled. Third, if a vessel has already learnt that there is disruption at the next port of call, it tries to slow down to arrive later than the disruption period. After finishing unloading and loading at the port, the vessel attempts to speed up to arrive at the next port of call as per the planed schedule; otherwise it is omitted. When the disruption is associated with the port, the implementation is the same as the first and third cases of disruption related to the ship, because the disruption happens at the port.

The aim of the repair phase is to transport cargo delayed due to disruption to its destinations. There are two types of cargo, on-board cargo and cargo that becomes available, which are recovered differently. There are three methods of recovering on-board cargo depending on the situation. First, when a vessel calls at the destination port of the cargo, the recovery plan is to increase the time in port for unloading the delayed cargo. Second, when a vessel calls at the transhipment port to unload cargo, the vessel which carries the on-board cargo has to arrive at the port before the second vessel arrives. The loading and unloading times for all port calls are lengthened to recover the delayed cargo. Third, if a vessel is at sea and does not call to the destination port of the cargo, the current vessel is forced to make an inducement to call at the destination port.

Cargoes that are available can be recovered by changing the schedule. If a vessel calls at both the origin and destination ports, both port calls are lengthened to recover the delayed cargo. Another method is to tranship the available cargo by forcing the first vessel to pick up the cargo at the origin port and send it to the transhipment port. Then, the second vessel is called to pick up the cargo after the first vessel finishes unloading and departs the port. After that, the second vessel calls at the destination port of the cargo. These four related port times are lengthened to recover the delayed cargo. The third method of recovering available cargo, when a vessel calls immediately after it becomes available, is to insert a destination port of call immediately and increase the loading and unloading time at that port. This is in case the vessel calls at the destination port after the cargo becomes available. The insertion of the origin port call is made before the destination port call. The experiment evaluates the solution quality and computational time of the algorithm. A summary of the recovery disruption literature in liner shipping is presented in Table 2.7.

Table 2.7: Summary of recovery disruption literature in liner shipping

Reference	Recovery objects	Model constraints	Methodology	Delay location	Independent variables	Approaches
Notteboom (2006)	Vessels and containers	N/A	Qualitative	Legs and ports of call	N/A	Speeding up, port skipping, port swapping, cut and run, speeding up turnaround time at port and hiring other vessels to recover disrupted containers
Li et al. (2015)	A vessel	Planned arrival time, speed limit	Deterministic model, NLP, CPLEX and dynamic programming	Ports of call	Distance, initial degree of delay, delay function, maximum speed limit, speed, extra delay time, buffer time, fuel price	Speeding up, port skipping, port swapping, adding buffer time and expanding maximum velocity
Li et al. (2016)	A vessel	Time window, speed limit	Multi-stage stochastic model, NLP, dynamic programming	Ports of call	Initial degrees of delay, extra delay from disruption event, delay realisation points,	Speeding up, port skipping, dynamic control policy and speeding up turnaround time at port

					time window	
Brouer et al. (2013)	Vessels and containers	Multiple vessel routes, berth occupation	MIP, CPLEX, time-space network	Legs and ports of call	N/A	Speeding up, port skipping, port swapping, hiring other vessels to recover disrupted containers
Kjeldsen (2012)	Vessels and containers	Vessel capacity, port productivity, multiple vessel routes and multiple container routes, vessel and port compatibility	MIP, CPLEX, time-space network and large neighbourhood search	Legs and ports of call	N/A	Speeding up, port skipping, port swapping, hiring other vessels to recover disrupted containers
Hasheminia and Jiang (2017)	N/A	N/A	Quantitative, empirical study	N/A	Vessel delay cost, schedule recovery cost	Trade-off between vessel delay cost and schedule recovery cost

2.4 Limitations of Previous Literature

The disruption problem is one of the most important problems in marine transportation. Disruption can happen for many reasons. Notteboom (2006) suggests that it may be due to unexpected waiting times (e.g. before berthing or beginning operations), uncertain port productivity or unavailability of tug boats or tidal windows at the access channel. Rarely, it may be due to labour strikes or severe weather. For example, pilots at Antwerp protested against a change to national pension regulations, stopping work from 8 a.m. to 5 p.m. on a working day. This led to disruption of MSC's container services for 21 vessels in February 2012. A hurricane in November 2012 at New York - New Jersey forced container terminal operations to close for a week. Other examples of disruption events can be seen in Li et al. (2016), Notteboom (2006) and Qi (2015).

Various negative impacts occur if a vessel faces an unpredictable situation (Vernimmen et al., 2007). Terminal operators may face difficulty in reorganising vessels' berthing time slots. Yard planning and inland transport (e.g. truck and rail) may have to be rescheduled. Shippers (e.g. owners of cargo) may need to increase inventory levels to ensure enough cargo has been sent to manufacturers. The shipping line itself may face increased operating costs (e.g. capital, crewing, bunker, etc.) in order to pursue operational excellence. We note that liner shipping is marine transportation in which a vessel has to meet its preannounced schedule.

Few relevant studies have been made of how to cope with disruption events in liner shipping. Brouer et al. (2013) propose a mixed integer programming (MIP) model to solve disruption problem in networks correlated by transhipment for multiple vessels. Li et al. (2015) focus on conceptualising how to recover from a disruption event affecting a single vessel. Li et al. (2016) extend Li et al. (2015) by considering real-time schedule recovery policy to avoid, and recover from, disruption events. Structural rules have been derived analytically, and case studies have been used to validate the model empirically. Such recovery rules compare three options, speeding up, skipping and swapping, in order for a vessel to catch up with its original schedule, summarised below (Li et al., 2015).

The first issue is the degree of delay. If the delay is large, both skipping and swapping are preferable to speeding up. A vessel prefers to skip ports of call rather than speed up because no matter how fast the speed is, it cannot catch up with its original schedule. Similar logic is applied to the swapping option. Ports with heavier loading and unloading operations, considered more important ports, are swapped before lesser ones. This result is in line with common sense.

The effect of maximum speed is the second construct presented for recommending operational options. Port skipping is preferable to speeding up when the vessel's maximum speed is low. This can be explained as an inability to catch up with its original plan of low speed, and vice versa. Port swapping is a bit different. It tends to be slightly more valuable when a vessel has a high maximum speed. A possible explanation for this is that a higher maximum speed can reduce delay by rerouting to a less important port.

The third parameter is the impact of fuel price on the suggested option. Both port skipping and port swapping bring savings when fuel prices are high. It should be emphasised that port skipping leads to higher cost savings (the savings from implementing only the speeding up option) than the swapping option. The reason for this is that rerouting may lead to longer distances and larger fuel consumption costs, reducing costs savings.

Table 2.8: Summary of recovery plans and the models and factors which affect them

Category of factor	Factor	Li et al. (2015)	Li et al. (2016)	This study
Model	Deterministic and static	x		x
	Stochastic and dynamic model		x	
	Without time window	x		x
	With time window		x	x

Objective function	Single objective: 1. fuel cost 2. delay penalty	x	x	x
	Multi objective: 1. fuel cost 2. service level			
Parameters	Degree of port time		x	
	Degree of disruption	x	x	x
	Distance	x		
	Maximum speed limit	x		x
	Fuel price (IFO)	x		x
	Skipping penalty			**x**
	Accelerator penalty		x	
	Time window		x	**x**
	Delay realisation point		x	
Recovery plan	Speeding	x	x	x
	Port skipping	x	x	x
	Port swapping	x		
	Speeding up turnaround time at port		x	

	Buffer time	x		

Other recovery rules found in the literature are described below.

The first factor is time window (Fagerholt et al., 2010). If ports enforce time windows for vessels to arrive, there is a possibility to reduce fuel consumption. This can be explained by the fact that there is no need to hurry to arrive before the start of the time window in a speeding up option.

The second rule relates to the realisation point, when the disruption happens in the following ports of call during a journey. Li et al. (2016) indicate that learning the information at an early waypoint contributes a smaller relative cost saving than a later waypoint. An explanation for this is that there is no need to hurry, speed up or slow down in order to avoid the disruption, because the disruption may end before the vessel arrives, and vice versa.

The other interesting established area of conceptual knowledge is the structural rules related to the pattern of application of the options to recover from disruption events (Li et al., 2015). For the speeding option, a vessel applies a higher speed immediately after facing a disruption event. Its speed tends to decrease over the journey until the delay has been caught up. This is consistent with intuition, because it prevents the delay being propagated into the later segments.

For the skipping option, a similar pattern emerges. A vessel is likely to skip some ports immediately after the disruption event to decrease the negative impact along the journey. This rule holds true no matter how long the segments are, the degree of delay, or the delay penalty function. It should be noted that the rules may not be true in cases where different fuel consumption is applied to each segment or the case where the optimal solution is on the boundary of the feasible region. This is because a vessel may have already recovered its planned schedule, and therefore the speed's decreasing tendency does not hold.

According to all the rules mentioned above, even though Li et al. (2016) study how to avoid or recover from disruption events dynamically, the stochastic model does not always bring about more significant performance than the deterministic model

(Aydin et al., 2016). It also consumes large amounts of computational time. This study therefore applies a deterministic model to generate managerial rules for recovering from a disruption event, as Li et al. (2015) do. Although Li et al. (2015) generate many operational rules to recover from disruption events, they omit rules related to time windows and assume skipping penalties to have only one value, which may cause bias in the study, as presented in Table 2.5. One contribution of this study is to include these two parameters in the simulation experiment.

Moreover, Li et al. (2015) compare speeding, skipping and swapping to obtain managerial rules in various conditions. They criticise the swapping option in that the value of swapping cannot be generalised to be a managerial rule that can save total operational cost, because it depends on each case. Li et al. (2016) therefore ignore the swapping option in their study. Accordingly, we follow the recommendation not to investigate the effect of swapping under various conditions.

The conditions we investigate in the case study therefore include degrees of disruption, maximum speeds, fuel prices, time windows and skipping penalties. We omit length of each leg and the location at which a vessel learns of the disruption. The reason for omitting the distance parameter is that it is quite inaccurate for acquiring generic rules, because it changes on a case by case basis. For the realisation point, the reason is the disadvantage of the stochastic model mentioned above.

In summary, the main contribution of this study is to investigate the impact of various conditions of degrees of disruption, maximum speeds, fuel prices, time windows and skipping penalties on selecting the appropriate option (speeding up or skipping) in a deterministic model.

Chapter 3. Methodology

Chapter 3 presents methodology of this study starting with research paradigm in management studies. Then, optimization and simulation is used as an experimental methodology to guide this research by beginning with research questions and simple theory and ending with experiment to build novel theory.

3.1 Research Paradigm in Management Studies

Positivism, interpretivism and critical realism are the three main paradigms in management studies. Positivism assumes that there is one absolute truth which is independent of the researcher (Kuhn, 1970). Universal laws are expected to be observed empirically to show the pattern of their particular instance. If an event X happens, then an event Y will happen. The aim of the positivist researcher is to discover theory by a deductive approach (observation and experiment) in order to derive a model which can be used for prediction. Interpretivism, on the other hand, believes that social reality is not objective but rather subject to each individual's perception (Kant, 1998). The aim of this paradigm is not measuring social phenomena, but rather focusing on how to gain an interpretative understanding of the complexity of social phenomena. A qualitative approach is therefore adopted, instead of a quantitative approach, to describing or translating the meaning of social phenomena.

Even though positivism can generalise findings to explain and predict causal laws, Collis and Hussy (2009) present key criticisms of positivism in social science research. First, human perception cannot be separated from society. The researcher is therefore not objective, but rather part of what they observe, leading to subjective findings influenced by their attitude. Second, a systematic research design imposes limitations on results, because it may ignore some relevant factors. It has also been criticised because a single measurement (e.g. assigning numerical values to human intelligence) may not capture the complexity of real world systems. The interpretivism research paradigm is therefore suggested for supplementary explanations when constraints occur in the positivism paradigm.

Interpretivism provides an ability to understand human meanings, observe how processes change over time, and adapt the new ideas which emerge in order to generate new theory. However, the weaknesses of this paradigm are the tedious process of data collection, the difficulty of analysis and interpretation of the data, and the difficulty of controlling the pace, progress and end-point of research. Most importantly, the results have low credibility because less research samples can be obtained. Due to the limitations of these two extreme research paradigms, critical realism has been developed as a compromise.

The philosophy of critical realism is similar to positivism. Rather than assuming that there is one universal law as in the positivism paradigm, critical realism defines the domain of law as many small events which are simplified forms of the law and human perception can capture only some events (Mingers, 2016). In other words, the realist assumes the existence of the world regardless of human perception. The pattern of occurrences can therefore be generalised within the domain space. Mingers (2016) highlights that critical realism is a suitable philosophy for OR/MS disciplines. One popular OR/MS approach is the simulation and optimisation method, described below.

3.2 Optimisation or Simulation as an Experimental Methodology

Conducting simulation studies starts with research questions that conceptualise a model of real world systems or simple theory from literature, and obtaining data (input analysis). Assumptions are made to simplify the world into small events within limited spaces. Then simulation is used. The model design (the design of the construct which consists of data, components, model execution, etc.) and the simulation method are coded in a computer software package to represent the conceptual model. The computational representation is verified to assure the correctness of the theoretical logics, constructs and assumptions. A pilot run is made to validate the model with empirical data. Finally, an experiment is undertaken to generate new theory by varying the values of constructs, unpacking constructs into sub-constructs with their own unique effects, suggesting alternative processes or adding new features to provide a better understanding of the complex interactions among processes during a production run. We refer to Law and Kelton (1991), Eldabi et al. (2002), Davis et al. (2007), and Robinson (2008) for simulation methodology. The process is presented in Figure 3.1.

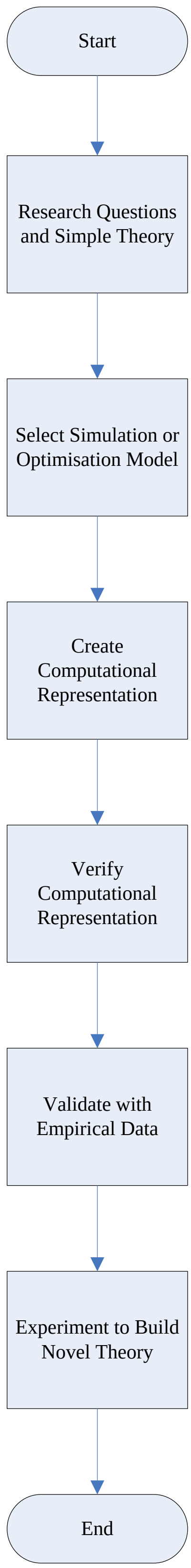

Figure 3.1: Simulation or Optimisation as an Experimental Study Diagram

3.2.1 Start with Research Questions and Simple Theory

Good research questions bring about deeper understanding of existing theory. In order to come up with research questions, the researcher creates questions from observation of case studies. Sometimes, the researcher can begin by reviewing the substantial theory in the literature. Sometimes, research questions are motivated by extending the classic tradition formal analytic models. Sometimes, simple theory that involves a few constructs and related propositions with some empirical or analytic grounding, but limited by weak conceptualisation, can be a benchmark for generating research questions. Simulation is also useful for developing theory from research questions that involve a trade-off relationship. This relationship is often in a nonlinear form and difficult to handle by traditional statistical methods. Simulation can be used to suggest interesting or non-intuitive results.

There are two main methods of acquiring and synthesising existing knowledge, narrative review and systematic review (Boland et al., 2014). Narrative review is a traditional way to identify research gaps and encourage new research. Since the process is not well-defined, authors who apply this type of review do not claim to obtain a comprehensive overview of the existing body of knowledge. Systematic literature review is the best way to synthesise the available evidence when conducting research. Its structure is well-defined in order to come up with research questions, and identify, critically assess and synthesise the findings leading to relevant conclusions. Due to the systematic steps, it is very beneficial for comprehending a large amount of literature.

Since there are a small number of studies related to disruption problems in liner shipping, we obtain the simple theory using narrative review (Boland et al., 2014). The research question is developed from an analytical model and the simple theory from a simulation model. All constructs that have contradicting relationships are experimented with, to get a deeper understanding of the theory. The existing theory from an analytical model proposed by Li et al. (2015) is presented in Section 2.4.

The simple theory from analytical and simulation models shows some contradicting relationships, as criticised in Section 2.4. Therefore, the research questions are:

1. What should the appropriate options be to recover from a disruption event for a ship liner with various design configurations of degree of disruption event, designed speed, IFO cost, time window and skipping penalty?
2. To what extent do operational managers manage the disruption in such configurations?

3.2.2 Select Simulation or Optimisation Method

As the research questions are established, the model representing the real world system is formulated, and the proper simulation or optimisation approach is chosen. Four popular methods in OR or MS study are simulation, simulation optimisation, simulation for optimisation, and optimisation. The aim of simulation is investigating the behaviour of real world systems, while the strength of optimisation is searching for optimal solutions within a set of constraints.

Examples of simulation methods are system dynamics, agent-based simulation and discrete event simulation. System dynamics is suitable when there is a high abstraction level with minimal detail at a strategic level (Mchaney et al., 2016). Agent-based simulation is suitable for modelling the behaviours and interactions of autonomous artificial entities to form a social system at the medium abstraction level (Macy and Willer, 2002; Harrison et al., 2007; Macal and North, 2010). At an operational level, discrete event simulation is always applied, particularly when it simulates uncertainty through the creation of exception events (Pidd, 1986; Macal et al., 2010). A good point of discrete event simulation is that the clock updates the time based on the event which can save computational time of the simulator.

The aim of simulation optimisation is to optimise the simulation model (Better et al., 2008). The literature shows that an approach which considers stochastic variables always provides better solutions to the problem than a deterministic model (Aydin et al., 2017; Huang et al., 2012). A flowchart of simulation optimisation is shown in Figure 3.2 (Better et al., 2008). This demonstrates that the simulation model section is responsible for generating many possible fitness values for the optimisation algorithm to search for the optimal solution. On the other hand, the optimisation engine tries to improve the quality of the solution by evaluating the fitness value and providing new input values for the simulation model to find new fitness values again. The procedure continues repeating until the stopping criterion is reached. Finally, a near optimal solution can be obtained. Therefore, simulation optimisation is a candidate technique for applying to optimise stochastic behaviour in a real world problem.

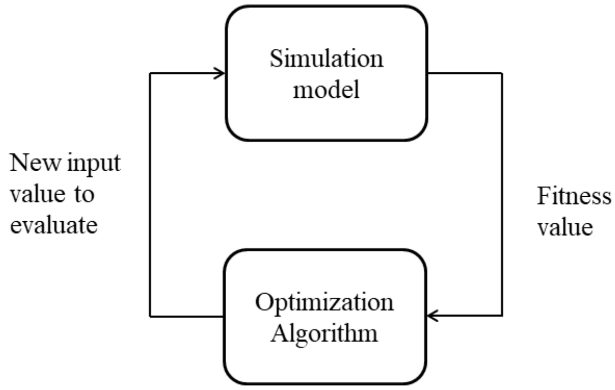

Figure 3.2: The coordination between simulation and optimisation

Simulation for optimisation, on the other hand, is the opposite view to simulation optimisation. This approach aims to understand and predict the behaviour of real world situations by simplifying real world systems into models and generalising the behaviour of the model to real world systems. The difference is that the method is embedded with optimisation routines that search for optimum solutions, which is superior to a pure simulation approach. The flowchart of simulation for optimisation is presented in Figure 3.3. The Monte Carlo simulation is implemented to generate realisation scenarios for a mathematical programming model (Fu, 2002).

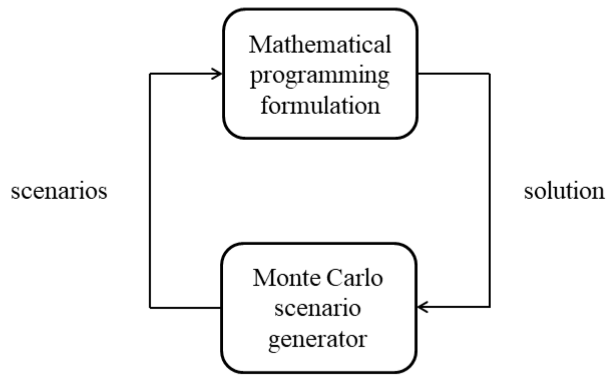

Figure 3.3: Simulation for optimisation

The optimisation approach is another prospective candidate for providing managerial rules for this study. There are two types of optimisation model, deterministic and stochastic mathematic models. Deterministic mathematical models are simpler than stochastic ones. Even though the stochastic model tends to provide better solutions to problems than the deterministic model (Aydin et al., 2017; Huang et al., 2012), many studies still use deterministic models to search for optimal solutions, due to them requiring less computational time and the insignificant difference between the stochastic and deterministic models (Fagerholt et al., 2010; Li et al., 2015). They still have the ability to conduct experiments with various configurations.

In order to answer the research questions of this study, which aim to propose the best strategic rules to recover from a disruption event for a ship liner with various design configurations, an optimisation approach is needed. This study therefore applies a deterministic model and a particle swarm optimisation (PSO) optimiser to suggest managerial rules for the different configurations of liner shipping: degree of disruption event, designed speed, IFO cost, time windows and skipping penalty.

The simulation software package is suitable for the simulation and simulation optimisation approaches (Glover and Kelly, 1996; Fu et al., 2005). However, simulation for optimisation and optimisation are difficult to implement in the software package. We therefore execute the simulator in Visual C# under the Visual Studio.Net environment on a computer with the specification of 1.80 GHz of Intel (R) Core (TM) and 8.00 GB of RAM with Microsoft Windows 8.1 using the concept of Pareto front.

3.2.3 Create Computational Representation

Creating a computational representation includes three activities, operationalising theoretical constructs, specifying assumptions and building algorithms.

In the process of operationalising the theoretical constructs, the measurement of each construct is computationally defined. This is similar to empirical research. The constructs in a simulation (or optimisation) study should be consistent with those in the exiting literature for the correctness of the analysis.

After the theoretical constructs are created, simulation (or optimisation) research is always limited by specific assumptions in the modelling process. However, we can make an assumption to exclude several constructs because they are not important to answering the research questions. All the constructs and assumptions in this study are represented in the form of a mathematical model presented in Chapter 4.

To build the algorithm, the constructs and assumptions are coded in the computer program. The trade-off between parsimony and accuracy is one of the most important issues in building algorithms. In order to verify whether the complicated model is correct, simple algorithm which is intuitively understood is used as a basis for extracting more complex implications. In this study, we implement the simulator in Visual C# software package.

3.2.4 Verify Computational Representation

In a simulation study, it is very important to verify the computational representation. This process helps confirm the internal validation and whether the theoretical logics, constructs and assumptions run correctly without any errors, providing high internal validity. There are many ways to verify computational representations. The correctness of coding needs to be verified through monitoring the values of key variables at each step of an optimisation (or simulation) model. The optimisation (or simulation) model can be internally validated with the existing propositions of the simple theories shown in Section 2.4. The internal validity is presented in Section 5.2.

3.2.5 Validate with Empirical Data

Validation of the optimisation (or simulation) model is the next step in simulation research. This procedure strengthens the simulation model with external validity or empirical data. The importance of external validation is controversial. External validation is less significant in simulation study when there is a lot of empirical data in the literature. However, it is more important when the theory mainly depends on analytical arguments.

As research into disruption problems in liner shipping is based on both analytical and case study of empirical data, the validation issue is less important in this study.

3.2.6 Experiment to Build Novel Theory

New theory is generated through appropriate simulation experiments. There are four ways of setting up simulation experiments. First, new theory is established by varying the values of constructs which are fixed in simple theories. Second, if a multidimensional construct can be divided into several sub-constructs which have their own unique effects, unpacking these constructs is helpful. Third, alternative processes and assumptions are different from the existing model. The fourth method is generating new theory by adding new features that provide a better understanding of the complex interactions among processes. In this study, we apply the first and fourth methods to build novelty into the disruption problem in the literature. This is presented in Chapter 6.

Chapter 4. Model Formulation and Solution Approach

In this chapter, we demonstrate model formulation and solution approach. It starts with model formulation of speeding and skipping model. Then, constructive heuristics in designing speeding and skipping option of PSO algorithm is presented.

4.1 Model formulation

The disruption problem is one variant of the speed optimisation problem. There are many ways to design networks in liner shipping, such as hub and spoke, pendulum, and line bundling or loop (Notteboom, 2006). In this study, a single vessel closed loop is adapted from Fagerholt et al. (2010), Aydin et al. (2017) and Li et al. (2015, 2016) to prescribe managerial rules for recovering from a disruption event.

Parameter settings

j	Segment between port j-1 to Port j
d_j	The distance of segment j
$\bar{v}_j$	The speed of segment j in the planned schedule
α_j	The arrival time at port P_j in the planned schedule
ε_j	The port time at port P_j , i.e., the time for cargo loading and unloading
$\bar{T}_j^d$	The departure time at port P_j in the planned schedule
T_j^a	The arrival time at port P_j in the recovery schedule
T_j^d	The departure time at port P_j in the recovery schedule
Δ	Disruption time (Hours) occurs once at the beginning of the journey
$f_j(v_j)$	Fuel consumption function $f(v_j) = (0.0036v_j^2 - 0.1015v_j + 0.8848)$ tons per mile at vessel size 1001 – 2000 TEU
$\{\alpha_j, \beta_j\}$	Time window (planned arrival time, latest time window)

Decision variables

v_j	The speed of segment j in the recovery schedule

To formally describe the planned schedule and actual journey, the problem is modelled in the form of NLP. A vessel embarks a journey calling at n ports of call along the route. The service agreement for berthing status is negotiated during the planning stage. However, during the actual journey there may be a disruption event. In order for a vessel to keep to the planned time slot, it may need to sail with high speed at the expense of high fuel consumption. It is, therefore, important to minimise these two costs, fuel cost and delay penalty costs.

The fuel consumption functions are derived from Fagerholt et al. (2010) and Yao et al. (2012). Since the unit of fuel consumption derived from Fagerholt et al. (2010) is tonnes per mile, the formulation of fuel consumption during sailing depends on the distance and fuel consumption rate of the main engine at sailing speed v_j and the IFO fuel price as shown in (4.1).

$$Min\ Z = IFO \sum_{j=1}^{n} \left[f(v_j) \times d_j \right] + \sum_{j=1}^{n} J_j\ (T_j^a - \beta_j)^+$$	(4.1)

4.1.1 Speed Optimization

In the planned schedule, we assume that a vessel starts a journey at port 0 with the arrival time 0 $\alpha_0 = 0$. ε_j is a notation of port time j. We therefore have the departure time at the origin port as $\bar{T}_0^d = \varepsilon_0$.

The vessel sails with appropriate speed in each leg to arrive at the following port of call within the predefined time. (4.2) shows the calculation from the planned departure time at port $j-1$ plus the sailing time at leg j which is derived from distance divided by planned speed at leg j. We note that leg n is the leg between port $n-1$ and the origin port, because of closed loop liner shipping.

$\alpha_j = \bar{T}_{j-1}^d + d_j/\bar{v}_j$; j=1, 2, ..., n	(4.2)

The recursive calculation from arrival time to departure time is shown in (4.2). The departure time at port j is plus the port time at the corresponding port. Since the origin and destination port are the same, this explains why (4.1) considers port index up to $n-1$.

$\bar{T}_j^d = \alpha_j + \varepsilon_j$; j=1, 2, ..., n-1	(4.3)

The actual journey, however, does not always follow the planned schedule. A disruption event such as severe weather conditions or a labour strike may happen and cause delay to the original plan.

In the actual journey, we assume the arrival time at port 0 to be the same as the planned schedule. However, a disruption event may occur at the port. The actual departure therefore may need to include the original port time with the delay time $T_0^d = \varepsilon_0 + \Delta$ The same concept of actual arrival and actual departure time are applied to the following ports of call in the voyage, shown in (4.4) and (4.5).

$T_j^a = T_{j-1}^d + d_j/\bar{v}_j$; j=1, 2, ..., n	(4.4)
$T_j^d = T_j^a + \varepsilon_j$; j=1, 2, ..., n-1	(4.5)

Intuitively, it is never be beneficial if a vessel arrives earlier than the planned arrival time because other vessels may still be in the operation process meaning unavailability of the berthing slot. It is therefore better to slow down to save fuel

consumption as presented in (4.6).

$T_j^a \geq \alpha_j$; j=1, 2, ..., n	(4.6)

It should be noted that the vessel can only sail within a range of speeds, from a minimum (the most fuel efficient speed) to a maximum which is a technical specification, as presented in (4.7).

$\bar{v}_j < v_j < v_{max}$; j=1, 2, ..., n	(4.7)

4.1.2 Skipping Option

In skipping option, it extends speeding option by adding following limitations.

1. Identify the number of skipping ports of call m_s
2. Randomly select the first skipping port of call *j+1* between port of call 1 and port of call *n-1* and add all skipping ports *j+1, j+2, …, i-1* into the skipping ports vector
3. Assign extra skipping port time to previous port $\delta_j = \varepsilon_{j+1} + \varepsilon_{j+2} + \cdots + \varepsilon_{i-1}$ for handling containers that have to be transported to port *j+1, j+2, …, i-1*

4.2 Particle Swarm Optimisation (PSO) algorithm

In biology, the behaviour of a group of birds foraging for food can be explained as follows. The group has the ability to reach to the best location for food. Each bird has not only its own cognitive ability to find the best location but also a social ability to communicate with the group what they have learned so far. Kennedy and Eberhart (1995) adopt this biological concept to propose a framework called a PSO algorithm to find optimal solutions in simulation studies in the OR/MS field. PSO is a successful metaheuristic algorithm due to its efficiency and effectiveness shown over several decades (Kachitvichyanukul, 2012). We therefore adopt this concept as an optimisation tool, suggesting an optimal plan to avoid and recover from disruption events. The detailed PSO framework and the design of the solution representations and constructive heuristics of each option are demonstrated as follows.

There is an *H*-dimensional vector for each particle *l*. The position, velocity, personal best position and global best particle for each particle can be represented by $\theta_{lh}(\tau)$, $\omega_{lh}(\tau)$, $\psi_{lh}(\tau)$ and $\psi_{gh}(\tau)$. τ is the iteration number. $Z_l(\tau)$ denote the fitness value of particle l at iteration τ.

First, the number of the particles in the swarm and the maximum number of iteration T for the stopping criterion are initialized. The solution representation of the position and constructive heuristics for each option are designed as shown in section 4.1 to 4.3. The velocity $\omega_{lh}(1)$ is assigned as 0 for every particle in the swarm.

Second, the evaluation process is calculated by using (4.1) to (4.7) as presented in section 4.1. for each particle in the swarm, in order to calculate total costs.

Third, the algorithm updates the personal best position by comparing the fitness value of each particle l whether $Z_l\psi_l(\tau)$ at iteration τ is less than that $Z_l\psi_l(\tau - 1)$ at iteration $\tau - 1$. If it is, $Z_l\psi_l(\tau)$ is updated to be personal best particle. The personal best position is then assigned $\psi_{lh}(\tau)$.

Fourth, the global best particle is assigned by selecting the best particle so far. If

$Z_l(\tau)$ is less than $Z_g(\tau)$, updating $Z_g(\tau)$ to be equal to $Z_l(\tau)$. The global best position is therefore equal to $\psi_{gh}(\tau) = \psi_{lh}(\tau)$.

Fifth, the particles are moved to the next position by velocity and previous position following the equations. (4.8) shows that the velocity is updated based on a combination of six components which are the summation of the product of the current velocity of each particle and inertia weight, the product of the personal best and personal accelerating constant, and the product of the global best position and global accelerating constant.

$\omega_{lh}(\tau+1) = w(\tau)\omega_{lh}(\tau) + c_p\mu(\psi_{lh} - \theta_{lh}(\tau)) + c_g\mu\left(\psi_{gh} - \theta_{lh}(\tau)\right)$	(4.8)

After updating the velocity of each particle, the particles move to new positions as shown in (4.9).

$\theta_{lh}(\tau+1) = \theta_{lh}(\tau) + \omega_{lh}(\tau+1)$	(4.9)

We note that c_p and c_g are accelerating constants, which are random number between 0 and 1. The inertia weight at each iteration is shown in (4.10). The duties of inertia weight, global and personal accelerating constant are to guide the direction of each particle in the swarm.

$w(\tau) = w(T) + \frac{\tau - T}{1 - T}[w(1) - w(T)]$	(4.10)

Sixth, this step is an additional step in case the new position becomes an infeasible solution due to not meeting sailing speed constraints. Therefore, the conditions, as presented in (4.11) and (4.12), force the position of each particle to be within the feasible region, which is in the minimum θ_{min} and maximum θ_{max} position value.

If $\theta_{lh}(\tau+1) > \theta_{max}$, then $\theta_{lh}(\tau+1) = \theta_{max}$ and $\omega_{lh}(\tau+1) = 0$	(4.11)
If $\theta_{lh}(\tau+1) < \theta_{min}$, then $\theta_{lh}(\tau+1) = \theta_{min}$ and $\omega_{lh}(\tau+1) = 0$	(4.12)

Finally, the iterative process repeats from the second step until the termination criterion is met.

4.2. 1 Solution representation

It should be noted that we apply the direct encoding scheme to represent the decision variables (average vessel speed v_i at leg i) of the position of the particle in the swarm. Generally, there are H dimensions for each position. Since we use direct encoding in this study and there are n ports of call, n dimensions are assigned to all elements of each particle in the swarm. The position $\theta_{lh}(1)$ at iteration 1 is randomly generated by setting the average speed v_i at leg I between the range of minimum and maximum sailing speed [v_{min}, v_{max}]. The velocity $\omega_{lh}(1)$ is assigned as 0 for every particle in the swarm. The personal best position and global best position also consist of n dimensions and each dimension is the speed of the vessel in each leg that provides minimum total cost for each individual and among the group so far. This solution representation is presented in Figure 4.1.

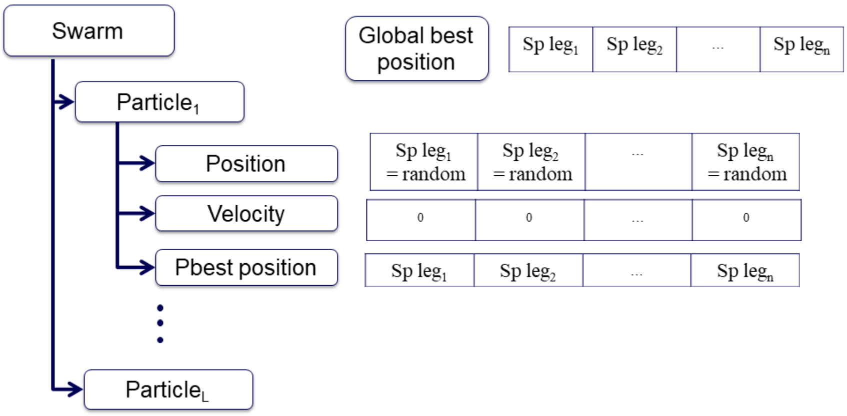

Figure 4.1: Solution representation

4.2. 2 Constructive Heuristics of Speeding Option

The closed loop of a journey applying the vessel speeding option means a vessel starts from the origin port and sails through the predefined schedule and back to the origin port, as presented in Figure 4.2. The advantage of this algorithm is that a vessel may be able to arrive within the predefined schedule without sacrificing penalty costs for skipping or swapping any ports. The pseudo code for this option is enumerated in Algorithm 4.1.

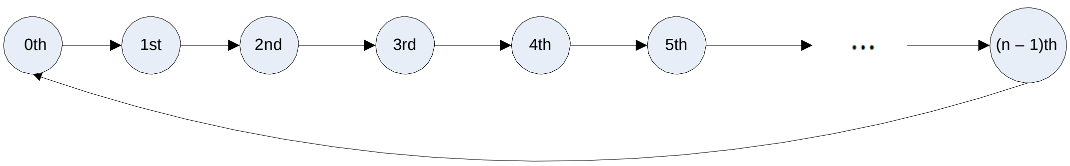

Figure 4.2: Speeding option

Algorithm 4.1: Speeding option

$T_0^a = 0$

$T_0^d = \varepsilon_0 + \delta_0 + \Delta$

For $j = 1$ To $n - 1$

  $T_j^a = T_{j-1}^d + d_j / v_j$

  If $T_j^a < \alpha_j$

    $v_j = d_j / (\alpha_j - T_{j-1}^d)$

    $T_j^a = T_{j-1}^d + d_j / v_j$

```
        End If
        T_j^d = T_j^a + ε_j
    End For
    T_0^a = T_{n-1}^d + d_0/v_0
```

According to Algorithm 4.1, a vessel begins its journey at port 0 with arrival time equal to 0. The departure time at port 0 is the sum of the arrival time, the port time and disruption time. Then, there is a recursive loop of arrival and departure time from port 1 to port *n-1*. The arrival time is the time between previous port departure plus sailing time. The departure time is the arrival time plus port time.

4.2. 3 Constructive Heuristics of Skipping Option

The skipping option is an extended version of the speeding option. Instead of sailing through all ports of call as in the previous option, the vessel can skip some ports of call, which may not be important ports. The skipping option is useful when fuel prices are high or there is a long delay time and the vessel's maximum speed is low (Li et al., 2015).

Li et al. (2015) only consider a few port skipping decisions located within a geographical region. We assume that the sequence of ports of call {P0, P1, …, Pn} can be partitioned into m + 1 sub-routes {Q0, Q1, …, Qm}. The notation for each sub-route Qq includes is Q0 ={P0}, Q1 = {P1, …, P|Q1|}, Q2 = {P|Q1|+1, …, P|Q1|+|Q2|}, …, and Qm = {Pn−|Qm|+1, …, Pn}. It should be noted that we assume the sub-route Q0 includes only port P0. The threshold parameter ω is used to categorise a sub-route. Specifically, the ports start from j = 1. Port P_j is in the a new sub-route if sailing distance $d_j > \omega$; however, if the sailing distance $d_j \leq \omega$, port P_j is in the same sub-route as port P_{j-1}. It is obvious that if a value of ω is large, it leads to a larger sub-route. Therefore, a better quality solution tends to be obtained. For an easier understanding, Figure 4.3 depicts practical possible skipping ports from a real case study of a Trans-Pacific route: {P0, P1}, {P3, P4}, and {P5, P6}. The skipping option is presented in Algorithm 4.2.

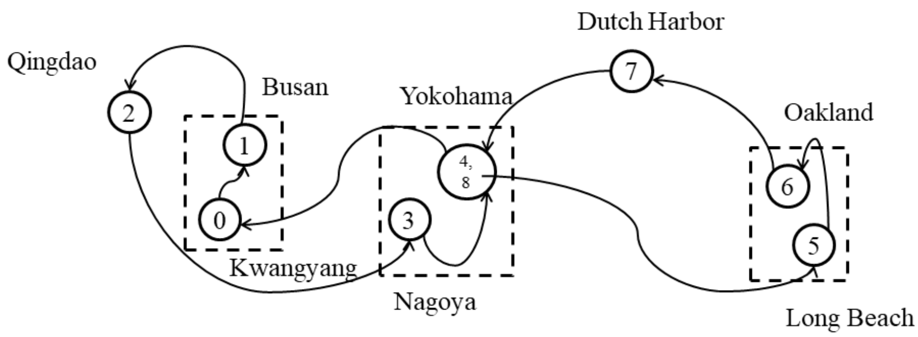

Figure 4.3: Skipping option (Li et al., 2015)

Algorithm 4.2: Selecting the skipping ports proposed by Li et al. (2015)

1. Group the ports which are located within the same region by letting port Pj be in the same sub-route as port Pj−1 if their sailing distance dj ≤ ω and generate a new sub-route if dj > ω.
2. Randomly select the first skipping port of call *j+1* between port of call 1 and port of call *n-1* and add all skipping ports *j+1, j+2, …, i-1* into the skipping ports vector
3. Assign extra skipping port time to previous port $\delta_j = \varepsilon_{j+1} + \varepsilon_{j+2} + \cdots + \varepsilon_{i-1}$ for handling containers that have to be transported to port *j+1, j+2, …, i-1*

However, the skipping ports proposed by Li et al. (2015) may provide local optimal solutions due to the limited choices when selecting skipping ports. We therefore propose a more general possibility for selecting skipping ports by not limiting the ports to the same region. **Figure 4.4** shows that port $\boldsymbol{j+1}$ until port $\boldsymbol{i-1}$ are skipped. The skipping option is presented in **Algorithm 4.3**.

Algorithm 4.3 provides details of how the skipping ports of call are designed. First, the number of skipping ports of call are set. Then, the first skipping port of call *j+1* is randomly selected between port of call 1 to *n-1*. The maximum number of skipping pors is calculated as *n-2* because the origin port (port 0) and another one in the voyage have to be visited to make a closed loop journey. The final step is calculating the handling time for the containers carried to all skipping ports *j+1, j+2, …, i-1* and assign them extra handling time $\delta_j = \varepsilon_{j+1} + \varepsilon_{j+2} + \cdots + \ \varepsilon_{i-1}$ at j port of call.

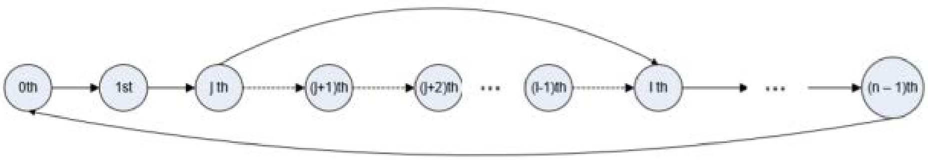

Figure 4.4: Proposed skipping option

Algorithm 4. 3: Proposed selection of skipping ports

1. Identify the number of skipping ports of call m_s
2. Randomly select the first skipping port of call *j+1* between port of call 1 and port of call *n-1* and add all skipping ports *j+1, j+2, …, i-1* into the skipping ports vector
3. Assign extra skipping port time to previous port $\delta_j = \varepsilon_{j+1} + \varepsilon_{j+2} + \cdots + \ \varepsilon_{i-1}$ for handling containers that have to be transported to port *j+1, j+2, …, i-1*

Algorithm 4.4: Calculating the arrival and departure time

$T_0^a = 0$

$T_0^d = \varepsilon_0 + \delta_0 + \Delta$

For $j = 1$ To $n - 1$

$\quad T_j^a = T_{j-1}^d + d_j/v_j$

$\quad$ If $T_j^a < \alpha_j$

$\quad\quad v_j = d_j/(\alpha_j - T_{j-1}^d)$

$\quad\quad T_j^a = T_{j-1}^d + d_j/v_j$

$\quad$ End If

$\quad T_j^d = T_j^a + \varepsilon_j + \delta_j$

10 $j = i$

11 End For

12 $T_0^a = T_{n-1}^d + d_0/v_0$

= ��$^{\boldsymbol{d}}$ $+ \boldsymbol{d} / \boldsymbol{v}$

After the skipping ports of call are set, the arrival and departure time at all ports of call except the skipping ports are scheduled as presented in Algorithm 4.4. Almost all the steps of the skipping option are the same as the vessel speeding up option. The only difference is that there is extra unloading and loading time δ_j incurred at port j if skipping the following ports $j+1, j+2, \ldots, i-1$ as shown in line 2 and line 9. It should be noted that line 10 tries to skip all the skipping ports of call to the next port of call i.

Chapter 5. Experiment and Result

Chapter 5 illustrates experiment and result of the study. It starts the chapter with input data. Then, model validation is presented. Experimental studies of various configurations which are the degrees of disruption, maximum speeds, fuel prices, time windows and skipping penalties are finally demonstrated.

5.1 Input Data

This study adopts the setting of the trans-Pacific route from Li et al. (2015). The trans-Pacific route consists of nine ports of call sequenced Kwangyang (KWA, SK); Busan (BUS, SK); Qingdao (QIN, CN); Nagoya (NAG, JP); Yokohama (YOK, JP); Long Beach (LON, US); Oakland (OAK, US); Dutch Harbor (DUT, US); Yokohama; and back to Kwangyang, as shown in Figure 5.1. The schedule and distances between each port of call on the voyage are presented in Table 5.1 and Table 5.2.

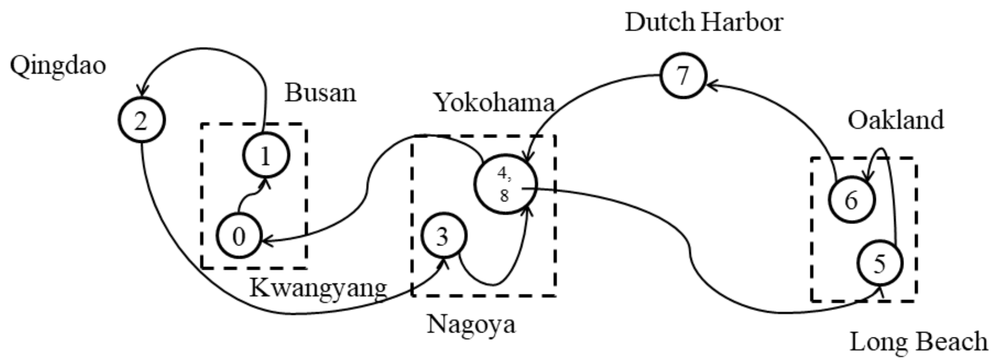

Figure 5.1: Trans-Pacific route

Table 5.1: Schedule for trans-Pacific route

Port	Planned arrival time	Port time (hours)
Kwangyang	Friday 03:30	8
Busan	Friday 21:00	18
Qingdao	Sunday 21:00	10
Nagoya	Thursday 08:00	8
Yokohama	Friday 08:00	8

Long Beach	Monday 08:00 (one week later)	43
Oakland	Thursday 08:00	9
Dutch Harbor	Tuesday 08:00	21
Yokohama	Tuesday 18:00 (one week later)	10
Kwangyang	Friday 03:30	8

Table 5.2: Distance (nautical miles) between each port of call

	KWA	BUS	QIN	NAG	YOK	LON	OAK	DUT
KWA	0	103	421	724	837	5,377	5,061	3,044
BUS	103	0	476	699	813	5,294	4,978	2,961
QIN	421	476	0	1,029	1,143	5,748	5,431	3,414
NAG	724	699	1,029	0	205	4,977	4,674	2,692
YOK	837	813	1,143	205	0	4,844	4,536	2,550
LON	5,377	5,294	5,748	4,977	4,844	0	364	2,404
OAK	5,061	4,978	5,431	4,674	4,536	364	0	2,062
DUT	3,044	2,961	3,414	2,692	2,550	2,404	2,062	0

We adopt some simple setting from this trans-Pacific route as follows. First, a linear delay penalty function $J(\delta) = w_j \cdot \delta$ where the weight w_j is assumed at port P_j linearly depends on the port time ε_j; i.e., $w_j = \alpha \cdot \varepsilon_j$ is used in this study. If a port time is longer, it usually implied that there are a larger number of containers unloaded and loaded at the port. A delay will therefore affect more containers, leading to a higher delay penalty. We assume $\alpha = \$230$ in this study (Li et al., 2015). This results in a delay costs in the range [\$1,840, \$9,890] per hour for the ports of call on the route.

We refer to the skipping option used in this study in section 4.2.3. We also set skipping cost $C_{ij} = \beta \cdot \sum_{k=i+1}^{j-1} \varepsilon_k$ and skipping port time $S_{ij}^i = S_{ij}^j = 0$. We use the fuel cost function suggested by Fagerholt et al. (2010) to be $f(v) = \$Q(0.0036v^2 - 0.1015v + 0.8848)$ for all segments with v_{max} knots. We note that Q, v_{max} and β are set as presented in Appendix A.

In order to measure the effect of port skipping, we set $S_{ij}^i = \sum_{k=i+1}^{j-1} \varepsilon_k$, to be the total port time at the skipping ports. Then, we set $S_{ij}^i = S_{ij}^j = 0.5 S_{ij}$, assuming the load to be shared by port P_i and P_j. Let the skipping cost $C_{ij} = \beta \cdot S_{ij}$, where β is experimented with in section 5.7.

5.2 Model Validation

In a simulation study, we must first validate the basic model of the recovery schedules of speeding and port skipping options under different scenarios. We use the trans-Pacific route and show the details of some schedules. First, we demonstrate various recovery schedules beginning with port P_0 with various initial delays Δ (in hours), shown in Table 5.3. Each column indicates the arrival delays of a vessel at each port of call under a specific initial delay Δ. We note that "/" stands for the skipping port while "-" means planned schedule catch up with by a vessel at the ports of call.

Table 5.3: Remaining delay before recovering the planned schedules

Initial Delay	24	48	72	96	120
Trans-Pacific routes					
Schedule of speeding option					
Delay time at P_1	19.54	42.84	66.63	90.62	114.62
Delay time at P_2	15.33	33.96	56.60	79.66	103.66
Delay time at P_3	2.78	8.21	27.96	48.66	71.85
Delay time at P_4	-	1.91	21.00	41.18	64.19
Delay time at P_5	-	1.91	8.46	14.92	33.34
Delay time at P_6	-	-	-	3.93	21.67
Delay time at P_7	-	-	-	-	12.93
Delay time at P_8	-	-	-	-	-
Delay time at P_0	-	-	-	-	-
Schedule with the option of port skipping					
Delay time at P_1	18.62	44.64	68.08	91.50	/
Delay time at P_2	15.38	/	/	/	/
Delay time at P_3	-	-	-	9.50	/
Delay time at P_4	-	-	-	2.46	/
Delay time at P_5	-	-	-	-	-

Delay time at P_6	-	-	-	-	-
Delay time at P_7	-	-	-	-	-
Delay time at P_8	-	-	-	-	-
Delay time at P_0	-	-	-	-	-

Table 5.3 demonstrates that the vessel may not use its maximum speed in recovering the schedule in the case of low initial delay, while it tends to use its full speed to recover the delay when the initial delay tends to increase. For instance, in the case of the speeding option, when the initial delay $\Delta = 24$ hours, the vessel recovers the delay by $24-19.54 = 4.46$ hours in the first segment. Moreover, when the initial delay $\Delta = 48$ hours, the vessel recovers the delay by 48 – 42.84 = 5.16 hours in the first segment. As the initial delay increases, the vessel speeds up more. For example, when the initial delay Δ **=** 120 hours**,** the vessel makes up the delay by 120 – 114.62 = 5.38 hours. This is in line with the finding of Li et al. (2015).

In the case of the port skipping option, it can be seen that when the initial delay is low $\Delta = 24$ hours, the vessel does not skip any ports but it skips when initial delay is higher $\Delta = 48$ hours or more. Moreover, when $\Delta = 120$ hours or more, the vessel even skips four ports. This finding validates those of Li et al. (2015), that port skipping is more beneficial for longer delays.

Table 5.4: Speeds before recovering planned schedules

Initial Delay Δ	**24**	**48**	**72**	**96**	**120**
			Trans-Pacific routes		
			Speeding option		
Speed from P_0 to P_1	20.42	23.74	24.90	25.00	25.00
Speed from P_1 to P_2	18.46	22.54	23.85	25.00	25.00
Speed from P_2 to P_3	17.03	21.79	23.21	24.51	25.00
Speed from P_3 to P_4	15.51	21.13	22.66	24.04	24.55
Speed from P_4 to P_5	-	20.88	22.07	23.55	24.08
Speed from P_5 to P_6	-	13.44	17.72	20.20	21.00
Speed from P_6 to P_7	-	-	-	19.26	20.17
Speed from P_7 to P_8	-	-	-	-	17.70

Port skipping option					
Speed from P_0 to P_1	25.00	16.77	18.46	20.59	/
Speed from P_1 to P_2	17.79	/	/	/	/
Speed from P_2 to P_3	17.86	10.23	15.57	22.57	/
Speed from P_3 to P_4	-	-	-	22.88	/
Speed from P_4 to P_5	-	-	-	21.10	18.90
Speed from P_5 to P_6	-	-	-	-	-
Speed from P_6 to P_7	-	-	-	-	-
Speed from P_7 to P_8	-	-	-	-	-

Table 5.4 shows the sailing speeds for each of the schedules given in Table 5.3. Since we focus on the speeds in each segment before the vessel catches up with its planned schedule, the remaining speeds after it catches up with its planned schedule are omitted. Table 5.4 demonstrates a decreasing trend in the sailing speed over consecutive segments along each schedule. In other words, if the journey is delayed, it is better to speed up more in early segments so that the delay is not propagated too far. This claim verifies the results of Li et al. (2015).

Since the basic model is validated in Sections 4.2.1 to 4.2.3, we use the model to generate a new theory. Managerial rules for the appropriate plan (speeding or skipping) under various degrees of disruption, maximum speeds, fuel prices, time windows and skipping penalties are proposed as follows.

5.3 Value of Port Skipping Option under Various Degrees of Disruption

We show the relative savings by the option of port skipping under different initial delay Δ and linear delay penalty functions $J(\delta)$ as presented in Table 5.5. We measure the relative saving as follows.

$$\left(1-\frac{cost\ of\ an\ optimal\ schedule\ with\ the\ option\ of\ port\ skipping}{cost\ of\ an\ optimal\ schedule\ without\ hte\ option\ of\ port\ skipping}\right)\times 100\%$$

Table 5.5: Relative total savings by the option of port skipping under various degrees of disruption

Initial Delay	Skipping IFO	Skipping Delay	Skipping Total	Skipping (Li et al., 2015) Total
24	- 0.74%	5.01%	- 0.34%	0%
48	14.98%	- 85.47%	1.53%	0.76%
72	25.07%	- 5.51%	18.24%	3.08%
96	34.53%	0.95%	25.41%	8.85%
120	39.81%	19.21%	32.52%	16.31%
144	42.46%	31.92%	37.68%	26.83%

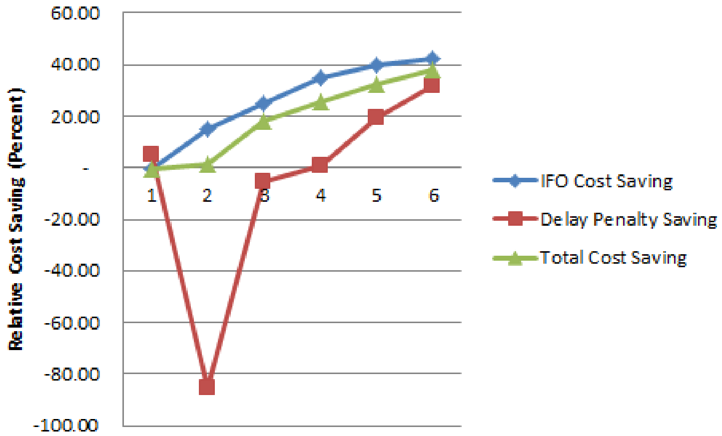

Figure 5.2: Relative savings by the option of port skipping under various degrees of disruption

The first experiment investigates the impact of various degrees of disruption on setting the proper option. Not surprisingly, the findings confirm those of Li et al. (2015) who found port skipping always brings more savings under high degrees of disruption. Table 5.5 and **Figure 5.2** reveal that the speeding option performs better than the skipping option when the disruption time is 24 hours, because total relative saving is -0.34 percent. The explanation for this is that at the lower delay level, a vessel does not skip any ports of call and applies a higher vessel speed, as presented in Table 5.4. Higher speed leads to higher IFO cost. Not surprisingly, higher speed always brings about lower delay penalties as presented in Table 5.5. Therefore, the combination of these two components and the dominant factor of high speed, results in the finding presented above.

There is, however, a tendency for skipping to provide more total savings than speeding when the disruption period increases from 48 hours to 144 hours. This total saving rises sharply from 1.53 percent to 25.41 percent when the initial delay increases from 48 hours to 96 hours, because of the steady increase of IFO costs and the sharp change in delay penalties. This result is explained by the fact that the skipping option can reduce the speed and distance, as demonstrated in Table 5.4. Nevertheless, it does not always lead to lower delay penalties as presented in Table 5.5. Given the dominant factors of speed and distance, the skipping option can save on total cost more than the speeding option in the case of medium degrees of disruption.

For large degrees of disruption, the relative savings slightly increase after 96 hours (25.41 percent to 37.68 percent). These results are likely to be related to the consistent saving of IFO costs and delay penalties. Intuitively, since the degree of disruption is large, the skipping option can save more IFO costs and delay penalties than the speeding option.

Even though the general concept reinforces that of Li et al. (2015), the total savings at many levels of initial delay are different. Li et al. (2015) show a steady total cost saving increase from 0 percent to 26.83 percent as the initial delay rises from 24 hours to 144 hours. The proposed skipping option provides greater total saving than shown by Li et al. (2015), as presented in Table 5.5. This discrepancy could be attributed to the design of the algorithm because the proposed skipping option is more flexible in selecting skipping ports of call than that proposed by Li et al. (2015). The proposed skipping option and the skipping option proposed by Li et al. (2015) are presented in Section 4.2.3.

5.4 Value of Port Skipping Option under Various Maximum Speeds

The second experiment investigates the effect of various maximum speeds and disruption period on choosing the proper option (speeding or skipping).

Table 5.6: Relative total savings by the option of port skipping under various maximum speeds

Initial Delay	Port skipping				
	V_{max} = 20	V_{max} = 22.5	V_{max} = 25	V_{max} = 27.5	V_{max} = 30
24	- 0.34%	- 0.29%	- 0.34%	- 0.45%	- 0.38%
48	3.70%	1.51%	1.53%	1.54%	1.55%
72	24.98%	18.49%	18.24%	18.24%	18.32%
96	31.79%	26.70%	25.41%	25.39%	25.27%
120	36.98%	33.73%	32.52%	32.60%	32.60%
144	42.16%	38.84%	37.68%	37.66%	37.66%

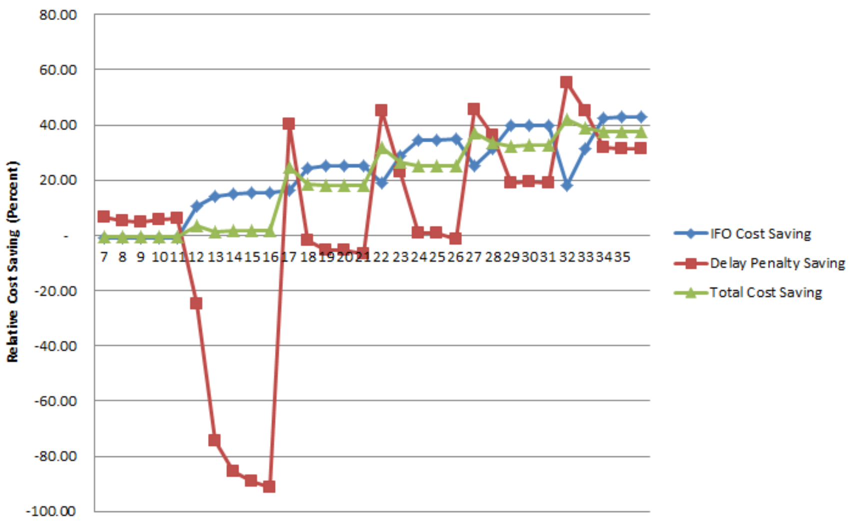

Figure 5.3: Relative savings by the option of port skipping under various maximum speeds

As shown in Table 5.6 and **Figure 5.3**, the results are in line with those obtained by Li et al. (2015), who suggest that port skipping is more valuable when the maximum vessel speed is low. The explanation for these results is that port skipping can recover the disruption and save the delay penalty. On the other hand, the speeding option cannot use high speed to catch up with the delay when the vessel has a low maximum speed, as presented in Table 5.7. An interesting pattern is that there is no significant difference between v_{max} = 22.5 knots and v_{max} = 30 knots for the speeding and skipping options. This implies that a vessel rarely speeds up to over 22.5 knots, as demonstrated in Table 5.7. This observation also confirms Li et al. (2015).

Table 5.7: Speed on each leg under various maximum speeds

Initial Delay Δ	Maximum speed 20					Maximum speed 25					Maximum speed 30				
	24	48	72	96	120	24	48	72	96	120	24	48	72	96	120
								Speeds without the option of port skipping							
Speed from P_0 to P_1	20.42	20.00	20.00	20	20	20.42	23.74	24.90	25.00	25.00	20.00	24.17	24.90	26.00	26.41
Speed from P_1 to P_2	18.46	20.00	20.00	20	20	18.46	22.54	23.85	25.00	25.00	20.00	23.03	23.85	25.06	25.52
Speed from P_2 to P_3	17.03	20.00	20.00	20	20	17.03	21.79	23.21	24.51	25.00	20.00	22.32	23.21	24.51	24.99
Speed from P_3 to P_4	15.51	20.00	20.00	20	20	15.51	21.13	22.66	24.04	24.55	20.00	21.71	22.66	24.03	24.54
Speed from P_4 to P_5	-	20.88	20.88	20.88	20.88	-	20.88	22.07	23.55	24.08	20.88	-	22.07	23.54	24.07
Speed from P_5 to P_6	-	19.33	20.00	20	20	-	13.44	17.72	20.20	21.00	19.33	-	17.72	20.19	20.98
Speed from P_6 to P_7	-	-	20.00	20	20	-	-	-	19.26	20.17	-	-	-	19.25	20.14
Speed from P_7 to P_8	-	-	17.75	17.75	17.75	-	-	-	-	17.70	-	-	-	-	17.66
Speed from P_8 to P_0	-	-	17.62	17.62	17.62	-	-	-	-	-	-	-	-	-	-
								Speeds with the option of port skipping							
Speed from P_0 to P_1	20	16.75	18.44	/	/	25.00	16.78	18.46	20.59	/	26.05	16.73	18.50	/	/
Speed from P_1 to P_2	20	/	/	/	/	17.79	/	/	/	/	18.04	/	/	/	/

Speed from P_2 to P_3	17.28	10.23	15.57	15.92	/	17.86	10.23	15.57	22.57	/	16.74	10.23	15.56	15.92	/
Speed from P_3 to P_4	-	-	-	13.67	/	-	-	-	22.88	/	16.20			13.66	/
Speed from P_4 to P_5	-	-	-	-	18.90	-	-	-	21.10	18.90	-	-	-	-	18.81
Speed from P_5 to P_6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Speed from P_6 to P_7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Speed from P_7 to P_8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

As shown in Table 5.7 and Table 5.8, another explanation is that the option of port skipping can save more IFO cost than the speeding option because the total distance in the voyage is shorter. We note that the total distance shortens as the degree of disruption increases. In contrast, the distance is not sensitive to increase in maximum speed. Since there is no literature which observes this theory and it confirms our intuition, this finding can be considered one contribution to the disruption problem in liner shipping.

Table 5.8: Relative IFO savings by the option of port skipping under various maximum speeds

Initial Delay	**Port skipping**				
	$V_{max} = 20$	$V_{max} = 22.5$	$V_{max} = 25$	$V_{max} = 27.5$	$V_{max} = 30$
24	-0.89%	-0.72%	-0.74%	-0.93%	-0.86%
48	10.65%	14.12%	14.98%	15.26%	15.40%
72	16.18%	24.54%	25.07%	25.07%	25.39%
96	18.79%	28.79%	34.53%	34.51%	35.10%
120	25.20%	31.42%	39.81%	39.62%	39.88%
144					

	18.09%	31.38%	42.46%	42.75%	42.72%

Even though it saves IFO costs, a vessel needs to pay higher skipping penalties, particularly in the case where a vessel has a high maximum speed, as presented in Table 5.9. This result is explained by the fact that a vessel prefers to skip many ports to reduce the total distance in the voyage and apply not such high speed. This is because distance and maximum speed are the dominant factors in marine transportation. As a result, the skipping option saves less delay penalty costs than the speeding option.

Table 5.9: Relative delay penalty savings by the option of port skipping under various maximum speeds

Initial Delay	**Port skipping**				
	V_{max} = 20	V_{max} = 22.5	V_{max} = 25	V_{max} = 27.5	V_{max} = 30
24	6.63%	5.46%	5.01%	5.92%	6.04%
48	-24.79%	-74.30%	-85.47%	-89.16%	-91.20%
72	40.43%	-1.62%	-5.51%	-5.51%	-6.65%
96	45.01%	22.90%	0.95%	0.70%	-1.39%
120	45.41%	36.38%	19.21%	19.63%	19.21%
144	55.46%	44.94%	31.92%	31.45%	31.49%

5.5 Value of Port Skipping Option under Various Fuel Prices

The third experiment is to find the effect of various fuel prices and disruption periods on choosing the proper option (speeding or skipping).

Table 5.10: Relative total savings by the option of port skipping under various fuel costs

Initial Delay	Port skipping Q=100	Q=300	Q=500	Q=700	Q=900
24	- 0.04%	- 0.14%	- 0.34%	- 1.92%	4.97%
48	- 2.58%	- 5.20%	1.53%	6.93%	12.86%
72	- 0.13%	14.42%	18.24%	19.70%	22.80%
96	16.27%	24.33%	25.41%	27.17%	28.27%
120	28.54%	31.39%	32.52%	33.33%	33.47%
144	39.32%	35.82%	37.68%	37.40%	35.83%

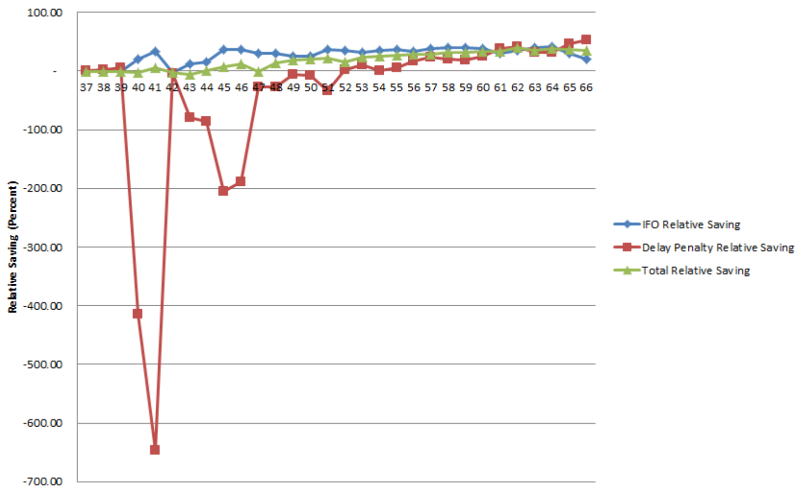

Figure 5.4: Relative savings by the option of port skipping under various fuel costs

In the case of low initial delay (24 hours), the skipping option is recommended when fuel prices are high ($900), as presented in Table 5.10 and Table 5.11. An explanation is that skipping some ports of call can reduce distance and speed which are the dominant factors, as presented in Table 5.11 and Table 5.12, even though skipping leads to higher delay costs. This result is consistent with the findings of Li et al. (2015).

In the case of lower medium initial delay (48 hours), the skipping option is also suggested when the fuel price is greater than medium. For example, Table 5.10 shows that if the fuel price ranges between $500 and $900, the skipping option is recommended. The higher the fuel price, the higher the savings from fuel costs, as demonstrated in Table 5.12, even though delay costs tend to increase due to skipping some ports of call, which costs a large amount of money, as shown in Table 5.13. However, in general, due to the reduction of distance and speed the skipping option is recommended in this case.

In the case of medium initial delay (72 hours), the skipping option is recommended when the fuel price is greater than lower medium ($300), as shown in Table 5.10.

Table 5.11: Speed on each leg under various fuel prices

Initial Delay Δ	Fuel price = 100					Fuel price = 500					Fuel price = 900				
	24	**48**	**72**	**96**	**120**	**24**	**48**	**72**	**96**	**120**	**24**	**48**	**72**	**96**	**120**
Speeds without the option of port skipping															
Speed from P_0 to P_1	25.00	25.00	25.00	25.00	25.00	20.42	23.74	24.90	25.00	25.00	19.20	21.90	23.09	23.09	
Speed from P_1 to P_2	21.99	25.00	25.00	25.00	25.00	18.46	22.54	23.85	25.00	25.00	17.96	21.08	22.38	22.38	23.09
Speed from P_2 to P_3	16.41	22.26	25.00	25.00	25.00	17.03	21.79	23.21	24.51	25.00	17.13	20.59	21.97	21.97	22.38
Speed from P_3 to P_4	12.81	18.47	24.95	25.00	25.00	15.51	21.13	22.66	24.04	24.55	16.36	20.16	21.62	21.62	21.97
Speed from P_4 to P_5	-	-	22.43	25.00	25.00	-	20.88	22.07	23.55	24.08	-	20.88	21.25	21.25	21.62
Speed from P_5 to P_6	-	-	-	13.39	24.08	-	13.44	17.72	20.20	21.00	-	16.51	18.88	18.88	21.25
Speed from P_6 to P_7	-	-	-	-	20.82	-	-	-	19.26	20.17	-	-	18.58	18.58	18.88
Speed from P_7 to P_8	-	-	-	-	-	-	-	-	-	17.70	-	-	16.24	16.46	18.58
Speed from P_8	-	-	-	-	-	-	-	-	-	-	-	-	17	17	17.6

to P_0													.62	.62	2
Speeds with the option of port skipping															
Speed from P_0 to P_1	24.61	25.00	24.27	25.00	/	25.00	16.78	18.46	20.59	/	17.16	17.67	18.56	19.71	/
Speed from P_1 to P_2	22.13	25.00	/	/	/	17.79	/	/	/	/	/	/	/	/	/
Speed from P_2 to P_3	16.39	24.90	15.12	24.30	25.00	17.86	10.23	15.57	22.57	/	/	/	/	/	/
Speed from P_3 to P_4	-	12.82	-	21.36	23.39	-	-	-	22.88	/	/	/	/	/	/
Speed from P_4 to P_5	-	-	-	-	20.99	-	-	-	21.10	18.90	14.85	15.92	17.14	18.56	18.90
Speed from P_5 to P_6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Speed from P_6 to P_7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Speed from P_7 to P_8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

It is interesting that, when the degree of disruption is high, there is no significant impact of fuel price on the option selected. Obviously, this can be seen in cases of disruption from 120 hours to 144 hours. The vessel should select the skipping option, as presented in Table 5.10. This result may be explained by the fact that skipping can simultaneously decrease the distance of the voyage, reduce the speed of the vessel and the IFO costs and delay penalties, as shown in Table 5.11 and Table 5.12. Since there is no literature suggesting this rule, this can be considered a contribution to the liner shipping literature.

Turning to the case where the speeding option would be recommended rather than the skipping option. The combination of fuel prices being $100 to $300 with 24 to 48 hours delay, makes speeding more valuable than skipping, as presented in Tables 5.10 to 5.12. This confirms our intuition that it is not important to skip ports, which may lead to high skipping delay penalties.

Another observation is that the speeding option provides lower total costs than the skipping option, even when a vessel elects to skip. For instance, as shown in Tables 5.11 and 5.12, when the fuel price is $100 and initial delay is 72 hours, or the fuel price is $300 and initial delay is 48 hours, or the fuel price is $700 and initial delay is 24 hours, the speeding option is recommended. The reason for this is the dominant factor of high penalties. This is the most interesting finding, where Li et al. (2015) just assume one value of delay penalty, $33,000. We therefore experiment with this limitation in Section 5.7.

Table 5.12: Relative IFO savings by the option of port skipping under various fuel costs

Initial Delay	Port skipping				
	Q=100	Q=300	Q=500	Q=700	Q=900
24	-0.14%	-0.51%	-0.74%	20.82%	33.39%
48	-1.90%	12.63%	14.98%	36.71%	36.29%
72	29.53%	29.69%	25.07%	25.59%	37.24%
96	35.32%	31.88%	34.53%	36.11%	33.62%
120	38.24%	39.76%	39.81%	38.73%	30.23%
144	34.52%	40.77%	42.46%	29.66%	19.87%

Table 5.13: Relative delay penalty savings by the option of port skipping under various fuel costs

Initial Delay	Port skipping				
	Q=100	Q=300	Q=500	Q=700	Q=900
24	0.28%	3.03%	5.01%	-415.06%	-646.96%
48	-3.55%	-78.55%	-85.47%	-205.60%	-189.08%
72	-	-26.46%	-5.51%	-7.69%	-33.23%

	27.04%				
96	2.88%	10.55%	0.95%	5.19%	17.15%
120	24.25%	20.37%	19.21%	25.15%	38.07%
144	40.95%	31.26%	31.92%	45.90%	52.99%

5.6 Value of Port Skipping Option under Various Time Windows

The fourth experiment investigates the impact of various time windows at different disruption periods on choosing the proper option (speeding or skipping).

Table 5.14: Relative total savings by the option of port skipping under various time windows

Initial Delay	**Port skipping**				
	TW=0	TW=4	TW=8	TW=12	TW=16
24	- 24.16%	- 0.77%	15.57%	27.74%	- 1.12%
48	1.53%	- 1.54%	- 4.18%	- 6.10%	- 5.84%
72	18.24%	15.95%	13.47%	10.87%	8.16%
96	25.41%	25.63%	24.64%	23.17%	21.41%
120	32.52%	31.69%	30.99%	29.98%	28.68%
144	37.68%	35.98%	34.29%	32.80%	31.95%

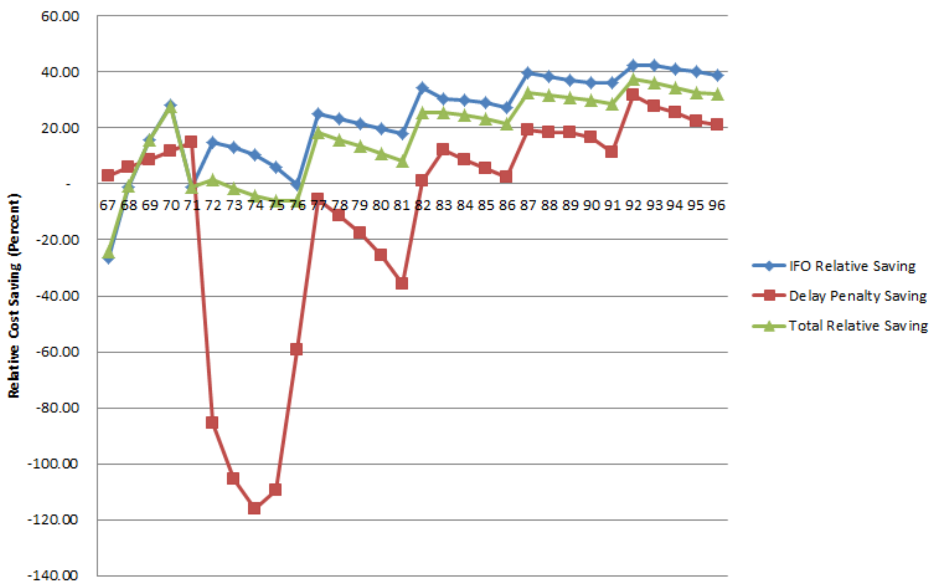

Figure 5.5: Relative total savings by the option of port skipping under various time windows

For cases with low initial delay (24 hours), the speeding option is recommended rather than the skipping option no matter how wide the time window is. The reason for choosing the speeding option is that the vessel is able to catch up with the delay with its predefined speed (25 knots). We note that even though Table 5.14 and Figure 5.5 seem to show that the speeding option is better when the time window is small and the skipping option is better when the time window is large, this can be explained by the design of the skipping option that combines with the speeding option. The algorithm automatically chooses the near optimal solution, whether to skip or speed up to recover from a disruption event. According to Table 5.15, it is obviously doesn't matter how wide the time window is, the vessel should always select the skipping option.

Another observation in this case is that the vessel even tends to slow down as the time window increases. For example, Table 5.15 shows that a vessel's speed decreases when the time widow increases from 0 to 16 hours. This finding is also in accord with Fagerholt et al. (2010) and our intuition that a vessel can use a slower speed in the case of a wide time window. The speeding option is therefore suggested rather than the skipping option in the case of low initial delay and any width of time window.

Table 5.15: Speed on each leg under various time windows

Initial Delay Δ	TW = 0					TW = 8					TW = 16				
	24	**48**	**72**	**96**	**120**	**24**	**48**	**72**	**96**	**120**	**24**	**48**	**72**	**96**	**120**
Speeds without the option of port skipping															
Speed from P_0 to P_1	20.42	23.74	24.90	25.00	25.00	19.80	22.55	24.65	25.00	25.00	19.21	21.32	24.20	25.00	25.00
Speed from P_1 to P_2	18.46	22.54	23.85	25.00	25.00	17.73	21.14	23.48	24.79	25.00	16.73	19.62	23.06	24.32	25.00
Speed from P_2 to P_3	17.03	21.79	23.21	24.51	25.00	15.64	20.23	22.76	24.22	24.82	14.56	18.52	22.39	23.72	24.86
Speed from P_3 to P_4	15.51	21.13	22.66	24.04	24.55	14.10	19.45	22.18	23.73	24.36	-	17.34	21.80	23.20	24.24
Speed from P_4 to P_5	-	20.88	22.07	23.55	24.08	-	-	21.55	23.22	23.89	-	20.88	21.08	22.61	23.72
Speed from P_5 to P_6	-	13.44	17.72	20.20	21.00	-	-	16.69	19.72	20.71	-	14.08	15.58	18.79	20.43
Speed from P_6 to P_7	-	-	-	19.26	20.17	-	-	-	18.59	19.85	-	-	-	18.58	19.52
Speed from P_7 to P_8	-	-	-	-	17.70	-	-	-	16.24	17.20	-	-	-	16.24	16.69
Speed from P_8 to P_0	-	-	-	-	-	-	-	-			-	-	-	-	-
Speeds with the option of port skipping															
Speed from P_0 to P_1	25.00	16.78	18.46	20.59	/	17.41	16.77	18.37	24.19	/	21.06	16.76	18.37	22.29	/
Speed from P_1 to P_2	17.79	/	/	/	/	17.79	/	/	/	/	15.87	/	/	/	/
Speed from P_2 to P_3	17.86	10.23	15.57	22.57	/	17.8	10.	14.	20.	19.	15.	10.2	14	16	20.7

						3	23	10	96	98	70	3	.1 0	.0 9	0
Speed from P_3 to P_4	-	-	-	22. 88	/	-	-	-	18. 37	-	-	-	-	-	-
Speed from P_4 to P_5	-	-	-	21. 10	18.9 0	-	-	-	-	-	-	-	-	-	-
Speed from P_5 to P_6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Speed from P_6 to P_7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Speed from P_7 to P_8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

In the case of medium initial delay (48 hours and 72 hours), speeding is preferred to skipping as the time window tends to increase. As presented in Table 5.14 and Figure 5.5, we can see that when the initial delay is 48 hours and the time window is 0, the skipping option is recommended. On the other hand, as the time window increases speeding becomes preferable. An explanation is that the vessel tends to slow down when the time window increases from 0 to 16 hours. This results in a reduction in IFO savings as presented in Table 5.16 and Figure 5.5. However, the skipping option causes higher delay penalties, as demonstrated in Table 5.17. As a result, the speeding option is suggested when the time window increases in this case.

In the case of large initial delay (from 96 hours to 144 hours), as shown in Table 5.14 and Figure 5.5, the skipping option is recommended, as presented in Section 5.3. Even though using the skipping option can save more total cost when the initial delay increases, it tends to slightly decrease when the time windows increases from 0 to 16 hours. This can be explained by the reduction in IFO savings and delay penalty savings as the time window increases, because the speeding option allows lowering the speed and still arriving within the time window. This impact is obviously illustrated in the IFO and delay penalty results presented in Tables 5.16 and 5.17.

Since there is no comparison between the speeding and skipping options considering the effect of time windows in the previous study, this outcome extends the boundary of knowledge in the literature.

Table 5.16: Relative IFO savings by the option of port skipping under various time windows

Initial Delay	Port skipping				
	TW=0	TW=4	TW=8	TW=12	TW=16
24	-26.65%	-1.18%	15.84%	28.08%	-1.33%
48	14.98%	12.86%	10.18%	5.91%	-0.30%
72	25.07%	23.34%	21.46%	19.61%	17.80%
96	34.53%	30.35%	29.94%	28.84%	27.34%
120	39.81%	38.59%	37.17%	36.25%	36.17%
144	42.46%	42.34%	40.87%	39.93%	39.03%

Table 5.17: Relative delay penalty savings by the option of port skipping under various time windows

Initial Delay	Port skipping				
	TW=0	TW=4	TW=8	TW=12	TW=16
24	2.84%	6.04%	8.57%	11.79%	14.63%
48	-85.47%	-105.57%	-116.33%	-109.43%	-59.39%
72	-5.51%	-11.15%	-17.65%	-25.74%	-35.82%
96	0.95%	12.27%	8.72%	5.61%	2.43%
120	19.21%	18.44%	18.46%	16.50%	11.44%
144	31.92%	27.89%	25.32%	22.44%	20.89%

5.7 Value of Port Skipping Option under Various Skipping Penalties

The fifth experiment investigates the effect of various skipping penalties at different disruption periods on choosing the proper option (speeding or skipping).

Table 5.18: Relative total savings by the option of port skipping under various skipping penalties

Initial Delay	Port skipping				
	$\beta = \$11{,}000$	$\beta = \$33{,}000$	$\beta = \$55{,}000$	$\beta = \$77{,}000$	$\beta = \$99{,}000$
24	3.35%	-0.34%	15.80%	27.40%	-0.35%
48	30.08%	1.53%	-2.87%	-1.23%	-0.83%
72	44.04%	18.24%	9.77%	1.30%	-6.30%
96	55.41%	25.41%	19.60%	12.79%	6.00%
120	62.32%	32.52%	21.34%	16.25%	10.69%
144	67.36%	37.68%	21.77%	15.56%	11.85%

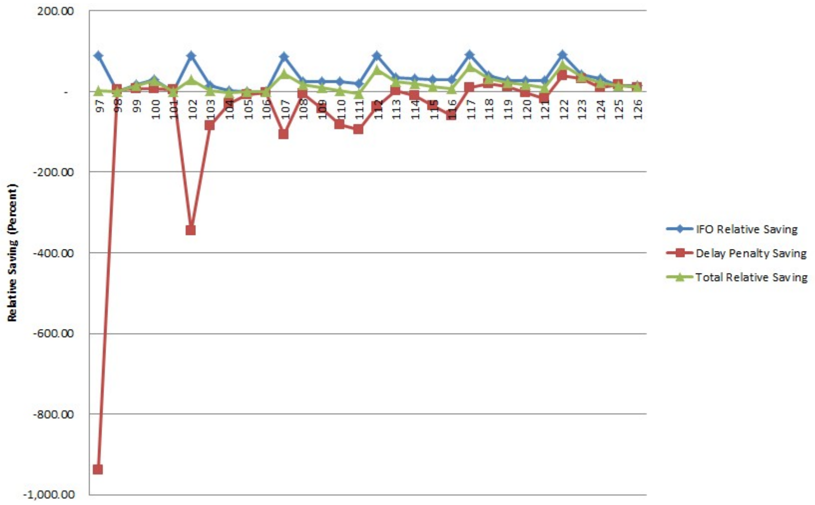

Figure 5.6: Relative total savings by the option of port skipping under various skipping penalties

In the case of low initial delay (24 hours and 48 hours) and low skipping penalties ($11,000), the skipping option is recommended, as shown in Table 5.17 and Figure 5.6. However, when the skipping delay penalty tends to increase, the speeding option is preferable. Table 5.19 shows that at $55,000 to $99,000 skipping delay penalty, a vessel does not skip any ports of call to recover its delay. Even though the relative total saving, relative IFO saving and delay penalties cannot be seen from the pattern presented in Table 5.20 and Table 5.21, it is clear that the skipping option includes the speeding option. As presented in Table 5.19, it is clear that the speeding option is suggested. Therefore, skipping provides lower costs than speeding when the skipping penalty is low, while speeding is more valuable when the initial delay is short but there is a high skipping penalty. These results are in line with our intuition.

Table 5.19: Speed on each leg under various skipping penalties

Initial Delay Δ	**skipping penalty = $11k**					**skipping penalty = $55k**					**skipping penalty = $99k**				
	24	**48**	**72**	**96**	**120**	**24**	**48**	**72**	**96**	**120**	**24**	**48**	**72**	**96**	**120**
							Speeds without the option of port skipping								
Speed from P_0 to P_1	20.20	23.74	24.90	25.00	25.00	20.60	23.74	24.90	25.00	25.00	20.42	23.74	24.90	25.00	25.00
Speed from P_1 to P_2	18.03	22.54	23.85	25.00	25.00	18.83	22.54	23.85	25.00	25.00	18.46	22.54	23.85	25.00	25.00

Speed from P_2 to P_3	17.36	21.79	23.21	24.51	25.00	16.83	21.79	23.21	24.51	25.00	17.03	21.79	23.21	24.51	25.00
Speed from P_3 to P_4	14.96	21.13	22.66	24.04	24.55	15.69	21.13	22.66	24.04	24.55	15.51	21.13	22.66	24.04	24.55
Speed from P_4 to P_5	-	20.88	22.07	23.55	24.08	-	20.88	22.07	23.55	24.08	-	20.88	22.07	23.55	24.08
Speed from P_5 to P_6	-	13.44	17.72	20.20	21.00	-	13.44	17.72	20.20	21.00	-	13.44	17.72	20.20	21.00
Speed from P_6 to P_7	-	-	-	19.26	20.17	-	-	-	19.26	20.17	-	-	-	19.26	20.17
Speed from P_7 to P_8	-	-	-	-	-	-	-	-	-	17.70	-	-	-	-	17.70
Speed from P_8 to P_0	-	-	-	-	-	-	-	-	-		-	-	-	-	-
Speeds with the option of port skipping															
Speed from P_0 to P_1	25.00	16.27	/	/	/	24.39	18.51	18.53	25.00	25.00	19.65	23.13	18.53	22.20	24.01
Speed from P_1 to P_2	17.29	/	/	/	/	18.17	20.87	/	/	/	18.11	20.87	/	/	/
Speed from P_2 to P_3	16.57	10.26	10.57	14.10	14.10	17.73	24.70	15.56	22.56	25.00	18.07	25.00	15.56	21.20	24.00
Speed from P_3 to P_4	/	/	/	/	/	-	19.61	-	22.88	25.00	-	17.00	-	20.10	22.66
Speed from P_4 to P_5	/	/	/	/	/	-	-	-	20.88	22.11	-	-	-	20.88	22.58
Speed from P_5 to P_6	/	/	/	/	/	-	-	-	13.28	18.15	-	-	-	15.38	16.16

Speed from P_6 to P_7	/	/	/	/	/	-	-	-	-	-	-	-	-	-	-
Speed from P_7 to P_8	/	/	/	/	/	-	-	-	-	-	-	-	-	-	-
Speed from P_8 to P_0	17.62	17.62	17.62	17.62	17.62	-	-	-	-	-	-	-	-	-	-

In the case of medium initial delay (72 hours), from low levels of skipping penalty to almost the highest levels of skipping penalty ($11,000 to $77,000), the skipping option is recommended, although the total relative saving tends to decrease when levels of skipping penalty increase, as shown in Table 5.18 and Figure 5.6. These decreasing trends originate from the steady trend of saving IFO costs and the steady skipping pattern shown in Table 5.19 and Table 5.20. Also, the decreasing trend of delay penalties is presented in Table 5.21. In other words, as the skipping penalty tends to increase, the vessel prefers not to skip any ports of call, or skip ports of call as little as possible. Therefore, the speeding option tends to be the better choice when the skipping penalty is high for a medium disruption event.

In the case of a large initial delay (96 hours to 144 hours), the skipping option is valuable at any level of skipping penalty, even though it tends to decrease as the level of skipping penalty increases, as illustrated in Table 5.18 and Figure 5.6. The explanation for these decreasing trends is divided into two stages. The first (96 hours) results from the steady trend of saving IFO costs and the steady skipping pattern shown in Table 5.19 and Table 5.20, along with the decreasing trend in delay penalties presented in Table 5.21. The other reason (120 hours and 144 hours initial delay) is the decreasing trend of relative IFO savings and the decreasing trend of relative delay penalty savings demonstrated in Table 5.19 and Table 5.20. Although there is a decreasing trend, due to high degrees of disruption, the skipping option is still a better choice for a vessel because of the dominant factors of speed and distance.

All these observations are in agreement with our intuition, and since no literature suggests such findings, this study makes a theoretical contribution to the literature.

Table 5.20: Relative IFO savings by the option of port skipping under various skipping penalties

Initial Delay	Port skipping

	$\beta = \$11{,}000$	$\beta = \$33{,}000$	$\beta = \$55{,}000$	$\beta = \$77{,}000$	$\beta = \$99{,}000$
24	89.93%	-0.74%	16.41%	28.48%	-0.80%
48	88.18%	14.98%	1.27%	-0.40%	-0.52%
72	87.39%	25.07%	25.07%	25.07%	19.12%
96	89.68%	34.53%	30.76%	30.58%	30.59%
120	90.57%	39.81%	26.50%	26.05%	26.07%
144	90.60%	42.46%	32.25%	15.23%	13.60%

Table 5.21: Relative delay penalty savings by the option of port skipping under various skipping penalties

Initial	**Port skipping**				
Delay	$\beta = \$11{,}000$	$\beta = \$33{,}000$	$\beta = \$55{,}000$	$\beta = \$77{,}000$	$\beta = \$99{,}000$
24	-938.05%	5.01%	6.23%	7.60%	5.59%
48	-345.54%	-85.47%	-29.62%	-6.63%	-2.83%
72	-106.78%	-5.51%	-43.45%	-81.39%	-94.75%
96	-36.59%	0.95%	-10.36%	-34.96%	-59.99%
120	10.73%	19.21%	11.92%	-1.65%	-17.39%
144	39.36%	31.92%	9.14%	15.96%	9.73%

6. Discussion

This chapter presents the discussion, theoretical contribution, practical implications, research limitations and future research.

6.1 Findings

There are three main paradigms of management study researcher design. A positivist approach perceives the world as having absolute truth independent of the researcher. Findings can be obtained via a deductive approach. An interpretivist approach believes that there are many realities, subjective to each researcher. The aim of interpretivist study is to understand complex phenomenon rather than achieve regularity in the findings. However, these two paradigms are extreme beliefs. As a compromise between these two, the critical realist views the world as many actual events. The researcher perceives just some parts of these actual events, and those that the researcher cannot see still exit. Critical realist findings can therefore be generalised only within the boundary the researcher observes. This viewpoint corresponds to how OR and MS literature designs research. Since this study is categorised as an OR and MS study, this section discusses how critical realism guides the findings.

As mentioned in Chapter 3, the methodology of optimisation and simulation in OR and MS literature starts with the research questions and identifies simple theory. The second step is selecting a simulation or optimisation method. The third step is creating a computational representation. This process is used to simplify reality into a model by creating a measure of each construct. In other words, some specific assumptions are added to the modelling stage to answer the research questions. All the constructs and assumptions in this study are represented in the form of a mathematical model, presented in Chapter 4. This process is consistent with the way the critical realism paradigm observes only part of reality, which implies that the findings of the model in Chapter 4 can only be generalised within the limitations of the model. Verification and validation are implemented on the model. Finally, experimentation is conducted to generate new theory which can be generalised within the limitations.

Table 6.1: Summary of selecting speeding or skipping options under various conditions

No.	**Experiment**	**Our simulation model**		**Li et al. (2015)**	
		Measurement that suggest skipping option	Measurement that suggest speeding option	Measurement that suggest skipping option	Measurement that suggest speeding option
1	Degree of disruption	(48 hrs, 72 hrs, 96 hrs, 120 hrs, 144 hrs)	(24 hrs)	(48 hrs, 72 hrs, 120 hrs, 144 hrs)	(24 hrs)
2	Maximum speed	(48 hrs: 20 knots to 30 knots, 72 hrs: 20 knots to 30 knots, 96 hrs: 20 knots to 30 knots, 120 hrs: 20 knots to 30 knots, 144 hrs: 20 knots to 30 knots)	(24 hrs: 20 knots to 30 knots)	(24 hrs: 20 knots to 30 knots, 48 hrs: 20 knots to 30 knots, 72 hrs: 20 knots to 30 knots, 96 hrs: 20 knots to 30 knots, 120 hrs: 20 knots to 30 knots, 144 hrs: 20 knots to 30 knots)	-
3	Fuel price	(24 hrs: $900, 48 hrs: $500 to $900, 72 hrs: $300 to $900,	(24 hrs: $100 to $700, 48 hrs: $100 to $300, 72 hrs: $100)	(24 hrs: $300 to $900, 48 hrs: $300 to $900, 72 hrs: $300 to $900,	-

		96 hrs: $100 to $900 120 hrs: $100 to $900, 144 hrs: $100 to $900)		96 hrs: $300 to $900, 120 hrs: $300 to $900, 144 hrs: $300 to $900)	
4	Time window	(48 hrs: 0 hrs, 72 hrs: 0 hrs to 16 hrs, 96 hrs: 0 hrs to 16 hrs, 120 hrs: 0 hrs to 16 hrs, 144 hrs: 0 hrs to 16 hrs)	(24 hrs: 0 hrs to 16 hrs, 48 hrs: 4 hrs to 16hrs)	-	-
5	Skipping penalty	(48 hrs: 11k to 33k, 72 hrs: 11k to 77k, 96 hrs: 11k to 99k, 120 hrs: 11k to 99k, 144 hrs: 11k to 99k)	(24 hrs: 11k to 99k, 48 hrs: 55k to 99k, 72 hrs: 99k)	-	-

This research studies, in detail, how to recover from a disruption event in liner shipping. A single vessel starts a journey sailing to n ports of call along the route. It has to arrive at each port of call within a preannounced schedule. When a disruption event happens, it may delay the arrival at some ports of call. The options of speeding up or skipping ports need to be chosen appropriately in order to minimise two costs, fuel costs and delay penalty costs. This is the simplification model, and the finding from experimentation can be generalised as follows.

The first contribution is impact of the degree of the delay on the selected option. Our results confirm the findings of Li et al. (2015) that for a longer delay, the skipping option can save more costs than speeding up. For example, when the delay is 24 hours, the speeding up option is recommended, but when the delay is from 48 hours to 144 hours, the skipping option is suggested, as presented in Table 6.1. This can be explained by an inability to recover the planned schedule no matter how fast the speed.

The second contribution is the impact of ship design on the selected option. The design aspect considered is related to the vessel’s speed limits (minimum and maximum). A small vessel has a lower maximum speed limit, while a large vessel has a higher maximum speed limit. In the disruption problem, our findings validate Li et al.'s (2015) result that port skipping provides more benefits than speeding when the maximum speed limit is low. The explanation of this is that a vessel cannot speed up to recover from a disruption event because of the low speed limit. Another observation which contributes to the literature is for low level (24 hours) disruption events, a vessel is recommended to use the speeding option no matter what the maximum speed limit is, as presented in Table 6.1. In contrast, Li et al. (2015) suggest that whatever the maximum speed limit, the skipping option is recommended. This discrepancy could be attributed to the design of the algorithm. Generally however, this confirms the finding that the skipping option is more beneficial when the degree of disruption increases.

The third factor that has an effect on the chosen option is fuel price. Two types of fuel have to be considered, those for the main and auxiliaries engines, IFO380 and MGO. IFO380 is a lower grade of bunker consumption used at sea, while MGO is a fuel with low sulphur content consumed during mooring. We found a pattern consistent with Li et al. (2015), that port skipping is more useful when fuel prices increase. We suggest managerial rules in more detail than Li et al. (2015), as presented in Table 6.1 which shows that at low degrees of disruption (24 hours) a vessel is recommended to use the skipping option only if there is a high fuel price ($900). The skipping option is only suggested at medium ($300 to $900) and low ($100 to $900) levels of fuel price when the degree of disruption increases (from 48 - 72 hours to 96 - 144 hours). These details add to the literature, because Li et al. (2015) only show a tendency to select the speeding option when the fuel price is low, but all the experiments suggests the skipping option, as presented in Table 6.1.

The fourth managerial rule relates to the effect of the time window on the chosen option. The time window consists of the earliest planned arrival time and latest planned arrival time of the vessel at a port of call. The earliest pre-defined time is the time when liner shipping and the port of call agree to start loading and unloading operations. In other words, if vessels arrive before this time, they have to wait. The latest pre-defined time is the time both parties agree that if the vessel arrives later they are penalised. We find that if the time window is wide, the vessel slows down because there is room to arrive on time. These results match those observed by Fagerholt, Laporte & Norstad (2010). However, Fagerholt, Laporte & Norstad (2010) do not compare the speeding option with the skipping option. Our findings therefore add to the literature in that when the time window is wide and there is a low level of disruption, the speeding option is recommended over the skipping option. As shown in Table 6.1, at 24 hours delay, the vessel is suggested to use the speeding option for any time window. Another case when speeding option is recommended is when there are 48 hours of disruption and the time window is over 4 hours.

The last factor that has an effect on the selection is the skipping penalty. Ports of call which are skipped may impose a skipping penalty. This cost to shippers may result from high inventory costs, cargo misconnecting, rerouting, or intangible goodwill lost. The managerial rule from our experiment is that when the skipping penalty is low, the skipping option is recommended. This is consistent with our intuition. In other words, the speeding option is suggested at low levels of disruption and high levels of skipping penalty. For example, we found that if the degree of disruption is 24 hours and the skipping penalty ranges from $33,000 to $99,000, the speeding option is recommended, as presented in Table 6.1. We also note that other rules are presented in Table 6.1. Since there is no literature studying the effect of this factor on the selecting option, this can be considered a theoretical contribution to the disruption problem in liner shipping literature.

6.2 Theoretical Contribution

As demonstrated in the mathematical model in Chapter 4, the main construct is performance difference between skipping and speeding options, controlled by degrees of disruption event. The relationship between the key construct and the disruption event is controlled by many variables including the maximum speed limit, fuel prices, time windows and skipping penalties. Based on the findings derived from the experiments conducted in Chapter 5, this section elaborates on the theoretical contribution.

Algorithm 6.1 Managerial rules for the adoption of the skipping option

Configurations	

Degrees of disruption	IF (degrees of disruption ≥ lower medium)
	    Skipping option
	Else
	    Speeding option

Maximum speeds	IF (degrees of disruption ≥ lower medium
	AND maximum speed ≥ low maximum speed)
	    Skipping option
	Else
	    Speeding option

Fuel prices	IF ((degrees of disruption ≤ low AND fuel price ≥ high fuel price) OR (degrees of disruption = lower medium AND fuel price ≥ medium) OR (degrees of disruption = medium AND fuel price ≥ lower medium) OR (degrees of disruption ≥ upper medium AND fuel price ≥ low)) Skipping option

	Else
	Speeding option
Time windows	IF ((degrees of disruption = lower medium AND Time window = 0) OR (degrees of disruption ≥ medium AND Time window ≥ 0))
	Skipping option
	Else
	Speeding option
Skipping penalties	IF (degrees of disruption = lower medium AND skipping penalty ≤ lower medium) OR (degrees of disruption = medium AND skipping penalty ≤ upper medium) OR (degrees of disruption ≥ upper medium AND skipping penalty ≥ low)
	Skipping option
	Else
	Speeding option

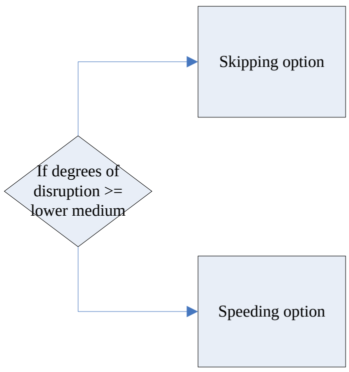

Figure 6.1 Managerial rules impacted by degrees of disruption to choose skipping or speeding option

First, high degrees of disruption have a positive impact on choosing the skipping option. According to Algorithm 6.1 and Figure 6.1 which depicts the adoption of the skipping option when the degree of disruption is greater than lower medium. This is consistent with the findings of Li et al. (2015) and our intuition. The main reason for this is that a vessel cannot speed up to recover from the disruption event when the degree of disruption is high.

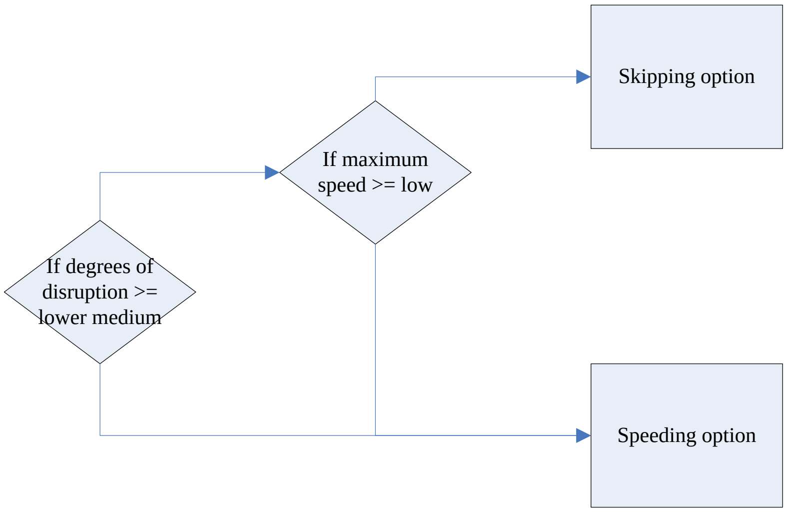

Figure 6.2 Managerial rules impacted by degrees of disruption and maximum speed to choose skipping or speeding option

Second, Algorithm 6.1 and Figure 6.2 shows the effect of maximum speed at different levels of relationship between degree of disruption and the adoption of the skipping option. The maximum speed limit does not have an effect on the option. When the degree of disruption is greater than lower medium, the skipping option is recommended. This finding is consistent with Li et al. (2015). The reason for this is the dominant factors, distance and speed, leading to high fuel costs. The skipping option is better than the speeding option when the maximum speed is low, as presented in Table 5.6. This can be explained as a vessel not being able to apply high speed to recover from the disruption event which is in line with the findings of Li et al. (2015).

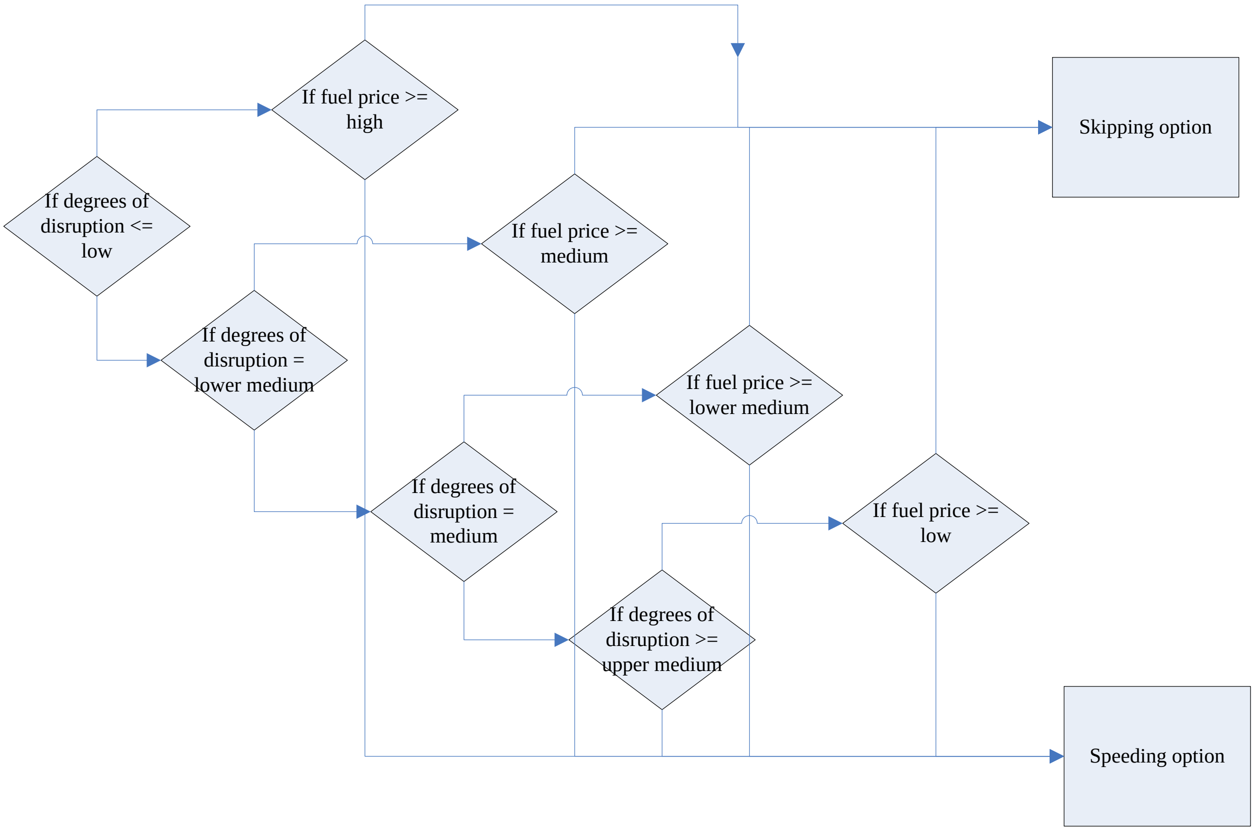

Figure 6.3 Managerial rules impacted by degrees of disruption and fuel price to choose skipping or speeding option

Third, Algorithm 6.1 and Figure 6.3 shows the impact of fuel prices at different levels of the relationship between degrees of disruption event and the adoption of the skipping option. The findings can be categorised by four degrees of disruption. At low degrees of disruption, the skipping option is recommended when the fuel price is high. At lower medium degrees of disruption, the skipping option is suggested when the fuel price is greater than medium. At medium degrees of disruption, the skipping option is suggested when the fuel price is greater than lower medium. These findings confirm those of Li et al. (2015) and our common sense. Finally, if the degree of disruption is greater than upper medium, the skipping option is recommended whatever the fuel price. This is due to the saving of distance from skipping ports, and the increasing IFO cost of applying the speeding option. Since there is no literature suggesting this finding, we claim that this finding contributes to the theory of disruption problems in the liner shipping literature.

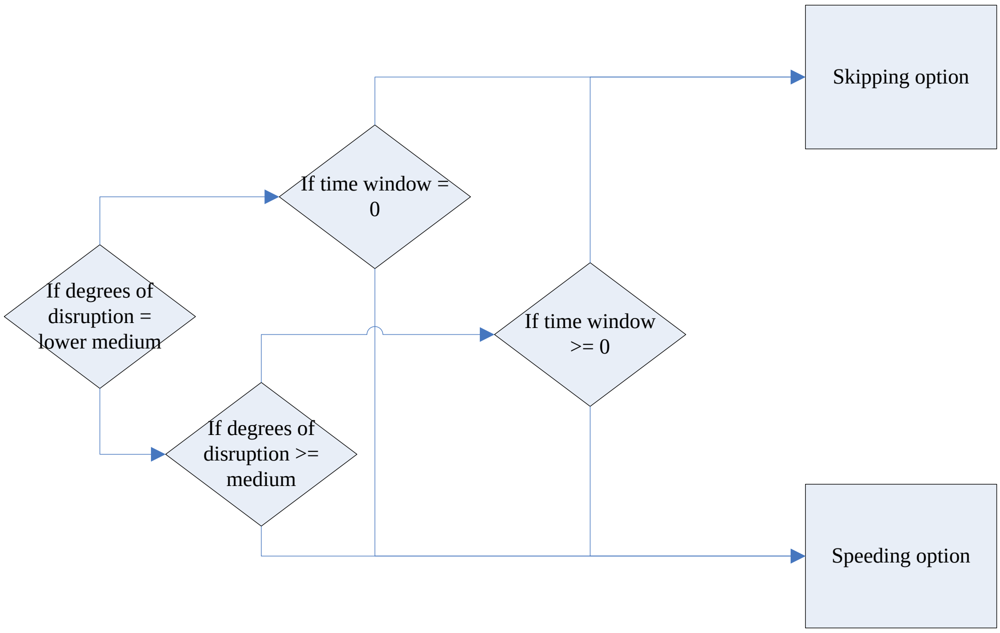

Figure 6.4 Managerial rules impacted by degrees of disruption and time window to choose skipping or speeding option

Fourth, the effect of the time window for different levels of disruption event on adopting the skipping option is investigated, as presented in Algorithm 6.1 and Figure 6.4. At lower medium degree of disruption and when there is a short time window, the skipping option is suggested. The reason for this is that for low level disruption when the time window is wide, a vessel can speed up to arrive within the predefined schedule (Fagerholt et al., 2010). Another case in which the skipping option is recommended is when the disruption degree is greater than medium, whatever the time window. This observation can be explained by the significant saving from reducing total distance in the voyage when applying the skipping option. This observation adds to the theoretical contribution to the literature.

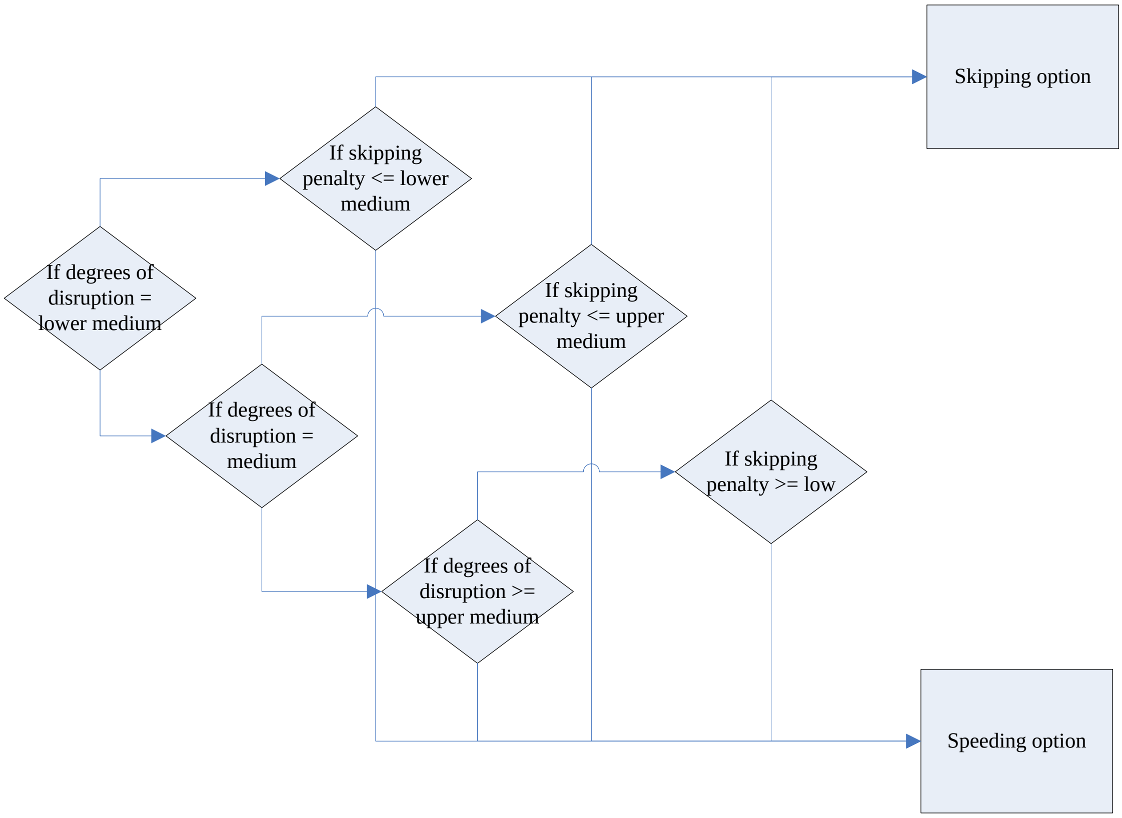

Figure 6.5 Managerial rules impacted by degrees of disruption and skipping penalty to choose skipping or speeding option

Fifth, Algorithm 6.1 and Figure 6.5 shows the impact of skipping penalties at various levels of disruption event on the adoption of the skipping option. At low level of disruption, if the skipping penalty is less than lower medium, the skipping option is recommended. Another possible case when the skipping option is adopted is when the disruption event is medium and the skipping penalty is less than upper medium. This is consistent with our intuition, because if the skipping penalty is high and the vessel can speed up to arrive within the predefined schedule, speeding up is recommended. The last case in which the skipping option is suggested is when the degree of disruption is high, whatever the skipping penalty level. This can be explained by the fact that the skipping option can reduce distance during the journey, leading to lower

IFO costs, which is the dominant saving. As there is no study which conducts an experiment on this factor, this result contributes to the literature.

6.3 Practical Implications

There are two main practical implications of this study. The first is that operational managers of liner shipping companies can use the proposed rules for handling disruption events. The second is that captains can use the disruption simulator as a decision support system to search for near optimal solutions during journeys (Vos, Santos and Omondi, 2015; Lee et al., 2016). Since the first practical implication has been discussed in the previous section, this section focuses on the second.

One advantage of the disruption simulator is that it shows the operational team when a vessel should arrive and depart at each port of call, and what the optimal speed should be during the journey, in the case where the speeding option is recommended. In the case of the skipping option, the decision support system provides which ports of call should be skipped and the speed of each leg during the voyage. These schedules are presented in Table 6.2 and Table 6.3.

Based on our interviews with a liner shipping company in Europe, normally, the operational process for deciding what the captain of a vessel should do when facing a disruption event is based on the experience of the operational team. There are three drawbacks to such a process. The first is that it wastes time sending information from the operational team to the captain of the vessel. Second, it may result in information transfer problems, for example the operator at the port or vessel may forget or delay sending or checking an e-mail. Third, the decision maker may not be able to make a decision accurately using only their own experience. Therefore, if liner shipping companies were to install this decision support system on a vessel, it would help overcome these drawbacks and lead to optimised total operating costs, including fuel costs and delay penalty costs.

Table 6.2: Speeding option

PortIndex	Distance	EarArr	LateArr	PortTime	DisrupPortTime	UnitIFO	UnitDelayPenalty	Speed	ActualArr	ActualDep	IFOCost	UnitDelayPenalty	TotalCost
0	837.00	839.98	839.98	8.00	24.00	500.00	1,840.00	17.62	839.98	32.00	89,576.51	-	89,576.51
1	103.00	17.50	17.50	18.00	-	500.00	4,140.00	20.42	37.04	55.04	16,141.14	80,901.80	97,042.93
2	476.00	65.50	65.50	10.00	-	500.00	2,300.00	18.46	80.82	90.82	56,643.24	35,255.40	91,898.64
3	1,029.00	148.47	148.47	8.00	-	500.00	1,840.00	17.03	151.26	159.26	103,041.96	5,118.20	108,160.15
4	205.00	172.48	172.48	8.00	-	500.00	1,840.00	15.51	172.48	180.48	18,091.37	-	18,091.37
5	4,844.00	412.47	412.47	43.00	-	500.00	9,890.00	20.88	412.47	455.47	811,340.55	-	811,340.55
6	364.00	484.47	484.47	9.00	-	500.00	2,070.00	12.55	484.47	493.47	32,393.09	-	32,393.09
7	2,062.00	604.45	604.45	21.00	-	500.00	4,830.00	18.58	604.45	625.45	249,202.02	-	249,202.02
8	2,550.00	782.47	782.47	10.00	-	500.00	2,300.00	16.24	782.47	792.47	237,016.58	-	237,016.58
Total											1,613,446.45	121,275.39	1,734,721.84

Table 6.3: Schedule for skipping option

PortIndex	Distance	EarArr	LateArr	SkipExtraPortTime	PortTime	DisrupPortTime	UnitIFO	UnitDelayPenalty	Speed	ActualArr	ActualDep	IFOCost	UnitDelayPenalty	TotalCost
0	837.00	839.98	839.98	44.00	8.00	144.00	500.00	1,840.00	17.62	839.98	152.00	89,576.51	1,452,000.00	1,541,576.51
1	-	17.50	17.50	-	-	-	500.00	4,140.00	-	-	-	-	-	-
2	-	65.50	65.50	-	-	-	500.00	2,300.00	-	-	-	-	-	-
3	-	148.47	148.47	-	-	-	500.00	1,840.00	-	-	-	-	-	-
4	-	172.48	172.48	-	-	-	500.00	1,840.00	-	-	-	-	-	-
5	5,377.00	412.47	412.47	-	43.00	-	500.00	9,890.00	20.64	412.47	455.47	870,101.44	-	870,101.44
6	364.00	484.47	484.47	-	9.00	-	500.00	2,070.00	12.55	484.47	493.47	32,393.09	-	32,393.09
7	2,062.00	604.45	604.45	-	21.00	-	500.00	4,830.00	18.58	604.45	625.45	249,202.02	-	249,202.02
8	2,550.00	782.47	782.47	-	10.00	-	500.00	2,300.00	16.24	782.47	792.47	237,016.58	-	237,016.58
Total												1,478,289.64	1,452,000.00	2,930,289.64

Chapter 7. Conclusion, Limitations and Future Research

In this chapter, we present research summary, research outcome, research limitations and future research.

7.1 Research Summary

This study proposes managerial rules for recovering from a disruption event in liner shipping. Experiments on the impact of various configurations of degrees of disruption, maximum speeds, fuel prices, time windows and skipping penalties on choosing the appropriate option are conducted using an optimisation model. A PSO algorithm is a solution approach used in this study. Constructive heuristics of PSO are designed for the speeding up and skipping options. Generally, the results show that skipping is preferable when the disruption degree is large, when the maximum speed is low, when fuel price is high, when the time window is narrow, or when the skipping penalty is low. The findings are discussed in more detail in the previous section.

7.2 Research Outcome

The research outcome can be divided into three categories, theoretical contribution, methodological contribution and practical implications.

Theoretical Contribution

The main contribution of this study is proposing managerial rules for choosing the speeding up option or the skipping option. The major experiment is investigating the effect of the degree of disruption on the adoption of the skipping option. The experiment investigates the impact of other factors, the maximum speed limit, fuel prices, time windows and skipping penalties, at different degrees of disruption on adopting the skipping option.

Methodological Contribution

This study makes a methodological contribution to the optimisation literature in terms of the design of constructive heuristics of a PSO algorithm. The speeding up and skipping options are designed to recover from a disruption problem in liner shipping with various configurations of degrees of disruption, maximum speeds, fuel prices, time windows and skipping penalties.

Practical Implications

This research presents the rules for recovering from a disruption event in liner shipping. Operational managers can use such rules to plan for speeding up or skipping ports of call when a disruption event happens, at different degrees of disruption, with other configurations.

7.3 Research Limitations

The limitations of this study are:

1. The findings are limited to the design of constructive heuristics. It is believed that if the constructive heuristics were designed differently instead of insertion search or other types of meta-heuristics, the structural rules for the speeding and skipping options may be different.
2. This research only investigates the simple version of the disruption problem in liner shipping. Many configurations such as container load, multiple types of vessel or routing, are not included in this study.
3. Some effects of parameters such as distance of each leg and realisation points of disruption events are omitted from this study.
4. Many other options such as the swapping option, speeding up ports of call, omitting port calls, inserting idle vessels and cut-and-run are ignored in this study.
5. Multi-objective which helps optimize both fuel consumption and service level simultaneously does not include in this study.
6. Stochastic process of disruption event is ignored in this study.

7.4 Future Research

Due to the limitations identified in the previous section, the recommendations for future research are:

1. Compare PSO algorithms with other types of meta-heuristics to investigate the best algorithm for speeding and skipping options.
2. Extend the disruption problem of liner shipping to include more detail, namely container load, multiple types of vessel or routing.
3. Design a different model, propose a benchmark problem and conduct experiments with more various configurations such as distance on each leg or realisation points of disruption.
4. Include other options in the study, such as the swapping option, speeding up ports of call, omitting port calls, inserting idle vessels and cut-and-run.
5. Multi-objective which is recommended to optimise both fuel consumption and service level simultaneously should be included in the study.
6. Proactive response to disruption event (dynamic and uncertainty) should be added to the system.

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Appendix A: Input Voyage

A.1 Various Degrees of Disruption

No	TW	V_{min}	V_{max}	IFO_{min}	IFO_{max}	TW_{min}	TW_{max}	$Disrup_{mean}$	$Disrup_{std}$	Delay $Penalty_{min}$	Delay $Penalty_{max}$	Skip $Penalty_{min}$	Skip $Penalty_{max}$
1	0	0	25	500	500	0	0	**24**	0	230	230	33000	33000
2	0	0	25	500	500	0	0	**48**	0	230	230	33000	33000
3	0	0	25	500	500	0	0	**72**	0	230	230	33000	33000
4	0	0	25	500	500	0	0	**96**	0	230	230	33000	33000
5	0	0	25	500	500	0	0	**120**	0	230	230	33000	33000
6	0	0	25	500	500	0	0	**144**	0	230	230	33000	33000

A.2 Various Maximum Speeds

No	TW	V_{min}	V_{max}	IFO_{min}	IFO_{max}	TW_{min}	TW_{max}	$Disrup_{mean}$	$Disrup_{std}$	Delay $Penalty_{min}$	Delay $Penalty_{max}$	Skip $Penalty_{min}$	Skip $Penalty_{max}$
7	0	**0**	**20**	500	500	0	0	**24**	0	230	230	33000	33000
8	0	**0**	**22.5**	500	500	0	0	**24**	0	230	230	33000	33000
9	0	**0**	**25**	500	500	0	0	**24**	0	230	230	33000	33000
10	0	**0**	**27.5**	500	500	0	0	**24**	0	230	230	33000	33000
11	0	**0**	**30**	500	500	0	0	**24**	0	230	230	33000	33000
12	0	**0**	**20**	500	500	0	0	**48**	0	230	230	33000	33000
13	0	**0**	**22.5**	500	500	0	0	**48**	0	230	230	33000	33000

14	0	**0**	**25**	500	500	0	0	**48**	0	230	230	33000	33000
15	0	**0**	**27.5**	500	500	0	0	**48**	0	230	230	33000	33000
16	0	**0**	**30**	500	500	0	0	**48**	0	230	230	33000	33000
17	0	**0**	**20**	500	500	0	0	**72**	0	230	230	33000	33000
18	0	**0**	**22.5**	500	500	0	0	**72**	0	230	230	33000	33000
19	0	**0**	**25**	500	500	0	0	**72**	0	230	230	33000	33000
20	0	**0**	**27.5**	500	500	0	0	**72**	0	230	230	33000	33000
21	0	**0**	**30**	500	500	0	0	**72**	0	230	230	33000	33000
22	0	**0**	**20**	500	500	0	0	**96**	0	230	230	33000	33000
23	0	**0**	**22.5**	500	500	0	0	**96**	0	230	230	33000	33000
24	0	**0**	**25**	500	500	0	0	**96**	0	230	230	33000	33000
25	0	**0**	**27.5**	500	500	0	0	**96**	0	230	230	33000	33000
26	0	**0**	**30**	500	500	0	0	**96**	0	230	230	33000	33000
27	0	**0**	**20**	500	500	0	0	**120**	0	230	230	33000	33000
28	0	**0**	**22.5**	500	500	0	0	**120**	0	230	230	33000	33000
29	0	**0**	**25**	500	500	0	0	**120**	0	230	230	33000	33000
30	0	**0**	**27.5**	500	500	0	0	**120**	0	230	230	33000	33000
31	0	**0**	**30**	500	500	0	0	**120**	0	230	230	33000	33000
32	0	**0**	**20**	500	500	0	0	**144**	0	230	230	33000	33000
33	0	**0**	**22.5**	500	500	0	0	**144**	0	230	230	33000	33000
34	0	**0**	**25**	500	500	0	0	**144**	0	230	230	33000	33000
35	0	**0**	**27.5**	500	500	0	0	**144**	0	230	230	33000	33000
36	0	**0**	**30**	500	500	0	0	**144**	0	230	230	33000	33000

A.3 Various Fuel Prices

No	TW	V_{min}	V_{max}	IFO_{min}	IFO_{max}	TW_{min}	TW_{max}	$Disrup_{mean}$	$Disrup_{std}$	**Delay Penalty$_{min}$**	**Delay Penalty$_{max}$**	**Skip Penalty$_{min}$**	**Skip Penalty$_{max}$**
37	0	**0**	25	**100**	**100**	0	0	**24**	0	230	230	33000	33000

38	0	**0**	25	**300**	**300**	0	0	**24**	0	230	230	33000	33000
39	0	**0**	25	**500**	**500**	0	0	**24**	0	230	230	33000	33000
40	0	**0**	25	**700**	**700**	0	0	**24**	0	230	230	33000	33000
41	0	**0**	25	**900**	**900**	0	0	**24**	0	230	230	33000	33000
42	0	**0**	25	**100**	**100**	0	0	**48**	0	230	230	33000	33000
43	0	**0**	25	**300**	**300**	0	0	**48**	0	230	230	33000	33000
44	0	**0**	25	**500**	**500**	0	0	**48**	0	230	230	33000	33000
45	0	**0**	25	**700**	**700**	0	0	**48**	0	230	230	33000	33000
46	0	**0**	25	**900**	**900**	0	0	**48**	0	230	230	33000	33000
47	0	**0**	25	**100**	**100**	0	0	**72**	0	230	230	33000	33000
48	0	**0**	25	**300**	**300**	0	0	**72**	0	230	230	33000	33000
49	0	**0**	25	**500**	**500**	0	0	**72**	0	230	230	33000	33000
50	0	**0**	25	**700**	**700**	0	0	**72**	0	230	230	33000	33000
51	0	**0**	25	**900**	**900**	0	0	**72**	0	230	230	33000	33000
52	0	**0**	25	**100**	**100**	0	0	**96**	0	230	230	33000	33000
53	0	**0**	25	**300**	**300**	0	0	**96**	0	230	230	33000	33000
54	0	**0**	25	**500**	**500**	0	0	**96**	0	230	230	33000	33000
55	0	**0**	25	**700**	**700**	0	0	**96**	0	230	230	33000	33000
56	0	**0**	25	**900**	**900**	0	0	**96**	0	230	230	33000	33000
57	0	**0**	25	**100**	**100**	0	0	**120**	0	230	230	33000	33000
58	0	**0**	25	**300**	**300**	0	0	**120**	0	230	230	33000	33000
59	0	**0**	25	**500**	**500**	0	0	**120**	0	230	230	33000	33000
60	0	**0**	25	**700**	**700**	0	0	**120**	0	230	230	33000	33000
61	0	**0**	25	**900**	**900**	0	0	**120**	0	230	230	33000	33000
62	0	**0**	25	**100**	**100**	0	0	**144**	0	230	230	33000	33000
63	0	**0**	25	**300**	**300**	0	0	**144**	0	230	230	33000	33000
64	0	**0**	25	**500**	**500**	0	0	**144**	0	230	230	33000	33000
65	0	**0**	25	**700**	**700**	0	0	**144**	0	230	230	33000	33000
66	0	**0**	25	**900**	**900**	0	0	**144**	0	230	230	33000	33000

A.4 Various Time Windows

No	TW	V_{min}	V_{max}	IFO_{min}	IFO_{max}	TW_{min}	TW_{max}	$Disrup_{mean}$	$Disrup_{std}$	**Delay Penalty$_{min}$**	**Delay Penalty$_{max}$**	**Skip Penalty$_{min}$**	**Skip Penalty$_{max}$**
67	1	**0**	25	500	500	**0**	**0**	**24**	0	230	230	33000	33000
68	1	**0**	25	500	500	**4**	**4**	**24**	0	230	230	33000	33000
69	1	**0**	25	500	500	**8**	**8**	**24**	0	230	230	33000	33000
70	1	**0**	25	500	500	**12**	**12**	**24**	0	230	230	33000	33000
71	1	**0**	25	500	500	**16**	**16**	**24**	0	230	230	33000	33000
72	1	**0**	25	500	500	**0**	**0**	**48**	0	230	230	33000	33000
73	1	**0**	25	500	500	**4**	**4**	**48**	0	230	230	33000	33000
74	1	**0**	25	500	500	**8**	**8**	**48**	0	230	230	33000	33000
75	1	**0**	25	500	500	**12**	**12**	**48**	0	230	230	33000	33000
76	1	**0**	25	500	500	**16**	**16**	**48**	0	230	230	33000	33000
77	1	**0**	25	500	500	**0**	**0**	**72**	0	230	230	33000	33000
78	1	**0**	25	500	500	**4**	**4**	**72**	0	230	230	33000	33000
79	1	**0**	25	500	500	**8**	**8**	**72**	0	230	230	33000	33000
80	1	**0**	25	500	500	**12**	**12**	**72**	0	230	230	33000	33000
81	1	**0**	25	500	500	**16**	**16**	**72**	0	230	230	33000	33000
82	1	**0**	25	500	500	**0**	**0**	**96**	0	230	230	33000	33000
83	1	**0**	25	500	500	**4**	**4**	**96**	0	230	230	33000	33000
84	1	**0**	25	500	500	**8**	**8**	**96**	0	230	230	33000	33000
85	1	**0**	25	500	500	**12**	**12**	**96**	0	230	230	33000	33000
86	1	**0**	25	500	500	**16**	**16**	**96**	0	230	230	33000	33000
87	1	**0**	25	500	500	**0**	**0**	**120**	0	230	230	33000	33000
88	1	**0**	25	500	500	**4**	**4**	**120**	0	230	230	33000	33000
89	1	**0**	25	500	500	**8**	**8**	**120**	0	230	230	33000	33000
90	1	**0**	25	500	500	**12**	**12**	**120**	0	230	230	33000	33000

91	1	**0**	25	500	500	**16**	**16**	**120**	0	230	230	33000	33000
92	1	**0**	25	500	500	**0**	**0**	**144**	0	230	230	33000	33000
93	1	**0**	25	500	500	**4**	**4**	**144**	0	230	230	33000	33000
94	1	**0**	25	500	500	**8**	**8**	**144**	0	230	230	33000	33000
95	1	**0**	25	500	500	**12**	**12**	**144**	0	230	230	33000	33000
96	1	**0**	25	500	500	**16**	**16**	**144**	0	230	230	33000	33000

A.5 Various Skipping Penalties

No	TW	V_{min}	V_{max}	IFO_{min}	IFO_{max}	TW_{min}	TW_{max}	$Disrup_{mean}$	$Disrup_{std}$	**Delay Penalty$_{min}$**	**Delay Penalty$_{max}$**	**Skip Penalty$_{min}$**	**Skip Penalty$_{max}$**
97	0	**0**	25	500	500	0	0	**24**	0	230	230	**11000**	**11000**
98	0	**0**	25	500	500	0	0	**24**	0	230	230	**33000**	**33000**
99	0	**0**	25	500	500	0	0	**24**	0	230	230	**55000**	**55000**
100	0	**0**	25	500	500	0	0	**24**	0	230	230	**77000**	**77000**
101	0	**0**	25	500	500	0	0	**24**	0	230	230	**99000**	**99000**
102	0	**0**	25	500	500	0	0	**48**	0	230	230	**11000**	**11000**
103	0	**0**	25	500	500	0	0	**48**	0	230	230	**33000**	**33000**
104	0	**0**	25	500	500	0	0	**48**	0	230	230	**55000**	**55000**
105	0	**0**	25	500	500	0	0	**48**	0	230	230	**77000**	**77000**
106	0	**0**	25	500	500	0	0	**48**	0	230	230	**99000**	**99000**
107	0	**0**	25	500	500	0	0	**72**	0	230	230	**11000**	**11000**
108	0	**0**	25	500	500	0	0	**72**	0	230	230	**33000**	**33000**
109	0	**0**	25	500	500	0	0	**72**	0	230	230	**55000**	**55000**
110	0	**0**	25	500	500	0	0	**72**	0	230	230	**77000**	**77000**
111	0	**0**	25	500	500	0	0	**72**	0	230	230	**99000**	**99000**
112	0	**0**	25	500	500	0	0	**96**	0	230	230	**11000**	**11000**
113	0	**0**	25	500	500	0	0	**96**	0	230	230	**33000**	**33000**
114	0	**0**	25	500	500	0	0	**96**	0	230	230	**55000**	**55000**

115	0	**0**	25	500	500	0	0	**96**	0	230	230	**77000**	**77000**
116	0	**0**	25	500	500	0	0	**96**	0	230	230	**99000**	**99000**
117	0	**0**	25	500	500	0	0	**120**	0	230	230	**11000**	**11000**
118	0	**0**	25	500	500	0	0	**120**	0	230	230	**33000**	**33000**
119	0	**0**	25	500	500	0	0	**120**	0	230	230	**55000**	**55000**
120	0	**0**	25	500	500	0	0	**120**	0	230	230	**77000**	**77000**
121	0	**0**	25	500	500	0	0	**120**	0	230	230	**99000**	**99000**
122	0	**0**	25	500	500	0	0	**144**	0	230	230	**11000**	**11000**
123	0	**0**	25	500	500	0	0	**144**	0	230	230	**33000**	**33000**
124	0	**0**	25	500	500	0	0	**144**	0	230	230	**55000**	**55000**
125	0	**0**	25	500	500	0	0	**144**	0	230	230	**77000**	**77000**
126	0	**0**	25	500	500	0	0	**144**	0	230	230	**99000**	**99000**