BLOCKCHAIN ADOPTION IN THE MARITIME INDUSTRY

PU SHUYI
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

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in partial fulfilment of the requirement for the degree of
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Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

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Prof. Lam Siu Lee Jasmine

Authorship Attribution Statement

This thesis contains material from 4 papers published in the following peer-reviewed journal(s) / from papers accepted at conferences in which I am listed as an author.

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The contributions of the co-authors are as follows:

- Prof Lam Siu Lee Jasmine provided the initial project direction, reviewed and edited the manuscript drafts.
- I prepared the manuscript drafts. The manuscript was revised by Prof Lam Siu Lee Jasmine.

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SUMMARY

Blockchain has become one of the emerging technologies set to disrupt the maritime industry. Increasingly, maritime logistics and services providers are looking to adopt the technology to stay ahead of competition. However, studies on blockchain adoption in the maritime sector have been scarce. Therefore, this research aims to narrow the literature gap by analysing blockchain adoption in the maritime industry deeply and solving related practical adoption questions quantitatively.

This research starts with a systematic analysis of current blockchain applications in various sectors of the maritime industry. A novel conceptual framework is also developed to provide a holistic view of how blockchain technology can be applied in the maritime industry and guide future research. Then, this research focuses on three practical problems regarding blockchain adoption in the maritime industry, namely optimal adoption time, evolution of adoption and greenhouse gas impact.

Firstly, a game theoretic model is built to analyse companies' optimal adoption time of blockchain when facing a request of a big customer, which is an emerging trend in the industry. A big shipper and multiple ship operators are used as a case in the study. The result indicates that substitution policies imposed by the big shipper is effective to promote blockchain adoption only for small ship operators. It also reflects the effectiveness of a mixed pricing model for blockchain, and the importance of blockchain's cost-effectiveness to promote early blockchain adoption. In addition, an Covid-19 model extension shows that the Covid-19 has a positive impact to accelerate blockchain adoption under a mixed pricing scheme but a mixed impact under a fixed pricing scheme.

Secondly, an asymmetric evolutionary game model is built to examine the potential evolution of blockchain adoption rate in multi-agent systems. This study uses blockchain electronic bills of lading as an example, as it is one of the most promising blockchain applications in the maritime industry. The findings suggest that it is more efficient to promote blockchain adoption by focusing on carriers than shippers because carriers require a lower critical mass than shippers. Players are more inclined to use blockchain eBLs for low-value products in the current market situation. The convergence speed is faster if carriers instead of shippers pay the blockchain eBL transaction fee when blockchain adoption is the evolutionarily stable strategy.

Thirdly, an estimation framework with concrete methods is developed to estimate the national greenhouse gas impact of blockchain for digitalising shipping documents. Taking Singapore and China as examples, the difference in greenhouse gas performance between blockchain and centralised systems is also compared in the study. The results indicate that digitalisation can reduce over 99% of document-related emissions. Car transport to transfer documents is the largest emission source in paper systems constituting over 90% of emissions per shipping event. Blockchain and centralised systems have similar effects on emission reductions.

This research contributes to academia and practitioners in the following ways. It deepens the literature by analysing blockchain adoption in the maritime industry in a holistic view. It makes novel attempts to solve practical problems of blockchain adoption in a quantitative way, including adoption time, evolution of adoption rate and environmental impact. It pushes the boundary of relevant literature from qualitative studies to more quantitative analysis. Meanwhile, it provides useful decision tools and insights to maritime stakeholders on policies and business strategies to foster and accelerate blockchain adoption in the industry.

LIST OF PUBLICATIONS

Pu, S., and Lam, J.S.L. (2021). “Greenhouse gas impact of digitalizing shipping documents: Blockchain vs. centralized systems.” *Transportation Research Part D: Transport and Environment*. 97, 102942. doi:10.1016/j.trd.2021.102942.

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CHAPTER 1 INTRODUCTION

With slower expansion of international trade, increasing uncertainties in the global economy and outbreak of Covid-19, the maritime industry is facing fierce competition and strives to differentiate itself with better service quality and reduced costs. Blockchain technology has the potential to reshape the industry and expedite post-Covid-19 recovery with abilities to streamline business processes, enhance information sharing and enable new business models. This thesis aims to study and address practical problems of blockchain adoption in the maritime industry. This chapter provides an overview of this report, introducing the background, objectives, scope and significance of the research, as well as the report structure.

1.1 Background

The expansion of international trade has slowed down and the appetite for trade liberalisation appears to be declining in recent years (Goldberg, 2019). Rising geopolitical uncertainties, ongoing U.S.-China trade tensions and recent outbreak of Covid-19 pandemic have clouded the world economic outlook. Many industries have suffered from weaker and more unpredictable demands, tighter financial conditions and longer supply chain lead time. To mitigate the risks, companies need to increase their competitiveness through higher productivity, higher efficiency, lower costs and better customer experience. The maritime industry is increasingly volatile (UNCTAD, 2020a). Maritime companies are under further pressure and have to look for innovative ways to stay competitive in the challenging and fast-changing world.

The maritime industry is seen making efforts to embrace the emergence of digital technologies in Industry 4.0 to revolutionise its processes, as process innovation plays an important role in improving shipping companies' competitive advantage (Lam and Zhang, 2019). For instance, the Internet of things (IoT), like sensors and RFID, is increasingly used in the industry (QinetiQ et al., 2016). This not only enhances the communication between equipment to human, but also generates valuable big data for deep analysis. Big data analytics provides powerful methods for decision making and predictive analysis. Port operators use it for optimising port operations (Noll and Hogeweg, 2015). Shipowners use it to optimise ship operations, predict engine fault and analyse reasons for machinery problems (Zhang and Lam, 2019). Maritime authorities use it for e-navigation and maritime domain awareness (Zhang and Lam, 2019).

Blockchain has recently become another promising technology that could potentially transform the maritime industry. Blockchain was initially introduced by Nakamoto in 2008 for building Bitcoin, which is a cryptocurrency that can be traded in the world without involving banks. Since then, blockchain has gained more and more attention globally. Industries started to examine the technology behind and realised its potential to be applied beyond the financial sector. For example, the digital signatures of blockchain could be applied to other areas to trace the ownership of properties and goods. A tamper-proof and transparent ledger can be used for electoral voting systems. Underlining the widespread applications of blockchain is the fast evolution of its ecosystems due to the introduction of Blockchain-as-a-Service from technology companies like IBM (Xu et al., 2017).

For the maritime industry, blockchain is highly promising in addressing the industry's pain points like intensive paperwork, tedious processes and data transparency. It enables maritime companies to differentiate their services and reduce costs at the same time, which is the most desirable hybrid business model for shipping companies (Lam and Wong, 2018). It is also a technological advancement to authenticate and validate information (Apte and Petrovsky, 2016), which is a main problem of the current supply chain (Wu et al., 2017). As such, more and more maritime companies started to join the wave of blockchain, such as Maersk, NYK, ZIM, APL and Port of Rotterdam (Xu 2017; Seatrade 2017). Some alliances (e.g., Global Shipping Business Network (GSBN)) have also been formed to better discover the potential of blockchain in the industry.

With the increasing demand regarding transparency, traceability, and sustainability, big shippers are deploying blockchain in their businesses at a growing pace, such as Royal Dutch Shell, BHP, Louis Dreyfus, and ABInBev (Reuters, 2018, 2019; Rizzo, 2016; Shell, 2018; The Maritime Executive, 2018). Some of them like BHP (a mining giant) even exert their influence on their vendors including ship operators to adopt blockchain as part of their supply chain (Rizzo, 2016). Besides, Louis Dreyfus Company (one of the world's biggest traders of agricultural goods) brought Russel Marine Group and Blue Water Shipping on board for its blockchain project (Reuters, 2018). AB InBev (the world's largest brewer) brought APL on board for its blockchain project (The Maritime Executive, 2018). It becomes an emerging trend in the industry that companies like ship operators are facing requests from big customers to join the customers' blockchain initiatives. Despite blockchain's potential and customers' requests, most companies are still unsure whether and when to adopt blockchain. Therefore, it is meaningful to investigate this important question.

Blockchain has great potential to be applied in electronic bills of lading (eBLs) to replace paper bills of lading (BLs). BLs are important documents in maritime trade as evidence of contract of carriage, receipt of goods by the carrier and document of title (UNCTAD, 1971). Original BLs must be surrendered to the carrier at the discharge port in order to get delivery of the cargo. Along the process, three main problems of the paper BL system exist, namely time delay, costs and security risks (UK P&I Club, 2017). To tackle these problems, eBLs are proposed with the advantages of instant delivery, reduced costs and higher security. Since 1999, early attempts of eBLs developed including Bolero, essDOCS and e-title^{TM}, which provide centralised platforms to issue, transfer and manage BLs digitally based on electronic data interchange (EDI) technology. The user base for EDI eBL systems has increased over time. For instance, 17% of Fortune Global 500 companies are using the essDOCS eBL system by 2020 (essDOCS, 2020a). However, EDI eBL solutions as centralised systems still have some problems such as confidentiality issues and insider fraud (Pagnoni and Visconti, 2010; Takahashi, 2016). Blockchain-based systems are considered a more suitable solution for eBLs because of their decentralisation, immutability and security (Takahashi, 2016; Todd, 2019). Organisations such as Maersk, APL, Sinochem and Louis Dreyfus Company have explored, tested and even applied blockchain eBL solutions since 2017 (Accenture, 2018; Maersk, 2018; OpenGov Asia, 2018). However, there may be strong pushback from the existing shipping systems when adopting a new technology (Jabbar and Bjørn, 2018). This could make the expansion of blockchain eBLs difficult at least in the short term, lead to a wait-and-see attitude of companies and affect the final adoption rate of blockchain eBLs. Thus, whether blockchain eBLs could eventually reach mass adoption is uncertain and worth being analysed.

The maritime industry is also on a pathway to decarbonisation. The International Maritime Organization (IMO)'s Greenhouse Gas (GHG) strategy adopted in 2018 emphasises the importance of sustainable development and emission accounting in the maritime industry. Digitalisation is a feasible and sustainable solution to significantly reduce GHG emissions relating to ocean shipping in the short term (UNCTAD, 2020b). The outbreak of Covid-19 has revealed gaps across countries in developing digitalisation in maritime services including ports and relevant government agencies. For instance, only 49 of the 174 member countries of IMO have port community systems by June 2020 (BIMCO, 2020a). There is an urgent need to accelerate the speed of digitalisation, notably in handling shipping documents, to reduce physical interaction and enhance efficiency simultaneously.

Blockchain is regarded as a promising technology to facilitate digitalisation and enabling fast post-Covid-19 recovery in the maritime industry (UNCTAD, 2020c). The technology has been increasingly tested and applied in the industry for reducing shipping paperwork (CargoX, 2018; Maersk, 2018; Global Trade Review, 2019). A recent example is a blockchain project initiated by The International Maritime Employer's Council (IMEC) and the International Transport Worker's Federation (ITF) to facilitate crew changes during and even after the Covid-19 pandemic (BIMCO, 2020b). Health pass is issued to seafarers using blockchain technology to address the concerns of fake Covid-19 test results. Digitalising documents is evaluated as the most value-added factor and a feasible solution in the short term in greening maritime transportation (Garg and Kashav, 2019; UNCTAD, 2020b). However, its GHG impact is barely studied before. Compared with traditional centralised digital systems, blockchain outperforms technically by providing more tamper-proof and intelligent systems. But it is often criticised for its low energy efficiency. Therefore, it is an important topic to estimate the GHG impact of blockchain in digitalising shipping documents and compare it with centralised systems.

Despite the increasing popularity of blockchain in the maritime industry, related literature remains limited. Previous researchers mainly focus on the benefits, drivers, barriers and adoption areas of blockchain in the industry. Most analyses are confined to a specific sector of the maritime industry. Besides, their methods are more qualitative in nature. Hence, this research aims to extend the boundary of literature in the area by first providing a more systematic and holistic analysis of blockchain adoption in the industry and then quantitatively solving practical problems relating to blockchain adoption in the industry, including optimal adoption time, evolution of adoption and its GHG impact.

1.2 Research objectives

The main objective of this research is to analyse the adoption of blockchain technology in the maritime industry. Based on the above-mentioned background and trends of blockchain adoption in the industry, the detailed research objectives are outlined as below:

1) To thoroughly analyse current and emerging blockchain applications from the perspectives of different sectors in the maritime industry.
2) To develop a conceptual framework of blockchain adoption in the maritime industry in a holistic view and guide future research.
3) To analyse companies’ optimal adoption time of blockchain when facing an adoption request from a big customer, using a big shipper and multiple ship operators as a case.
4) To analyse the evolution of blockchain adoption in the maritime industry in terms of adoption rate, using electronic bills of lading as a case.
5) To develop an estimation framework with concrete methods to evaluate the GHG impact of digitalising shipping documents with blockchain and compare blockchain with centralised systems in their GHG impact.

1.3 Research scope

This research focuses on blockchain adoption in the maritime industry. The adoption is discussed both qualitatively and quantitatively.

In the qualitative study, this research examines blockchain adoption in different sectors of the maritime industry and develops a conceptual framework covering the following research questions: how can blockchain be applied in different sectors of the maritime industry; why is it suitable for these applications; what are the challenges for adoption in the industry and what are the research opportunities in this field.

In the quantitative studies, important adoption questions are modelled from non-cooperative, evolutionary, and environmental perspectives. Major maritime stakeholders of each question are selected for analysis. Based on the nature of use cases in discussion, the blockchain systems in these studies are permissioned blockchain and but they are not restricted to blockchain technology only and can be applicable for other distributed ledger technologies.

From a non-cooperative point of view, competition exists among potential users. They make the optimal decisions in terms of whether and when to adopt blockchain as the best response to the decisions of others. This research analyses users' optimal adoption time of blockchain with competition. It models a current market trend that a big customer requests its vendors to adopt blockchain to digitalise their current documentation systems. A two-layer shipping market is used as a case with a big shipper and multiple ship operators. In this study ship operators refer to those who operate vessels and may not necessarily be the owner of the operated vessels.

From an evolutionary point of view, users from different groups of populations across supply chain interact with each other and evolve to figure out the best adoption decisions that help them to survive over time. This research examines how blockchain adoption will evolve, considering economic factors, network effects and impact of incumbent systems. eBL is used as a blockchain adoption case due to its great potential in the industry. The populations of carriers and shippers are selected for analysis as they are essential players involved in a typical BL. Carrier in this study is a special term used in bills of lading referring to the owner of the vessel.

From an environmental point of view, blockchain has the potential to facilitate digitalisation for shipping documents and provides a feasible and sustainable solution to reduce GHG emissions relating to maritime transportation. This research focuses on the GHG impact of digitalising shipping documents with blockchain at the national level. Two major maritime countries - Singapore and China are selected as cases for illustration as they vary significantly in shipping operational complexity, geographical size and governance structure.

1.4 Research significance

This section discusses the academic and practical significance of the research.

Academically, the research makes contributions in the following ways. Firstly, it develops a novel conceptual framework to systematically conceptualise blockchain adoptions in the maritime industry. It helps researchers and practitioners to converge their understanding of blockchain adoption in the industry and form a common basis and guide for future research. Secondly, it is the first in the literature to analyse the adoption time of blockchain technology in an industry. Thirdly, in terms of methodological significance, a novel algorithm is developed to obtain the numerical solutions of ship operators' optimal adoption time. Fourthly, it is also the first in the literature to analyse the evolution of blockchain in terms of adoption rate in an industry. An evolutionary game is developed to predict how the adoption rate of blockchain would evolve over time under different conditions. Lastly, it advances maritime digitalisation research in the environmental aspect by developing an estimation framework with concrete methods to quantify the GHG impact of digitalising shipping documents across maritime supply chains. The proposed framework is general in nature and can be applied to estimate document-related emissions with any digital technology in any industry.

Practically, the research benefits industry stakeholders. Firstly, it helps maritime stakeholders to better understand blockchain's potential and why and how it can be applied in different areas. Hence it assists stakeholders to better evaluate and design their own blockchain use cases. Secondly, the analysis of optimal adoption time helps ship operators in decision making regarding whether and when to adopt blockchain under competition in different market situations. Thirdly, the evolution analysis assists stakeholders to better understand the dynamic changes of blockchain adoption over time and make better decisions. Fourthly, it provides implications for stakeholders on how to facilitate and accelerate blockchain adoption both in the short term and in the long term. Lastly, it identifies the potential of blockchain and suggests key areas of focus for digitalising the processes of shipping documents.

1.5 Thesis structure

The structure of this thesis is as follows.

Chapter 1 introduces the background, objectives, scope, significance and overall structure of the report.

Chapter 2 reviews related literature on blockchain technology, blockchain adoption, evolution of blockchain, and carbon footprint relating to blockchain. Major literature gaps are identified accordingly.

Chapter 3 describes the overall research process flow and introduces the methods used in chapters 4, 5, 6 and 7.

Chapter 4 analyses blockchain adoption in various sectors of the maritime industry. A novel conceptual framework is proposed to provide a holistic view of blockchain adoption in the industry and guide future research.

Chapter 5 analyses the optimal adoption time of ship operators using a game theoretic model. Theoretical results are derived. A novel algorithm is developed to obtain numerical solutions. Industry data are applied for numerical applications with sensitivity analysis.

Chapter 6 investigates the evolution of blockchain adoption in multi-agent systems using eBL as a blockchain application case. An asymmetric evolutionary game model is developed to analyse the co-evolution of players from different populations based on their dynamic interactions.

Chapter 7 develops an estimation framework with concrete methods for national GHG emissions relating to shipping documents, based on a process analysis approach. It compares the potential GHG reductions from digitalising shipping documents with blockchain and centralised systems by applying the framework to Singapore and China.

Finally, Chapter 8 summarises the researching findings and contributions. It also points out research limitations and proposes future research directions.

CHAPTER 2 LITERATURE REVIEW

This chapter firstly reviews blockchain technology regarding its features, how it works, classifications, platforms, storage issues and concerns. Then, it reviews relevant studies on blockchain adoption in general and in various industries, evolution of blockchain, and carbon footprint relating to blockchain. Finally, the major literature gaps are identified and summarised.

2.1 Overview of blockchain in concept

2.1.1 What is blockchain?

Haber and Stornetta (1991) first came up with the idea of cryptographically secured chain of blocks. Two years later, Bayer and the above two authors (1993) incorporated Merkle trees to improve the efficiency of the chain so that it allows several documents to be collected into one block. In 2008, Satoshi Nakamoto first came up with the concept of blockchain. In 2009, Nakamoto launched Bitcoin, which is a decentralised cryptocurrency using blockchain technology to trade in the world without involving banks.

Blockchain is defined as a distributed database solution that holds a continuously growing list of data records which must be confirmed by all participating nodes (Yli-Huumo et al., 2016). The general key features of blockchain are summarised in Table 2.1. Because of these features, blockchain technology provides potential good solutions for businesses that require a high level of traceability, security, and transparency.

Blockchain has evolved rapidly from generation 1.0 to generation 3.0 since its introduction in 2008. The first generation of blockchain, denoted as blockchain 1.0, is a distributed ledger for money transactions with very limited programmable capabilities (Xu et al., 2016). A typical application is cryptocurrency, represented by Bitcoin. Cryptocurrency is a kind of virtual money and its transfer can be achieved without any central banks or central authorities. The creation of new units of cryptocurrency is realised through mining. Blockchain 2.0, considered the second generation of blockchain, is under development. It provides an infrastructure that users can add programmable functions on the network based on their specific needs (Xu et al., 2016). This is represented by smart contracts, which are computer programs built on the ledger (Deloitte, 2017). Smart contracts enable autonomous execution and they are independent of the parties involved (Chapron, 2017). For example, once pre-specified conditions are met, the contractual money will be automatically transferred from buyer to seller. The buyer cannot hold the money nor withdraw it from contracts. Swan (2015) proposed the idea of blockchain 3.0 which represents all the applications of blockchain beyond the financial and economic sectors, e.g., it can be used for digital asset proof and government voting.

Table 2.1 Summary of the main features of blockchain technology.

Key Features of Blockchain	Description	References
Distributed System	No single party controls the data. There must be a consensus of the whole chain, in order to add a new block.	(Xu et al., 2016; Berke, 2017)
Immutability	Any transactions that have been uploaded are irreversible, i.e., they cannot be changed or deleted.	(Xu et al., 2016, 2017; Berke, 2017)
Peer-to-peer transmission	Transactions and communications occur directly between parties without going through a central party. This replaces the need for a third-party to provide trust for transactions.	(World Economic Forum, 2015; Christidis and Devetsikiotis, 2016; Berke, 2017)
No single point of failure	All the nodes keep a full copy of ledgers. Even if a node is down, the data is still accessible in a 24/7 manner via other nodes within the network.	(Berke, 2017; Piscini et al., 2017; Abeyratne and Monfared, 2016)
Time-series data	Because of its immutability, any progress of old transactions can only be appended to the blockchain as new transactions.	(Xu et al., 2016; Yuan and Wang, 2016)
Visibility to all	All the transactions are transparent to all participants in the chain. However, in a private blockchain, the visibility of transactions can be limited to specified users.	(World Economic Forum, 2015; Xu et al., 2016, 2017)
Anonymity	Each user will have a public address and a private address to represent himself. Transactions occur only between addresses without knowing your real-life identity. Users can remain anonymous in this way.	(Berke, 2017; Xu et al., 2017)
Smart contracts	By incorporating smart contracts, additional rules can be added based on users' own needs via programming. The execution of the rules is independent and automatic and requires no trusted third party.	(Yuan and Wang, 2016; Berke, 2017)

2.1.2 How does blockchain work

A blockchain consists of an ordered collection of blocks that are linked together (Xu et al., 2016). The linkage is achieved by making every block contain the hash of its previous block (Christidis and Devetsikiotis, 2016). The only exception is the head block as it does not have a previous block. The transactions on blockchain are realised and secured mainly through 1) public and private keys, 2) validation rules, and 3) asymmetric cryptography.

The security and authentication of transactions are achieved through private and public keys generated by asymmetric cryptography technology (Christidis and Devetsikiotis, 2016). The public key is visible on the network, as an anonymous identity of the users. The private key is kept confidential by users like a password, and it is used to sign their own transactions.

Every blockchain network can establish its own rules for its transactions to comply. The rules are programmed into each node of the blockchain and are used by nodes to verify if a transaction is valid. Once a user signs a transaction, it will be propagated to neighbouring peer nodes, which will first check the validity of the new transaction based on the built-in rules. Only the valid transactions will be passed to other nodes for further validation until it reaches consensus of the whole network. The invalid ones will be discarded.

Asymmetric cryptography uses one-way cryptographic hash functions, which make it impossible to reversely calculate the input from the output. At the same time, the output can be easily verified by other nodes without knowing the input. As such, asymmetric cryptography provides high security while providing ease of validation without releasing users’ information. Therefore, it can be applied to encrypting information, digital signature and log-in authentication in blockchain (Yuan and Wang, 2016).

2.1.3 Classification of blockchain

Depending on the openness of network and the nature of validation process, blockchain can be categorised into two groups, namely permissionless and permissioned (Xu et al., 2016)：

- Permissionless blockchain, also known as **public** blockchain, is open to anyone in the world to join the network. Everyone has the permission to write, read and verify the data on the ledger and everyone on the chain can have an identical copy of full ledgers on the whole network (Xu et al., 2016). Such a blockchain cannot be owned (UK Government Office for Science, 2016).

- Permissioned blockchains, consisting of **private and consortium** blockchain, are only open to a group of parties which are whitelisted by the owners. The permissions to write and verify transactions are restricted to pre-selected participants and validators, whose actual identities have to be known before they join the network (UK Government Office for Science, 2016). But the permission to read can be open to the public or restricted to a certain level (Xu et al., 2017).

Table 2.2 compares the two types of blockchain. Unlike permissionless blockchains, permissioned blockchains are more congruent with the current regulatory environment because of the use of actual entities of participants (Ducas and Wilner, 2017). Hence, they are able to legally host off-chain properties in the real world, which makes them more suitable for business enterprises (Xu et al., 2016). Besides, they also provide flexibility for owners to change rules and reverse transactions (UK Government Office for Science, 2016). Therefore, permissioned blockchains are more suitable for business enterprises that require higher performance in privacy, speed, and regulatory conformance. Permissionless blockchains are more suitable for activities which require a high level of transparency and auditability.

Table 2.2 Comparison of permissionless and permissioned blockchain.

Properties	Permissionless blockchain	Permissioned blockchain
Consensus Process	Open to public	Only open to pre-selected validators
Right to write and read	Open to public	Only open to whitelisted organisations
Ability to host real-world assets	No	Yes
Ability to reverse transactions	No	Yes
Cost efficiency	Less favourable	More favourable
Speed	Slower	Faster
Openness	Higher	Lower

Source: Compiled by author from (UK Government Office for Science, 2016; Ducas and Wilner, 2017; Xu et al., 2017)

2.1.4 Distributed ledger platforms

2.1.4.1 Ethereum

Ethereum is a permissionless programmable blockchain launched in 2015 (Ethereum, 2019). Apart from the functions provided by Bitcoin, Ethereum allows developers to design new applications (smart contracts) on it (Ethereum, 2019). Therefore, it is like a decentralised computer where multiple parties can share information and run programs on it (Swan, 2018).

2.1.4.2 Ethereum quorum

Ethereum Quorum (Quorum in short) developed by J.P. Morgan, is a permissioned version of Ethereum focusing on providing solutions to business enterprises which require a certain level of privacy (CoinDesk, 2019). It supports both public and private transactions (Swan, 2018). Since Quorum is built based on Ethereum protocol, it is more developed with regard to codebase, user-base and developer community compared with the other two systems (Vukolić, 2017). The transparency of transactions can be either public or restricted to involved participants, depending on the requirements of customers (Swan, 2018).

2.1.4.3 Corda

Corda is developed by R3, which has changed from a consortium of 80 financial institutions to a blockchain firm with over 300 partners from various industries (R3, 2019). Corda is not a blockchain but another type of distributed ledger technology, as its transactions are not grouped in the form of blocks (Swan, 2018). It is specially designed for the financial services industry considering the heavily regulated environment of the industry (Swan, 2018). Corda's transparency is based on a need-to-know basis, which means that only the parties involved in a transaction would have the accessibility to the details of that transaction (Swan, 2018). It supports Java and Kotlin (similar to Java) to develop smart contracts, which makes it easy to be implemented as Java is a mainstream programming language (Swan, 2018). It also provides plug-and-play applications which make it more interoperable with organisations' existing IT infrastructure. In terms of smart contracts, Corda not only includes technical codes but also contains legal prose in natural language (Valenta and Sandner, 2017), while Hyperledger Fabric and Ethereum Quorum lack this feature. This special feature makes Corda outstanding in heavily regulated industries.

2.1.4.4 Hyperledger fabric

Hyperledger Fabric is initially contributed by Digital Asset Group and IBM (Swan, 2018). It is more to provide a modular platform that can be employed in various industries with customisation depending on different needs (Valenta and Sandner, 2017). It is also easy to use by supporting Golang and Java as smart contract languages. The transparency level of information is also subject to the need-to-know basis.

Table 2.3 provides a summary of the important features of these platforms for ease of comparison.

Table 2.3 Comparison of distributed ledger technologies (DLT) for the maritime industry.

Features	Ethereum	Ethereum Quorum	Hyperledger Fabric	Corda
Permission	Permissionless	Permissioned	Permissioned	Permissioned
Built-in Cryptocurrency	Yes	Yes	No (but possible to develop one with chaincode)	No
Smart Contract Execution	Ethereum Virtual Machine (EVM)	EVM	Dockers	Java Virtual Machine (JVM)
Smart Contract Language	Solidity	Solidity	Golang, Java	Kotlin, Java
Consensus	Hybrid PoW*/PoS*	Raft (similar to PoS)	Practical Byzantine Fault Tolerance (PBFT)	Raft (similar to PoS)
Transparency level	Public	Public or Private	Need-to-know basis	Need-to-know basis
Scalability	Less Favourable	More Favourable	More Favourable	More Favourable

*PoW: Proof of Work; PoS: Proof of Stake
Source: Compiled by author from (Dinh et al., 2017; Valenta and Sandner, 2017; Swan, 2018)

2.1.5 On-chain or off-chain storage

Data storage of blockchain is an important topic that requires specific attention. Data can be stored on blockchain by embedding data into transactions that will be submitted to the blockchain (Xu et al., 2016). After a transaction is accepted in the network, the transaction becomes publicly accessible to the parties within the blockchain. However, storing too much information on the blockchain may affect performance speed given limited computational power and limited storage space on-chain (Xu et al., 2016). A more common practice of data storage in blockchain is to only keep meta-data on-chain and put large and private raw data off-chain (Xu et al., 2016). Off-chain storage is also good for sensitive information that companies are not willing to share (Kuo et al., 2017).

2.1.6 Concerns of blockchain

Major concerns of blockchain in general are security, scalability and transactional speed. Even though blockchain is considered highly secured, it is still subject to Sybil attack (51% attack) despite the high attacking cost (Swan, 2015; Yuan and Wang, 2016). This risk is applicable to permissionless blockchain. Permissioned blockchain is considered to have the ability to mitigate the risk because of restricted access to the network (Davenport et al., 2019). In addition, smart contract is a weak point of blockchain in security. An attack on one small contract could have a domino effect on other parts of the network (Deloitte, 2017). In a distributed system, every node will keep a full copy of all transactions on the network, which requires large overall storage (Xu et al., 2017). The number of transactions that can be recorded in a single block is determined by the bandwidth of the network (Ali et al., 2016). Currently, Bitcoin's bandwidth per block is 1MB. With the growing trading volume and users, developers should ensure a scalable system regarding storage size and bandwidth (Xu et al., 2017). Users also complain about the time delay between submission and confirmation of a transaction which is caused by implementing consensus mechanisms. It takes Bitcoin 10 minutes in completing a transaction, while VISA only takes a few seconds (Swan, 2015). However, from a business perspective, especially in the context of cross-border remittance, the transactions speed using cryptocurrency is so much faster than the way using traditional SWIFT system.

2.2 Blockchain adoption in general and in non-maritime industries

In previous studies, blockchain adoption has been discussed either in general or in a specific industry. The themes covered by these studies are relatively the same, mainly about application areas, drivers, barriers, how to adopt and technical design of blockchain.

For general industries, White (2017) investigates the application areas of blockchain through a Delphi study. Biswas and Gupta (2019) and Grover et al. (2019) analyse the barriers and drivers of blockchain adoption across industries respectively. Janssen et al. (2020) develop a conceptual framework to guide companies on how to adopt blockchain. Toufaily et al. (2021) propose a conceptual framework that consolidates the challenges and expected socio-economic value of blockchain adoption in both private and public sectors from a multi-stakeholder perspective.

For specific industries, blockchain adoption has been discussed in various industries, with a lot in the supply chain and health care industry. In the supply chain industry, Kshetri (2018) discusses how blockchain could assist in meeting supply chain objectives based on case study analysis. Wong et al. (2020) investigate the factors that could influence users’ intention to use blockchain for supply chain management. Kouhizadeh et al. (2021) examine the barriers of blockchain adoption for sustainable supply chain management. In the health care industry, Kuo et al. (2017) analyse blockchain’s benefits, potential applications and challenges for the health care industry. Mackey et al. (2020) examine why and how blockchain could address the problems of current health care systems in Japan. Xiao et al. (2021) build a consortium blockchain for electronic health records and prove its superior performance in privacy, security and throughput. Meanwhile, studies on blockchain adoption can also be found in other industries such as insurance industry (Püttgen and Kaulartz, 2017; Kar and Navin, 2021), food industry (Duan et al., 2020), automotive industry (Oham et al., 2021; Jabbar et al., 2021) and construction industry (Elghaish et al., 2020). Current studies in these industries are also mainly about benefits, barriers, use cases and technical design of blockchain.

2.3 Blockchain adoption in the maritime industry

Previous studies on blockchain in the maritime industry are limited and they mainly focus on the following four areas: 1) drivers and barriers for blockchain adoption, 2) possible use cases, 3) how to adopt the technology, and 4) technical designs of blockchain for maritime cases. The detailed topics covered by these studies are summarised in Table 2.4.

The potential use cases of blockchain in the maritime industry are widely discussed in previous studies. However, most of them are from a specific point of view, such as the Norwegian offshore sector (Gausdal et al., 2018; Czachorowski et al., 2019), the Greek shipping market (Papathanasiou et al., 2020) and the port sector (Shuaian Wang et al., 2020; Ahmad et al., 2021). Regardless of the market sectors, the most commonly agreed cases in the industry are to digitise shipping documentation (e.g., bills of lading), and track and trace shipping information (Gausdal et al., 2018; Jabbar and Bjørn, 2018; Czachorowski et al., 2019; Maydanova et al., 2019; S. Wang and Qu, 2019; Li and Zhou, 2020). Apart from these typical use cases, Philipp (2020) suggests the use of blockchain and smart contracts in contracting liquified biogas in seaports. Among the various potential blockchain use cases in the maritime industry, which one has the highest potential to be adopted by stakeholders is an interesting topic. Yang (2019) answered this question using factor analysis and regression. The author finds that customs clearance and digitalising paperwork are the areas where maritime organisations have the highest intention to use.

Table 2.4 Research topics of previous studies on blockchain adoption in the maritime industry.

No	Previous Work	Use Cases	Technical Design	How to Adopt	Drivers/Benefits/ Success Factor	Barriers/ Challenges	Intention to Use
1	Gausdal et al. (2018)	✓			✓	✓	
2	Jabbar and Bjørn (2018)	✓		✓			
3	Mamunts et al. (2018)	✓					
4	Tan, Zhao and Halliday (2018)	✓	✓				
5	Czachorowski et al. (2019)	✓			✓	✓	✓
6	Hasan et al. (2019)		✓				
7	Jović et al. (2019)	✓			✓	✓	
8	Maydanova et al. (2019)	✓					
9	Pedersen, et al. (2019)			✓			
10	Wang and Qu (2019)	✓					
11	Yang (2019)	✓		✓	✓		✓
12	Bavassano, et al. (2020)			✓	✓	✓	
13	Irannezhad (2020)	✓			✓	✓	
14	Jović et al. (2020)	✓			✓	✓	
15	Lambourdiere and Corbin (2020)				✓		
16	Li and Zhou (2020)	✓			✓		
17	Panos et al. (2020)	✓			✓	✓	
18	Philipp (2020)	✓					
19	Wang et al. (2020)	✓		✓	✓		
20	Zhou et al. (2020)				✓	✓	
21	Ahmad et al. (2021)	✓	✓	✓		✓	
22	Tsiulin and Reinau (2021)	✓					

Source: Compiled by author.

There are a few studies analysing the drivers and barriers of blockchain adoption in the maritime industry, as well as benefits, success factors and challenges. For instance, Gausdal et al. (2018) and Czachorowski et al. (2019) conduct interviews in the Norwegian offshore sector and conclude that cost is the main enabler and also the main barrier to blockchain implementation in the sector. In contrast, Bavassano et al. (2020) apply a triangulation approach based on literature and media reports and find that the top barrier of blockchain adoption in the maritime industry is the lack of market standards. Zhou et al. (2020) conduct an analytic hierarchy process (AHP)analysis of survey and interview results and rank the challenges and success factors relating to blockchain adoption in the maritime industry. The top 3 challenges are identified as cost, experience and data privacy. The top 3 success factors are identified as capital, training and legislation.

Some papers discuss how to apply blockchain in the maritime industry conceptually. Gausdal et al. (2018) developed a blockchain process framework for basic shipping operations. In this framework, the blockchain system connects all operational data including accounting, documentation, and assets management. It also allows integration with other technologies such as the Internet of Things. Besides, Jabbar and Bjørn (2018) analyse how blockchain technology is introduced into the maritime industry using the concept of infrastructural grind from three dimensions, i.e., consolidation, permeability, and velocity. For different use cases, the different levels of consolidation and permeability would have a different effect on the velocity of blockchain adoption in the industry. Jabbar and Bjørn's work (2018) explains why most blockchain adopters for digitising shipping documentation come to a standstill after pilot tests despite the encouraging results. Next, Wang et al. (2020) propose a framework to employ blockchain for intelligent port management. They discuss three blockchain enabled data-driven models, focusing on decision making by a single party, multiple parties and multiple parties with uncertainty, respectively.

Apart from the above-mentioned research topics regarding blockchain in the Maritime industry, some focus on the technical design of blockchain systems for specific maritime use cases. For example, Hasan et al. (2019) develop an Ethereum system to track containers for a more visible and traceable supply chain. Ahmad et al. (2021) propose a system architecture of permissioned blockchain for potential port applications.

2.4 Evolution of blockchain

The previous literature on evolution of blockchain mainly focuses on the technical side, such as technical features and hardware development. There are scarce studies about the evolution of blockchain in terms of commercial adoption.

One technical trend in the research field is to analyse the evolution of blockchain technology in general. For instance, Cao et al. (2019) study the technical evolution of blockchain by examining 504 versions of six open-source blockchain projects. Yu and Pan (2021) study the same topic by analysing 14,560 patents with main path analysis. The two studies provide suggestions for future development and maintenance. Another technical trend is to analyse the evolution of bitcoin from different aspects, such as the underlying technology (Tomov, 2019), the hardware needed for bitcoin mining (Taylor, 2017), and the transaction fees (Easley et al., 2019).

Very limited research has been conducted to investigate the evolution of blockchain from other aspects, such as the commercial and strategic perspectives. Liu et al. (2018) study the evolution of individual miners' strategy to select a mining pool when they are already in a blockchain network. Dabbagh et al. (2019) examine the evolution of blockchain research directions through a systematic literature review.

2.5 Blockchain and carbon footprint

Two themes emerge in recent years from the research on blockchain and carbon footprint: 1) blockchain's application in carbon trading or carbon emission management, and 2) quantification of carbon emissions directly from a blockchain system. The emissions relating to blockchain adoption in any non-financial use case are barely discussed in the literature.

Most work on the first theme proposes blockchain-based systems for carbon trading with a conceptual design, in the fashion apparel manufacturing industry (Fu et al., 2018), in the Australian carbon market (Hartmann and Thomas, 2020), or in general (Khaqqi et al., 2018; Pan et al., 2019). Schletz, Franke and Salomo (2020) develop a framework to test the applicability of blockchain for carbon trading under the Paris agreement. Zhao and Chan (2020) investigate the optimal adoption decisions regarding blockchain carbon trading systems, such as trading volume and investment amount, from the different perspectives of users and the organiser. Manupati et al. (2020) prove the effectiveness of using blockchain to monitor carbon emissions of supply chains and adjust production, distribution and inventory accordingly via smart contracts. Diniz et al. (2021) propose a blockchain artifact to improve the Brazil GHG inventory process.

Relevant studies on estimating carbon emissions directly from a blockchain system are limited and mainly focus on Bitcoin. For instance, in order to quantify the carbon footprint of Bitcoin, Stoll, Klaaßen, and Gallersdörfer (2019) make an estimation based on the location of computing power in the bitcoin network, while Köhler and Pizzol (2019) conduct a more comprehensive analysis using a life cycle assessment model. Polemis and Tsionas (2021) investigate the driving forces of carbon footprint of Bitcoin and find that the carbon emissions of Bitcoin are significantly negatively related to miner's revenue. Instead of focusing on Bitcoin only, Sedlmeir et al. (2020) estimate and compare the energy consumption of various types of blockchain such as public proof-of-work (PoW), public non-PoW and enterprise blockchain.

2.6 Summary of major literature gaps

The review shows that research on blockchain technology in the maritime industry is still at its initial stage. Earlier studies in this field mainly focus on understanding blockchain's potential with major discussions on drivers, barriers and adoption areas. Most of these studies are qualitative in nature with interviews, case studies and theoretical concepts. More quantitative studies are needed in this area. With that, four major literature gaps are thereby identified:

Firstly, in previous studies, the discussions on blockchain's applications in the industry are confined to a specific sector, such as the Norwegian offshore sector, Greek shipping market and port management. Few consider blockchain's applications in other maritime sectors like ship finance and marine insurance. There is a lack of systematic analysis to provide a holistic view of blockchain adoption in the industry.

Secondly, previous work on blockchain adoption is mainly about understanding blockchain technology conceptually. No studies have been conducted to analyse the next step of blockchain adoption - whether and when to adopt blockchain - in general or in any industry.

Thirdly, the evolution of blockchain, which has important significance to guide the development of blockchain, is seldom analysed and mainly from the technical aspect. No research has been done to study the topic in terms of blockchain adoption rate in general or in any industry.

Fourthly, previous studies on the environmental impact of blockchain mainly focus on bitcoin, which is a permissionless blockchain. No studies have been conducted to estimate the GHG impact of blockchain relating to any non-financial applications, mostly with permissioned blockchain.

Hence, this research aims to address these gaps by developing a conceptual framework to provide a holistic view of blockchain adoption in the industry and studying the optimal time, evolution and GHG impact of blockchain adoption in the maritime industry in a quantitative way.

CHAPTER 3 RESEARCH METHODOLOGY

As mentioned in Chapter 1, the objectives of this research are to provide a systematic and holistic analysis of blockchain adoption in the maritime industry and to analyse the optimal time, evolution, and GHG impact of blockchain adoption in the industry in a quantitative way. The purpose of this chapter is to present the overall research flow and introduces the methods employed to fulfil each research objective.

3.1 Research process flow

The overall research flow of this research is depicted in Figure 3.1. It starts with a literature review on blockchain technology and various aspects relating to its adoption in industries. Then it provides a systematic analysis of blockchain adoption in the industry and develops a conceptual framework. Based on the conceptual framework, three important practical adoption questions are further investigated, namely the optional blockchain adoption time, evolution of blockchain adoption rate and environmental impact of blockchain adoption. Lastly, conclusions are made summarising key research findings, contributions, limitations and future research directions.

Due to different natures of the research objectives, a mixed-method approach using both qualitative and quantitative methods has been adopted for this research. To fulfil the research objective 1 and 2 which are more qualitative in nature, a method of content analysis is applied which is widely used in qualitative research for analysing the content of a variety of data (Harwood and Garry, 2003). It enables the consolidation of information into defined categories and hence assists better analysis and interpretation. To address research objective 3, a game-theoretical approach is used as it is the mainstream method in analysing technology adoption time. Regarding objective 4, in view of the multi-agent interactions and the dynamic nature of the problem, asymmetric evolutionary game theory is applied as it is commonly used in analysing evolutionary dynamics of adopting a new technology in multi-agent systems. For objective 5, given the study focuses on the documentation process across maritime supply chain, a process analysis approach is employed as it is one of major methods to measure GHG emissions and concentrates on a business process.

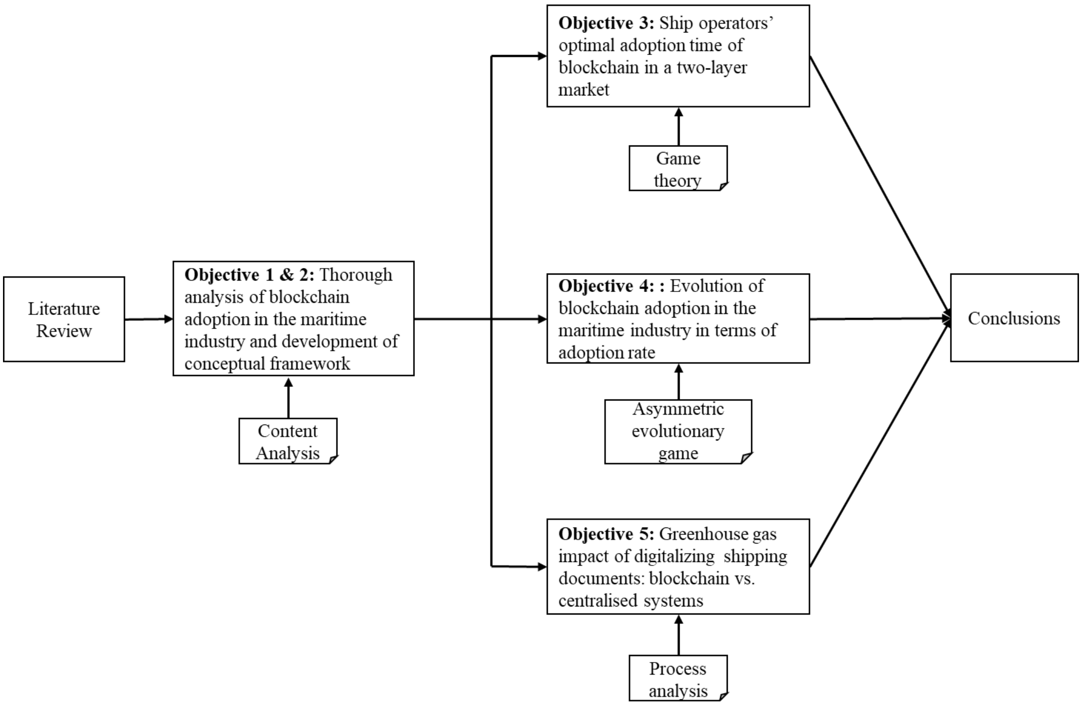

Figure 3.1 Flow chart for the overall research process.

3.2 Content analysis approach

This research applies a method of content analysis based on the four-step process model used by Seuring and Gold (2012) to perform a systematic analysis of blockchain applications in the maritime industry. The four steps include material collection, descriptive analysis, category selection and material evaluation.

When collecting material, the focus is on English articles relating to blockchain adoptions in the maritime industry from academia and industry. The keywords for search after trial and error are identified in two groups – one includes blockchain and distributed ledger; the other includes maritime, shipping, port, ship and vessel. Using different pairs of keywords from the two groups, related academic papers are searched in the fields of title, keywords and abstract in Scopus database, which has broader coverage than Web-of-Science database (Aksnes and Sivertsen, 2019). Then, related commercial publications, newspapers and magazine papers are searched in Google. According to the research objectives, the analytic categories are blockchain use cases, reasons for application and participating companies. The official websites of participating companies are also searched for useful articles to supplement the material. Then collected material is evaluated with an inductive approach which derives results through a detailed examination of material (Thomas, 2006). The different categories of blockchain applications are also derived inductively along with author’s experience in the industry.

3.3 Methods in new technology adoption time

A few studies have modelled the optimal adoption time of new technology among competing companies. The majority of them use game theoretic approaches, while some others use other methods like simulation (Bauner and Crago, 2015), Bayesian decision analysis (Huang et al., 2013), and operational model (Rajagopalan, 1999). Since game theory is the mainstream method to analyse new technology adoption time, it is employed in this research.

The early seminal work to use game theory to study technology adoption time is from Reinganum (1981a). In this study, Reinganum develops a game-theoretic approach to analyse the adoption time of new technology by competing companies in a duopoly market. The model is formulated with perfect information, first mover advantage and certainty of the value of the new technology. Since then, other game theoretic models are built to solve other complex problems about technology adoption time under different conditions. These adoption time models can be divided into two streams. One is for general technologies (Fudenberg and Tirole, 1985; Milliou and Petrakis, 2011; Riordan, 1992). The other is for a particular technology, such as electronic data interchange (EDI) system (Barua and Lee, 1997), clean technologies (Ben Jebli and Ben Youssef, 2014), and building information modelling system (Yuan and Yang, 2020). It is worth mentioning that the model of Yuan and Yang (2020) is based on the work of Barua and Lee (1997).

This research also refers to the model of Barua and Lee (1997) due to the similarities between blockchain and EDI that both are for building inter-organisational systems to exchange information (IBM, 2019). However, they are different to the extent that blockchain has the validation process through consensus mechanism and the data stored on the ledger are immutable (Kumar et al. 2019). These features make blockchain more capable to reduce fraud and costs of verification, compared with

EDI. Therefore, our model will be developed catering to the uniqueness of blockchain technology and the maritime industry.

The major differences between our model and Barua and Lee’s (1997) lie in four areas: 1) Our model captures the unique benefits of blockchain in the maritime industry in the form of reduced fraud in shipping documents and reduced costs of verification. 2) Our model considers the competition between multiple parties while Barua and Lee (1997) only consider the competition between two parties. 3) Our model has a different cost structure of technology adoption. 4) Our model introduces a new feature of cut-off time.

3.4 Evolutionary game theory

Evolutionary game theory focuses more on the dynamics of strategy change over time, while traditional game theory lacks the concept of time evolution and focuses more on equilibrium (Tanimoto, 2015). In evolutionary games, players interact with each other randomly in repeated form and dynamically change their strategies by updating the fittest strategy after learning from other players’ behaviour in the previous round (Tosh et al., 2018). Relatively inferior strategies are gradually replaced over time. An evolutionarily stable strategy (ESS) is a strategy if most members of a population adopt it and it cannot be replaced by alternative strategies (Maynard et al., 1973). Traditionally, evolutionary game theory has been applied in symmetric situations where interactions of players are within a single population with the same set of strategies and symmetric payoff structure. But in the real business world, when multi-agents are involved, asymmetric analysis is more suitable as players are from different populations and may have different strategies and payoff functions.

Asymmetric evolutionary games are often developed to analyse the evolutionary dynamics of adopting a new technology or practice or method in multi-agent systems (Tian et al., 2014; Encarnação et al., 2018; Chen et al., 2018; Shan and Yang, 2019). For instance, Encarnação et al. (2018) use an asymmetric evolutionary game approach to analyse the adoption of electric vehicles with interactions among governments, companies and consumers. Shan and yang (2019) apply asymmetric evolutionary game theory to examine the sustainability of adopting photovoltaic power generation systems for poverty alleviation among enterprises, poor households and the government. Similarly, this research will resort to an asymmetric evolutionary game model to analyse the co-evolution process of blockchain adoption among different maritime players.

3.5 Methods in carbon calculation

There are three methods to calculate carbon footprint of a process, a project, an organisation or a nation (Liu et al., 2016): input-output analysis (top-down approach), process analysis (bottom-up approach), and a combination of both. Among them, input-output analysis is the most widely adopted method in the literature (Liu et al., 2016). It is largely used for a macro estimation of carbon footprint at the national or international level (Wiedmann, 2009), but does not account for detailed processes. In contrast, process analysis allows users to distinguish the environmental impact of different processes and hence helps to identify opportunities for process re-design. Besides, process analysis is widely applied in industries as the foundation of major international carbon footprint standards like ISO14067, PAS2050, and GHG protocol (Liu et al., 2016). A combination of both methods is used by Heijungs and Suh (2006). However, they conclude that the new method is still immature and restricted in applications.

Compared with input-output analysis, process analysis provides users with a better understanding of carbon footprint from a business process. This could provide decision-makers with more insights on measures at a micro level (Recker et al., 2012). Since this study focuses on the documentation process of maritime supply chains, process analysis method is employed for the study. Furthermore, among the various standards for process analysis (i.e., GHG protocol, ISO standards and PAS 2050), GHG protocol will be used considering that it was built on ISO standards and the first version of PAS 2050 (Liu et al., 2016).

CHAPTER 4 BLOCKCHAIN ADOPTIONS IN THE MARITIME INDUSTRY: A CONCEPTUAL FRAMEWORK

This chapter first discusses the major current and future trends of blockchain applications in the maritime industry with an analysis of how blockchain technology helps to overcome the pain points in those areas. It analyses the major challenges of blockchain adoption in the industry. Then, it develops a novel conceptual framework to provide a systematic tool for understanding blockchain adoption in the maritime industry in a holistic view. At last, implications and recommendations are provided.[1]

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[1] The following paper is published based on this chapter:

Pu, S., and Lam, J. S. L. (2020), "Blockchain Adoptions in the Maritime Industry: A Conceptual Framework", Maritime Policy & Management, DOI: 10.1080/03088839.2020.1825855.

4.1 Current major blockchain applications and their benefits in the maritime industry

Since 2017, blockchain use cases have been gradually developed and tested in the maritime industry as shown in Table 4.1. These cases mainly fall into four fields: 1) electronic bills of lading, 2) ship operations, 3) ship finance and 4) marine insurance. The discussion below analyses the current challenges in the maritime industry and how blockchain helps to overcome these challenges in each of the fields.

4.1.1 Electronic bills of lading

Because of the legal importance of bills of lading, it is discussed separately in this section rather than being included under ship operations. In the paper bills of lading system, delays often happen because of the long processing and physical delivery time (Reed Smith, 2016). Although earlier attempts from Bolero, essDOCS, and e-title^{TM} to build electronic bills of lading (eBLs) systems have been gradually used to address this problem, concerns of insider fraud and confidentiality exist in these eBL systems (Dubovec, 2005; Pagnoni and Visconti, 2010; Takahashi, 2016). These systems rely on a central party to transmit original bills of lading. Users have no or limited control over the process within the central platform and all messages can be read by the core messaging platform.

Blockchain could mitigate the risks of insider fraud by enabling direct peer-to-peer communication without any central parties. At the same time, blockchain can address the confidentiality issue as information can be secured by one-way cryptography and can only be decrypted by the specified recipient (Christidis and Devetsikiotis, 2016). Current cargo owners can endorse eBLs with their own digital signatures and include the public key of the next owner in the transaction. With that, the transference of eBLs will be recorded in the blockchain in chronological order and can be used to trace the ownership history by verifying signatures.

Table 4.1 Examples of typical blockchain use cases in the maritime industry.

Application Areas	Specific Use Cases	Companies	Platform Used	References
Bills of Lading	Electronic Bills of Lading	Bolero	Voltron (based on Corda)	(Global Trade Review, 2019)
		CargoX	Ethereum	(CargoX, 2018)
		A.P.Møller-Maersk (TradeLens)	Hyperledger Fabric	(Maersk, 2018)
		American President Lines (APL)	Corda	(Accenture, 2018)
		Blue Water Shipping Louis Dreyfus	Ethereum Quorum	(CoinDesk, 2018)
		PIL	Hyperledger Fabric	(Seatrade, 2017)
Ship Operations	Reducing Paperwork	A.P.Møller-Maersk (TradeLens)	Hyperledger Fabric	(Maersk, 2018)
		DNV GL	Vechain Thor, Ethereum-like	(Global Trade Review, 2019)
	Enhancing Info Sharing	Kuehne + Nagel (Sharing container verified gross mass)	Hyperledger Fabric	(Ledger Insights, 2018a)
	Track and Trace Information	A.P. Møller-Maersk	Hyperledger Fabric	(Maersk, 2018)
		Pacific International Lines PSA International Pte Ltd	Hyperledger Fabric	(Seatrade, 2017)
Marine Insurance	Underwriting Claims	A.P. Møller-Maersk Willis Towers Waston MS Amilin XL Catlin	Corda	(Seatrade, 2018b)
	Fraud Reduction	B3i Services AG	Corda	(B3i.tech, 2018)
		RiskStream Collaborative (former RiskBlock)	Corda	(Ledger Insights, 2018b)
Ship Finance	Cross-Border Payment	Ripple Labs, Inc	Ripple	(Caron, 2018)
	Ship Financing (ICO)	Shipowners.io	Ethereum	(Splash247, 2018)
	Escrow Account	300cubits	Ethereum	(South China Morning Post, 2017)

Note: Platforms used by companies may be changed in the future.
Source: Author, based on online news and companies' official websites and white paper.

4.1.2 Ship operations

4.1.2.1 Reducing paperwork

The operational processes of shipping are archaic. A single transaction can create a pile of papers such as sales agreements, bills of lading, charter parties, customs clearance documents, and letters of credit. Traditionally, the shipping industry relies heavily on physical movements of paper documents. Those papers must pass through a long chain of workflows for approval, processing payments or customs clearance. The whole process is vulnerable to human errors, fraud and inadvertent delays (Lam and Zhang, 2019). The waiting time for processing documents was approximately 29% of the total delivery time from exporting farm to retailers (Bloomberg, 2018). The costs of paperwork were estimated 15% to 20% of the total shipping fee (Longman, 2017). Therefore, there is an opportunity to improve efficiency and save costs in shipping via reducing paperwork.

Blockchain comes into play to solve this problem in various ways. Firstly, it could make the whole process paperless in a tamper-proof way. Participants can use the public and private keys to safely communicate with each other, perform transactions, transfer documents and execute payments. Secondly, blockchain provides full transparency in the business. The on-chain information of transactions and ownership transfers is visible to all the accessing parties. Real-time updates and notifications are easy with a quick click. Thirdly, with the adoption of smart contracts, standard shipping contracts could be generalised in a coding format and players can have the freedom to negotiate price directly on the blockchain network.

4.1.2.2 Information sharing

Many studies highlight the importance of information sharing to enhance supply chain integration and the overall operations performance (Narasimhan and Nair, 2005; Jeong and Leon, 2012; Prajogo and Olhager, 2012; Wu et al., 2014; Lai et al., 2015). If information can be shared effectively, shipping costs could be reduced by up to US$300 per container (Seatrade, 2018a). Through sharing container capacity alone, the container business is expected to save nearly US$6 billion and reduce about 4.5

million tonnes of CO_2 emissions every year (Tradewinds, 2018a). However, lack of trust has been a main barrier to hinder companies from sharing information (Wu et al., 2014).

Blockchain could address the problem by building trust among participants (Kshetri, 2018). This is achieved through data integrity, reliability, responsibility and predictability, which are antecedents of trust (Beck, 2018). Moreover, it could not only integrate operational, informational and financial shipping data in a worldwide platform (Tan et al., 2018) but also provide security of data storage and transmission. Blockchain allows real-time update of information and such record is transparent and effectively unmodifiable. When a new status of a particular container is uploaded through sensors, the information will be automatically propagated to the involving parties.

4.1.2.3 Track and trace cargoes

One main challenge in logistics is to monitor product quality and track their physical movements until reaching end-users (Shankar et al., 2018). However, the current information systems are not able to provide valid and real-time shipment tracking during the transportation phase (Wu et al. 2017). This leaves the window open for fraud, which could cause serious financial losses to genuine companies (Kshetri, 2018).

Blockchain could improve the current tracking system in supply chains by keeping an immutable and traceable record of product movements from origin to end customers on a real-time basis. Every product is tagged with a unique ID and scanned at each transportation stage. The scanning data is then recorded in a distributed ledger and shared amongst parties in the transaction chain. It is possible to add more comprehensive data such as product temperature and container empty status. Therefore, blockchain serves as a trustful channel to check the genuineness of products, prevent the risks of counterfeiting and monitor the product quality along with the transportation phase.

4.1.3 Ship finance

4.1.3.1 Ship financing

The main resources of ship finance have traditionally been and are still banks (Kavussanos and Tsouknidis, 2016). However, nowadays banks are seen to limit their funds to the shipping industry due to stricter financial regulations like Basel III (Lozinskaia et al., 2017). Although there is an increasing trend for shipowners to raise funds by Initial Public Offering (IPO) or issuing bonds in capital markets (Albertijn et al., 2011), this method does not suit most shipping companies because they are relatively small in capital markets (Stopford, 2008). Blockchain provides an alternative way of financing for shipping companies through Initial Coin Offering (ICO). ICO is realised in a blockchain-based trading platform by issuing digital tokens, which is similar to Initial Public Offering (IPO) in the stock market by issuing shares. Compared with IPO, ICO cuts intermediaries, makes cross-border transactions easy, and provides high transparency and liquidity. It allows users like shipowners to create their own virtual tokens to represent their vessels. Such tokens are open to the public to buy at certain prices.

4.1.3.2 Cross-border payment

Currently, the cost of cross-border remittance is 5% - 20% of the amount remitted (Martin, 2017) and it takes a few days to reach the destination. Via intermediary cryptocurrency, the cost can be reduced to 2% - 3% and the payment is nearly real-time (Yuan and Wang, 2016; Martin, 2017). Hence, blockchain provides a faster, more economical and safer solution for cross-border payment than current SWIFT systems (Yuan and Wang, 2016).

4.1.3.3 Escrow

The cryptocurrency function together with smart contracts could be used as a trustful escrow account for solving disputes or managing deposits. For instance, the defaulting problem in container booking could be addressed by using blockchain. No matter who defaults in the end, the deposits in the form of cryptocurrency will be payable to the counterparty under a smart contract. If a container booking is fulfilled successfully, the deposits in cryptocurrency will be returned to the parties, respectively (Tradewinds, 2018b).

4.1.4 Marine re/insurance

The current popular blockchain applications in marine re/insurance industry lie in the following three areas: underwriting, claims management, and fraud reduction.

Underwriting evaluates the risks of insuring a company, an asset, an activity or an individual; and it determines whether the insurers should take the risks, how much coverage the client can get and how much the client should pay. Efficient data sharing enables a faster and more accurate underwriting process. With blockchain, the underwriting process becomes simplified since the information in the system remains verified and integrated and the record of policy applicants can be easily traced (Nath, 2016). Automatic adjustment of premium can also be achieved based on the behaviour of the insured (Püttgen and Kaulartz, 2017). For instance, it is possible to use blockchain to automatically charge an additional premium for vessels entering the high-risk area of piracy if GPS data are fed into the system.

Processing insurance claims often involves many parties such as insurers, policyholders and other third parties. However, the transparency of required information to process claims is currently insufficient among the participants (Nath, 2016). With blockchain, claim activities and supporting documents will become transparent to relevant parties. Besides, smart contracts can assist to accelerate the process of reviewing and approving claims and thereby to shorten the time to resolve a claim (Püttgen and Kaulartz, 2017).

Fraud is a big problem in the insurance industry in general (Henry and Hogan, 2018). Blockchain could address this problem due to its ability to provide cryptographic authentication and data transparency. With blockchain, insurers could easily verify identities, identify double claims, detect patterns of fraudulent behaviour, share indicators of potential fraud, and hence collaboratively reduce fraud (Henry and Hogan, 2018).

4.1.5 Distributed ledger platforms used by maritime companies

According to Table 4.1, permissioned systems appear more widely used by maritime enterprises than permissionless systems. This could be because permissioned systems provide better privacy and have a better performance in speed, throughput and scalability.

Among the permissioned systems, Corda and Hyperledger Fabric are more popular in the maritime industry. This may be partly attributed to their ease of usage and interoperability with companies' current IT systems (Valenta and Sandner, 2017). Besides, Corda appears popular in the marine insurance sector, which may be because it provides better legal functions supported by legal prose in natural language in smart contracts. As such, it has great potential to be applied to other legal shipping documents such as bills of lading and charter parties. The popularity of Corda, a non-blockchain distributed ledger, indicates a trend that distributed ledger systems other than blockchain may be increasingly applied in the industry in the future.

It is also interesting to note that although permissioned systems may be more suitable for business enterprises, there are still some companies choosing public blockchain Ethereum for their projects. These projects are mainly related to ship finance or payments. This is reasonable considering the maturity of Ethereum as a cryptocurrency and its well-established standards for smart contracts. However, Ethereum's position in ship finance and payment sector may be threatened by other blockchain platforms such as Ripple in the future because the latter is specifically designed to meet the stringent regulations in the financial industry.

4.2 Emerging trends of blockchain applications in the maritime industry

The implementation of blockchain in the maritime industry just started. Apart from the use-cases mentioned in section 3, integrating blockchain with other technologies, such as the Internet of Things (IoT), smart grid and 3D Printing, is an emerging trend.

4.2.1 Internet of things

Blockchain provides a favourable solution to address some limitations and enhance the performance of current IoT systems. For example, blockchain could solve the user privacy problem in IoT because it introduces a trusted mechanism to handle access control logic (Ouaddah et al., 2017). It could also solve the current synchronisation problem in IoT (Huh et al., 2017). Besides, it could improve the internal and external interactions between smart devices in the IoT system (Teslya and Ryabchikov, 2017). With increasingly cheaper and more accurate sensors, IoT will be more widely adopted in the maritime ecosystem (QinetiQ et al., 2016). If shipping lines and ports could incorporate blockchain into their IoT systems, they can achieve more efficient real-time monitoring, tracking and tracing. For instance, the conditions of engines in a vessel can be recorded and monitored using IoT and blockchain technologies, which could enhance the quality of deep learning for proactive maintenance before an incident happens (Bandyopadhyay and Sen, 2011).

4.2.2 Smart grid

Blockchain is hopeful to overcome the current constraints of smart grid as a centralised energy system. As presented by Aitzhan and Svetinovic (2016), the main problems of centralised energy systems are single point of failure and low privacy. These problems can be tackled by blockchain due to its property of decentralisation and cryptographic identity. Besides, blockchain could enhance real-time monitoring which plays an important role in smart grid operations (Pop et al., 2018). By adding smart contracts into the smart grid system, these distributed nodes are able to do smart communications among themselves and even make local decisions on how to distribute electricity during peak and non-peak periods (Prousalidis et al., 2017). In this way, blockchain enhances the efficiency of the smart grid system and reduces wastes (Fu et al., 2018). In the case when a port sells its extra energy to vessels or city areas via a blockchain-enabled smart grid, the amount payable can be calculated intelligently based on different conditions and the payment can be executed automatically via smart contracts.

4.2.3 3D printing

With the onset of 3D Printing technology, some maritime players such as classification societies like DNV GL and terminal operators like PSA Singapore and the Port of Rotterdam are looking to leverage this technology for manufacturing marine parts and even vessel building (DNV GL, 2018; MPA, 2018; Temple, 2018). However, 3D printing requires an effective digital thread - a seamless and secure strand of data that starts from the design stage to finished products – to protect against intellectual property and data security (Deloitte, 2016). A lack of effective digital threads is hindering the mass adoption of 3D printing. Blockchain provides a good technology solution to solve this problem. It safeguards the entire 3D printing value chain by protecting data against manipulation with immutability and cryptographic authentication (Klöckner et al., 2020). At the same time, the emergence of 3D printing indicates the shift of the manufacturing ecosystem from centralised systems to more open and distributed networks (Klöckner et al., 2020). As a distributed ledger technology, blockchain could foster the industrial change with a focus on distributed systems and strength in trusted networks with multiple stakeholders. Maritime organisations should keep an eye on the developments of blockchain in 3D printing, which offers new business opportunities in the maritime manufacturing sector.

4.3 Challenges of blockchain adoption in the maritime industry

The applications of blockchain in the maritime domain entail challenges and risks mainly from legal, technological and operational aspects. From a legal perspective, uncertainties exist in terms of legal enforcement, insurance cover, flexibility and loose regulations. In terms of maturity of technology, concerns mainly lie in security, scalability and interoperability. When it comes to operations, it is challenging to expand the applications to wide ranges and the applicable cases of blockchain may be limited to a certain level due to the complexity of the maritime business.

4.3.1 Legal uncertainties

It remains a big concern that how blockchain-based bills of lading are likely to be viewed by a court or tribunal when they become the subject of legal proceedings

(Hong, 2012; Reed Smith, 2016; Clyde&Co LLP, 2018). For example, might the Court in China refuse to recognise a blockchain bill of lading as a binding contract? The legal enforcement of current e-BOL systems like Bolero has yet been tested in real life (Reed Smith, 2016), even though they have been used in the industry for a while, let alone that of blockchain bills of lading. In order to address this uncertainty and keep pace with technological development, jurisdictions could consider making corresponding changes in regulation for recognition of electronic bills of lading. For example, they can consider adopting the United Nations Commission on International Trade Law (UNCITRAL) Model Law on Electronic Transferable Records, which covers bills of lading (Clyde&Co LLP, 2018).

Apart from jurisdiction, carriers have to be careful so that operating blockchain bills of lading should not deprive them of their insurances, especially, the Protection & Indemnity (P&I) insurance cover (Reed Smith, 2016). So far, P&I club has approved only six eBL systems, three out of which are blockchain supported eBL systems, namely edoxOnline, WAVE, and CargoX (The UK P&I Club, 2020).

Another legal concern, especially for maritime investors, is about loose regulations on ICO which lead to a high risk of fraud and manipulation. According to the analysis of 1,450 ICOs by Wall Street Journal (Wall Street Journal, 2018), nearly 20% of the ICOs are red-flagged owing to their deceptive or even fraudulent behaviours to lure investors. These improper behaviours include plagiarised whitepapers (the heart of a company’s ICO), fake or missing executive teams and exaggerated advertisements with guaranteed high returns without any risks. Unfortunately, more than US$1 billion have already been invested in the red-flagged ICOs. Losses in these projects claimed to be up to $273 million with the shutdown of some companies. Investors should bear in mind the high chances of fraud in the ICO market and do enough research before making the decisions. A civil website ICOcheck does background checks for some ICOs and has identified a few suspicious ICO companies. US Securities and Exchange Commission launched a website for people to experience a fake ICO as an example so as to learn what to avoid.

4.3.2 Technical challenges

The major technical concerns of blockchain are related to security, scalability and interoperability (Swan, 2015; White, 2017; Yuan and Wang, 2016).

The security concerns of blockchain are increasingly raised especially after several attacks for cryptocurrencies, such as the attack faced by decentralised autonomous organisation (DAO) with a loss of $60M Ether (Castillo, 2016). What's more, smart contract is a weak point of blockchain in security (Deloitte, 2017). An attack on one small contract could have a domino effect on other parts of the network (Deloitte, 2017). Given that smart contracts will be adopted more pervasively, possible dangers imposed by them should not be neglected and how the smart contracts are coded should be carefully examined.

In a distributed system, every node will keep a full copy of all data on the network, which requires large overall storage (Xu et al., 2017). However, with the growing number of users and transactions, how to ensure a scalable system with a suitable storage size remains challenging (Xu et al., 2016). Apart from improving the technology inherently, there are some operational ideas to address this issue such as to delete data which are more than certain years old or to store some data off-chain (Poon and Dryja, 2016; Kuo et al., 2017).

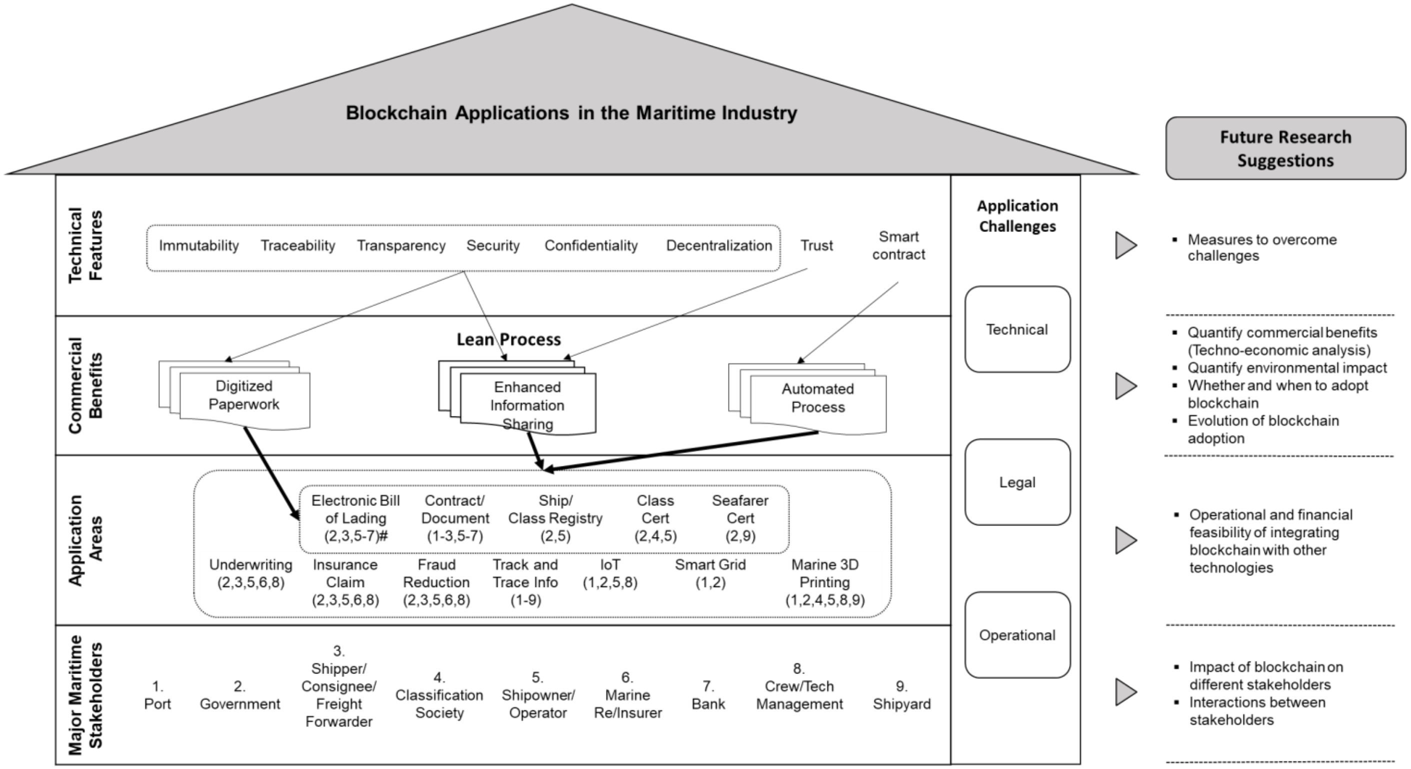
Furthermore, the blockchain platforms used by different companies are relatively fragmented as shown in Table 4.1. Common standards and interoperability are needed for blockchain to be truly effective (Kshetri, 2018; Seatrade, 2018a). These cannot be solved by a single organisation and requires the involvement of the whole ecosystem including both the private and public sectors.

4.3.3 Operational challenges

Successful pilot projects do not necessarily mean an easy transition to widespread use (The Financial Times, 2017). Different levels of difficulties in the transition are expected depending on the extent of pushback from the current shipping infrastructure (Jabbar and Bjørn, 2018). If the case is to address new shipping problems, like verified gross mass (VGM) reporting which is a relatively new requirement in the industry (commenced from 2016), the push back from the current system is weak and the blockchain diffusion in this area could be fast. If the case focuses on the core of the current shipping system like shipping documentation, strong pushback is expected, and the technology diffusion would be slow. At the same time, since information including mistakes or delays is exposed in blockchain, companies' performance can be compared easily. Therefore, organisations need to increase their overall service quality as a basis to prepare for any possible business risks that may be brought out by transparent information. Lastly, even if a certain degree of automation can be achieved through blockchain, several sophisticated cases like apportionment of liability may not be well handled by the rigid programming language of smart contracts and still require human expertise (Seatrade, 2018a).

4.4 Conceptual framework and future research suggestions

The analysis of previous sections indicates that the majority of maritime blockchain applications revolve around three themes: reducing paperwork, enhancing information sharing, and automating processes; and the ultimate goal is to achieve a lean process. On top of this finding, a conceptual framework is developed, as shown in Figure 4.1, to provide a holistic view of blockchain adoption in the industry. Future research suggestions are provided based on the framework.



Note: The arrows indicate a link between items from two different layers. A thick arrow denotes that the commercial value could be applied to all the application areas in the directed box.

#: the numbers in bracket represent the corresponding major maritime stakeholders of each application area.

Figure 4.1 A conceptual framework of how blockchain can be utilised in the maritime industry with application examples.

Source: Author.

The framework uses Moon and Ngai’s (2008) framework for radio frequency identification (RFID) as a reference, which shows how RFID generates values for the fashion retailing industry. Besides, technical features are included in the framework based on two popular technology adoption models – Technology Acceptance Model (TAM) and Technological, Organisation and Environment (TOE) model. Both models emphasise the importance of technical characteristics of a new technology to the technology adoption (Depietro et al., 1990; Venkatesh et al., 2003). In addition, the understanding of a new technology’s application requires the knowledge of stakeholders (Troshani and Doolin, 2007). Therefore, stakeholders are also considered in the framework.

The conceptual framework consists of five dimensions: technical features of blockchain, commercial benefits of blockchain to the maritime industry, applicable areas in the maritime domain, major maritime stakeholders involved in these applications, and potential adoption challenges in the industry. We derive the relationships between these dimensions and their effects on blockchain adoption in the maritime industry by examining the detailed factors in each dimension.

The result of the analysis shows that the technical features of blockchain form the foundation for creating commercial benefits for the maritime industry. The ultimate commercial benefit of blockchain is identified as achieving a lean process through three aspects: digitising paperwork, enhancing information sharing, and automating processes. The relationships between the technical features and the commercial benefits are proposed in the framework based on the analysis in section 3 about how blockchain could generate commercial benefits to address the current problems in the maritime industry. First, the technical features of blockchain including immutability, security, confidentiality and decentralisation could safeguard the digital system for paperwork as they ensure that documents are tamper-proof, accessible only to pre-selected participants and free from single point of failure (Berke, 2017). The immutability, traceability and transparency provided by blockchain could ensure the system efficiency as they facilitate data verification (Liu et al., 2017) and eliminate duplicate data entries (Banerjee, 2018). Thus, the six technical features mentioned above are supposed to have a positive effect on achieving digitalised paperwork in the industry by providing a more secure and efficient platform to manage paperwork. In addition, blockchain could build trust among users (Kshetri, 2018) by providing confidence, integrity, responsibility and predictability, which are antecedents of trust (Beck, 2018). Efficient information sharing is based on not only a secure and efficient digital system but also trust between players. Thus, the technical features useful for building a secure and efficient platform and the trust feature enabled by blockchain collectively form the foundation for promoting information sharing in the industry. At last, since automation in blockchain is realised through smart contracts (Christidis and Devetsikiotis, 2016), it is suggested that a higher level of smart contracts used would lead to a higher level of automation in the industry. Based on the above analysis, we propose that 1) blockchain's immutability, traceability, transparency, security, confidentiality, and decentralisation are positively associated with achieving digitised paperwork in the maritime industry; 2) blockchain's immutability, traceability, transparency, security, confidentiality, decentralisation and trust are positively associated with achieving enhanced information sharing in the maritime industry; 3) blockchain's smart contract is positively associated with achieving automated processes in the maritime industry. The positive association between the technical features and the commercial benefits means that the higher level of the technical features helps in achieving better results in the corresponding commercial benefits. Since the proposed relationships are derived from qualitative analysis, future research could consider empirical testing for these relationships.

The analysis identifies contextualised application areas of blockchain for each commercial benefit. Digitising paperwork could be realised in many areas such as ship registry, classification certificates, bills of lading, seafarer certification, and shipping contracts. Enhancing information sharing can be applicable to the whole maritime supply chain. This includes all the application areas in the framework because maritime transportation and relevant marine services rely on shared information to coordinate throughout the chain. The information ranges from commercial information such as cargo movements to technical information such as engine data. In addition, there is potential to realise a certain degree of automation along maritime supply chains. For instance, through the use of smart contract, payment transfer of freight and insurance premium can be automated between two relevant parties. While some above-mentioned application areas like electronic bills of lading and digitising ship registry process have been tested in the industry, others need to be explored further in future research. For instance, researchers could consider investigating the possibility of integrating blockchain with other emerging technologies to deal with the vulnerabilities of current maritime systems or revolutionise the way of doing business and handling operations. One specific example is to analyse how effective it is to integrate blockchain with smart grid to better realise smart distribution and trading of electricity in ports. Besides, future research could look to quantify the commercial and environmental impact of blockchain in each application area in the framework, investigate whether and when maritime organisations should adopt the technology and the evolution of blockchain adoption rate in these application areas.

Our study stresses the importance of stakeholder management in blockchain adoption. The knowledge of stakeholders, their market power, differences and possible attitudes, help to understand the potential impact of them on the adoption process (Troshani and Doolin, 2007). The major maritime stakeholders in each blockchain use case are identified based on their relevance to each case. For example, the major stakeholders in the marine insurance underwriting use case are recognised as shippers, consignees, freight forwarders, ship operators, marine re/insurers and ship technical management companies. These stakeholders need to purchase certain marine insurances for either marine cargoes or vessels related assets. Before embarking on blockchain adoption, decision makers need to understand the differences and possible reactions of stakeholders to better manage the potential conflicts and issues from stakeholders. Future research could investigate the impact of blockchain on different maritime stakeholders and analyse the interaction among stakeholders for blockchain adoption and implementation.

Our analysis also shows that blockchain adoption entails challenges in the maritime industry mainly from legal, technological and operational aspects. Uncertainties exist in terms of legal enforcement, insurance cover, and loose regulations on ICO (Reed Smith, 2016; Wall Street Journal, 2018). Major technological concerns centre around security, scalability and interoperability (Deloitte, 2017; Kshetri, 2018; Xu et al., 2018). Operationally, it is challenging to achieve widespread adoption due to pushback by the current shipping infrastructure (Jabbar and Bjørn, 2018) and potential conflicts among different stakeholders. The applicable cases of blockchain may also be limited to a certain level due to the complexity of shipping business in reality. The extent of these challenges would be different in different use cases. The conceptual framework provides a starting point for the industry to better identify the potential challenges for a specific use case and suggests collaborative efforts to overcome these challenges as various stakeholders are involved in the applications. The field of adoption challenges of blockchain has not been analysed deeply in the maritime context. Future research could examine the impact of these challenges on blockchain adoption in different use cases and investigate potential measures to tackle the challenges for faster and wider adoption of the technology.

With the five dimensions, the conceptual framework answers the fundamental questions of why, how and who regarding blockchain's adoption in the maritime industry. Ample future research opportunities are identified ranges from testing proposed relationships, examining the possibility and effectiveness of technology integration, quantifying the commercial benefits, exploring emerging applications, investigating when to adopt the technology and the evolution of adoption rate for each use case, conducting stakeholder analysis to analysing measures to overcome the adoption challenges.

Based on the research opportunities identified from the framework, three important research questions will be further investigated in following chapters, namely the optimal blockchain adoption time, evolution of blockchain adoption rate and GHG impact of blockchain adoption.

4.5 Implications and recommendations for maritime stakeholders

Although the conceptual framework indicates many opportunities provided by blockchain, the adoption of blockchain remains challenging. The following sections discuss the implications of blockchain adoption for individual organisations and governments, and provide detailed recommendations for different maritime stakeholders.

4.5.1 For individual organisations

Although facing challenges, maritime organisations should ride on the wave of blockchain to speed up their digital transformation and improve their competitive advantage in the industry. Before adopting blockchain, it is necessary for companies to have a thorough understanding of the technology itself and their own specific requirements such as wherewithal, transparency, privacy, scalability and interoperability. When it comes to the specific design of distributed systems, companies need to consider the technical requirements of platforms systematically and assess their impacts on the overall incumbent systems (Xu et al. 2017).

Besides, legal effects must be considered since the same system will be covered by multiple jurisdictions simultaneously. However, the current legal frameworks in most countries are not fully ready to effectively handle blockchain transactions, even though some of them are implementing proactive policies. To avoid potential legal matters, companies can start with simple use cases first. For example, when APL and PIL started their pilot tests on blockchain bills of lading, they chose to deal with non-negotiable bills of lading first so that they do not have to worry about the legal issues related to transference of title of goods.

In order to make blockchain fully effective, each maritime organisation should proactively seek cooperation with clients, governments and even competitors to share knowledge and establish standards, as the benefits of blockchain cannot be significant without reaching a critical mass.

4.5.2 For government agencies

The roles of government agencies for blockchain applications are mainly in two aspects. One is to explore the possibilities to incorporate the technology into the public sector. The other is to effectively govern the use of the technology as well as to promote relevant innovation. Although blockchain brings regulatory challenges to authorities, it creates opportunities for governments to improve the efficiency of public services and to fight corruption. As a promoter of technological innovation, governments should not only encourage other stakeholders to explore the potential of blockchain but also proactively develop use cases of blockchain for public services.

With regard to governance, the strategies adopted by policymakers will influence the future development of blockchain. Regulators have to be mindful when making policies to set boundaries of the technology. They should seek an appropriate balance between fostering innovation of the distributed ledger technology and safeguarding the safety and security of market participants and the interests of the public as a whole (Ducas and Wilner, 2017; Paech, 2017). The regulations need to be so flexible and adaptive that they can evolve in parallel with the changes in new applications (UK Government Office for Science, 2016).

When making rules to control operations in blockchain's digital world, apart from the classical legal code, policymakers could also consider the technical code (UK Government Office for Science, 2016). Technical code here refers to software and protocols that are used to determine how programming language is coded. The technical code for blockchain is currently maintained and improved through private participants such as the Bitcoin Improvement Proposal of Bitcoin. The public sector can also be involved in the process of designing and maintaining technical code. For instance, the Internet TCP/IP was created by US government-funded projects. Through involving in developing technical code for blockchain, the public sector can influence the rules of blockchain with the same regulatory effects as legal code.

While China and Russia adopt a restrictive policy at present to ban ICO and cryptocurrency exchange, a majority of jurisdictions in the world such as Canada are employing a wait-and-see approach (European Securities and Markets Authority, 2016; Ducas and Wilner, 2017). Nevertheless, the above two strategies are both not encouraging and may push the innovators away to a more regulatory-friendly country (Ducas and Wilner, 2017). In order to better utilise the potential of blockchain and minimise the identified risks at the same time, governments could consider a more facilitative approach to encourage pilot projects with a certain degree of restrictions. The Sandbox program adopted by the UK government is a good example. It provides a relatively relaxed environment where authorised organisations can test their innovations to a limited range of consumers for a limited duration while ensuring that appropriate safeguards are in place (UK Financial Conduct Authority, 2017).

Blockchain innovation could be expensive especially for small and medium enterprises. It is necessary for governments to step in to make the innovation more accessible so that the whole society can improve evenly. Therefore, governments can consider providing incentive schemes such as providing an innovation playground for companies to try. Other ways of encouraging blockchain for governments are to seek cooperation with international organisations and other jurisdictions to facilitate an establishment of global regulatory principles to enable wider adoption of blockchain (Ducas and Wilner, 2017), to promote the development of internationally recognised technical standards for blockchain, and to bridge various industry players to participate in the network.

Based on the above analysis, detailed implications and recommendations for different maritime stakeholders are provided in Table 4.2 for them to better capture the opportunities of blockchain and foster blockchain adoption.

Table 4.2 Implications and recommendations to maritime stakeholders in blockchain adoption.

Maritime Stakeholders	Implications and Recommendations
Ship Operators	• Start with small projects and selective areas first • Graduate adoption in parallel with the development of regulatory framework and maturity of the technology • Proactively seek cooperation as blockchain cannot be so beneficial without reaching a critical mass
Terminal Operators	• Integrate blockchain with port community systems • Embed blockchain in port systems like smart grid to enhance automation in terminals
Classification Societies	• Be a blockchain knowledge centre and blockchain service provider in the industry • Leverage their expertise especially in setting up standards to assist in establishing blockchain standards in the industry
Equipment Manufacturers	• Monitor the developments of blockchain • Integrate blockchain technology with 3D printing for a smoother and more secure service
Technology Providers	• Focus on developing interoperable solutions to maritime organisations • Be in parallel with the development of the regulatory framework and technology.

Maritime Stakeholders	Implications and Recommendations
Service Providers	• Proactively involve in developing industry standards of blockchain protocol • Make efforts to educate users because blockchain is in vain if few people use it • Be prepared with the low speed of blockchain diffusion in the industry
Government Agencies	• Combine legal and technical codes to govern the use of blockchain • Lead industrial cooperation by connecting different players to set up standards • Cooperate with international organisations and other jurisdictions to set up global regulatory principles • Cooperate with industrial organisations to develop common technical standards for blockchain • Revising its legal framework to encourage the use of blockchain in business

Source: Author.

4.6 Conclusion

Current research on blockchain applications in the maritime industry is scarce and mostly confined to a specific maritime sector. This chapter consolidates and analyses the current and emerging blockchain applications from different maritime sectors with detailed reasoning of why blockchain is suitable for each use case. The results suggest that the ultimate goal of these applications is to achieve lean process via reducing paperwork, enhancing information sharing and automating processes. As such, a novel conceptual framework is developed to provide a holistic view of blockchain adoption in the industry by answering why blockchain can be applied in the industry, how it can be applied, what challenges are expected and who are the major stakeholders in each use case. Based on the framework, future research directions are suggested around quantitative testing of suggested relationships between different dimensions of blockchain adoption, further investigation of the emerging trends of blockchain applications in the industry, quantitative analysis regarding adoption time, evolution, stakeholder analysis, commercial impact and environmental impact of blockchain adoption. Practically, the conceptual framework assists stakeholders to better understand why and how blockchain can be applied in different maritime sectors and hence stimulates use case development in the industry.

Lastly, implications for organisations and governments are discussed and recommendations to various maritime stakeholders are provided.

CHAPTER 5 OPTIMAL ADOPTION TIME OF BLOCKCHAIN FOR SHIP OPERATORS: A GAME THEORETICAL APPROACH

This chapter develops a game theoretical model to analyse the introduction of blockchain to companies from a big customer with bargaining power, using a big shipper and multiple ship operators as a case. In this study, ship operators need to decide their optimal adoption time when facing a request from a big shipper to adopt blockchain. If ship operators are not willing to join the blockchain network within cut-off time, the shipper would substitute these ship operators with others by transferring part of their shipping volume to others. In terms of methodological significance, a novel algorithm is developed to obtain the numerical solutions of ship operators' optimal adoption time. The model is further extended with a mixed pricing structure and under the impact of an existing exogenous disruption (e.g., Covid-19). Through numerical applications, the study examines how factors such as blockchain benefits, shipper's substitution policy, blockchain pricing structure and Covid-19 would affect ship operator's adoption time of blockchain in different situations. The findings provide significant implications for understanding ship operators' behaviour of blockchain adoption and how to promote blockchain in the maritime industry.[2]

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[2] The following paper is published based on this chapter:

Pu, S., and Lam, J. S. L. (2020), "Blockchain Adoption Time of Shipowners: A Game Theoretic Analysis", Proceedings of 2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Singapore, pp.989–991, IEEE, Singapore, DOI: 10.1109/IEEM45057.2020.9309798.

5.1 Background

In the maritime industry, an increasing number of companies started to explore the potential of blockchain and conducted test trials. Example companies include ship operators such as Maersk and APL (Accenture, 2018; Maersk, 2018), port operators such as Port of Rotterdam and PSA Singapore (Seatrade, 2017), classification societies such as DNV (previously known as DNV GL) (DNV GL, 2017, 2018), marine insurers such as Willis Towers Waston (Seatrade, 2018b), and other marine service providers such as Bolero (Global Trade Review, 2019). However, for ship operators, the proactive attitude to develop their own blockchain systems is limited to a few shipping tycoons like Maersk. A more common practice in the shipping sector is that ship operators have to react to the requests from a big shipper to join the shipper's blockchain system as part of the shipper's supply chain, as shown in the cases of BHP, Louis Dreyfus Company and AB InBev (Rizzo, 2016; Reuters, 2018, 2019; The Maritime Executive, 2018). Despite blockchain's potential and customers' requests, most companies are still unsure whether and when to adopt blockchain. Therefore, this paper will study the optimal adoption time of blockchain technology by employing game theory to model the current market trend that a big customer requests its vendors to adopt blockchain using a big shipper and multiple ship operators as a case.

In addition, the adoption time of a new technology may be affected by exogenous disruptions due to their impact on companies' business performance. For instance, the outbreak of Covid-19 pandemic caused changes in shipping quantities (Lam et al., 2021), companies' profit margin (Notteboom et al., 2021) and possibly users' perception of blockchain as there is an urgent need to digitalise shipping processes to reduce human interaction (BIMCO, 2020a). The impact of these disruptions on maritime organisations could be different, either positive or negative. Despite the understanding that digital technologies help to improve organisations' resilience to certain disruptions, some organisations may still prefer a wait-and-see strategy at least in the short term due to various reasons such as limited financial capabilities. It is unclear how maritime organisations would respond to an exogenous disruption regarding whether and when to adopt a new technology. Hence, in this study, we will extend the developed game theoretical model to analyse the potential impact of an existing exogenous disruption on ship operators’ optimal adoption time of blockchain using the case of Covid-19.

5.2 The model

The game model considers a two-layer vertical market of complete information with one large customer and its multiple vendors. Each vendor is aware of the information of other vendors and the benefits of blockchain technology. In this paper, we use one shipper and its ship operators as the case for problem formulation. The shipper intends to digitalise its current documentation systems using permissioned blockchain and requests its ship operators to join the network. In this study, ship operators refer to those who operate vessels and may not necessarily be the owner of vessels. The blockchain system can be provided by the shipper or a third-party company like IBM. The notations used in the model are defined in Table 5.1.

Table 5.1 Notations.

Parameters	
q_i^t	Shipping volume between the shipper and ship operator i at time t
β	The substitution ratio imposed by the shipper on followers[1]
T_c	Cut-off time set by the shipper
γ	The discount rate in calculating the present value of future payoff
λ	The discount rate in calculating the present value of future cost on blockchain adoption, taking into account the cost reduction in the future
C_i^0	The initial setup cost of blockchain for ship operator i at time 0 when the shipper announces the blockchain initiative
C_i^a	The annual subscription fee of blockchain for ship operator i
θ	The probability of cargoes being mistakenly delivered upon forged bills of lading (BLs)
v	The average unit value of cargoes transported by the shipper
e_i	The reduction in ship operator i’s data verification efforts per container
c_i^f	The cost saving from reduced BL fraud by using blockchain for ship operator i
c_i^v	The reduced cost of data verification by using blockchain for ship operator i
$u_i(\cdot)$	Ship operator i's normal profit flow without adoption of blockchain
$\epsilon_i(\cdot)$	Benefits of blockchain adoption for ship operator i
T_i	The adoption time of blockchain for ship operator i
Ψ_{-i}	The combination of blockchain adoption time for all ship operators except for ship operator i
Decision Variables	

α	The substitution gain factor, namely the percentage increase in business volume of leaders[2]
U_i^l (U_i^f)	Ship operator *i*'s total payoff as a leader (follower)
$T_i^l(T_i^f)$	The optimal adoption time of ship operator *i* as a leader (follower)
$T_{il}^{max}(T_{if}^{max})$	The maximum adoption time among all ship operators when ship operator i is a leader (follower)
T_i^*	The final optimal adoption time of ship operator *i*
s_i^*	The final optimal adoption strategy of ship operator i regarding being a leader or a follower

Note: [1,2] The definitions of leaders and followers are provided in section 5.2.2.

5.2.1 Model assumptions and definitions

Shipping volume

The total shipping volume of the shipper per unit time is defined as Q. It is assumed to remain constant over time $Q^t = Q$ for $t \in N^+$. This assumption allows us to focus on the impacts of blockchain cost-effectiveness and penalty factors on ship operators' adoption time. Let n denote the total number of ship operators. The equation of Q is given by

$$Q^t = \sum_{i=1}^{n} q_i^t = Q, \quad for\ i \in \{1,2,\dots,n\}\ and\ t \in N^+. \tag{5.1}$$

where q_i^t denotes the shipping volume between the shipper and ship operator *i* at time t. It may vary at different time due to shipper's substitution policy which will be explained later.

Cost of blockchain system

An initial setup cost (C_i^0) and annual subscription fee (C_i^a) are considered in the model. It is assumed that the initial setup cost and the annual cost of the blockchain system declines with time at a rate of λ, where $\lambda > \gamma$ which provides a late mover advantage. It is also assumed that $\lambda T_c < 1$ and $\gamma T_c < 1$. This assumption is reasonable in real life situations[3] and necessary to determine the sign of the second-order derivative of a ship operator's payoff function (details are given in APPENDIX A). As per industry practice, the annual subscription starts at the joining time and needs to be renewed at the beginning of every membership year. With that, the total cost for ship operator i to join the blockchain system at time T_i can be given by (Barua and Lee, 1997)

$$C_i(T_i) = C_i^0 e^{-\lambda T_i} + \sum_{t=T_i}^{\infty} C_i^a e^{-\lambda t}, where\ t = T_i, T_i + 1, T_i + 2, \cdots. \tag{5.2}$$

<u>Benefits of blockchain</u>

The speciality of blockchain in exchanging inter-organisational information lies in the validation process through consensus mechanism and the immutability of data stored on the ledger to ensure data integrity (Kumar et al., 2019). Due to this, in the maritime industry, blockchain could safeguard bills of lading (BLs), which are critical legal documents in shipping and fraud of which could lead to massive financial losses to genuine parties. It could also remove repetitive checks at each stage to ascertain the legitimacy and integrity of data received (The Straits Times, 2019). With that, the benefits of blockchain to ship operator i are captured as the cost-saving of reduced BL fraud c_i^f and reduced cost of data verification c_i^v.

Ship operators face a risk of misdelivery of cargoes due to forged BLs with a probability of θ. The average unit cargo value is represented by v. Thus, the cost saving from reduced BL fraud for ship operator i is $c_i^f = \theta v q_i^t$.

With blockchain, companies take lesser efforts to verify data and documents. The reduction in company i's verification efforts per container is represented by e_i. We model the cost of verification with a quadratic function of the reduced verification

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[3] The introduction of cut-off time is to pressure ship operators to join blockchain system in a reasonable short time. Therefore, the cut-off time in real-life should not be too long (for example not more than 5 years), otherwise there is no point introducing such a policy. In addition, the discount rates for technology costs and normal business revenues/costs in real-life are mostly within 20%. Therefore, λT_c<1 and γT_c<1 is reasonable in life.

efforts. The method is commonly used in incentive contracts (Chen et al., 2016; Hu et al., 2016). Hence, the reduced cost of data verification is $c_i^v = \frac{1}{2}{e_i}^2 q_i^t$.

With that, the benefits of blockchain adoption to ship operator i at time t can be written as follows:

$$\epsilon_i\left(q_i^t\right) = c_i^f + c_i^v = \theta v q_i^t + \frac{1}{2}{e_i}^2 q_i^t, \text{for } t \in N^+ \text{ and } \forall i \in \{1,2,\dots,n\}. \tag{5.3}$$

Bargaining power

It is assumed that the shipper has a very strong bargaining power such that it can request its ship operators to join the blockchain system and even impose a substitution policy on ship operators.

Ship operator’s blockchain cost-effectiveness

Similar to Barua and Lee (1997), we define the blockchain cost-effectiveness to ship operators as a ratio of adoption benefits to marginal adoption cost at time 0. Since the benefits of blockchain adoption vary to leaders and followers, the leadership and followership blockchain cost-effectiveness ratios are defined separately as below. The numerators represent the benefits of blockchain adoption. The denominator represents the marginal cost of blockchain adoption at time 0 which represents the change in total blockchain adoption cost that comes from delaying the adoption one additional unit period at time 0.

The leadership blockchain cost-effectiveness ratio: $r_i^l = \frac{\epsilon_i(q_i^0)}{C_i'(0)}$.

The followership blockchain cost-effectiveness ratio: $r_i^f = \frac{\epsilon_i(q_i^0 - \beta q_i^0)}{C_i'(0)}$.

5.2.2 The base model – Fixed pricing of blockchain

At time 0, the shipper announces its blockchain initiative, together with a substitution policy with cut-off time (T_c) and a substitution ratio (β). Before going to the details of the policy, it is necessary to define leaders and followers as follows: Leaders are ship operators which join the blockchain system no later than the specified cut-off time, i.e., $T_i \leq T_c$. Followers are ship operators which join the blockchain system later than the specified cut-off time, i.e., $T_i > T_c$. A fixed pricing model of blockchain is considered under which the annual subscription fee of blockchain is fixed.

The substitution policy works in the way that the shipper will cut down the shipping volume with followers by a ratio of β. The reduced shipping volume from followers will be shared among leaders proportional to leaders' original shipping volume. Once all ship operators join the network, their business shipping volume will be restored to the original one, i.e., q_i^0. The ship operators are numbered in decreasing order of q_i^0, i.e., $q_1^0 \geq q_2^0 \geq q_3^0 \geq \cdots \geq q_n^0$. Let *N* be the set of all ship operators. Let *M* be the set of all leaders. Since the total volume lost to followers ($\sum_{i \in N/M} \beta q_i^0$) equals the total amount increased to leaders ($\sum_{i \in M} \alpha q_i^0$), the substitution gain factor (α) can be given by

$$\alpha = \frac{\sum_{i \in N/M} \beta q_i^0}{\sum_{i \in M} q_i^0}. \tag{5.4}$$

Ship operator i's profit flow at time t can be given by

$$u_i^t = \begin{cases} u_i\left(q_i^t\right), if\ t < T_i, \\ u_i\left(q_i^t\right) + \epsilon_i\left(q_i^t\right), if\ t \geq T_i, \end{cases} \tag{5.5}$$

$$\text{where } q_i^t = \begin{cases} q_i^0, \text{if } t \leq T_c \text{ or } (T_i \leq T_c \text{ and } t \geq T_{il}^{max}) \text{ or } \left(T_i > T_c \text{ and } t \geq T_{if}^{max}\right), \\ q_i^0 + \alpha q_i^0, \text{if } T_i \leq T_c \text{ and } T_c < t < T_{il}^{max}, \\ q_i^0 - \beta q_i^0, \text{if } T_i > T_c \text{ and } T_c < t < T_{if}^{max}. \end{cases}$$

Therefore, the payoff function of ship operator i can be written as

$$U_i(T_i, T_{-i}) = \begin{cases} U_i^l(T_i, T_{-i}), \text{if } T_i \leq T_c, \\ U_i^f(T_i, T_{-i}), \text{if } T_i > T_c, \end{cases} \tag{5.6}$$

where $U_i^l(T_i, T_{-i})$ and $U_i^f(T_i, T_{-i})$ are ship operator i's payoff as a leader and as a follower, respectively, which can be obtained by

$$U_i^l(T_i, T_{-i}) = \int_0^{T_i} u_i^0 e^{-\gamma t} dt + \int_{T_i}^{T_c} u_i^1 e^{-\gamma t} dt + \int_{T_c}^{T_{il}^{max}} u_i^2 e^{-\gamma t} dt + \int_{T_{il}^{max}}^{\infty} u_i^1 e^{-\gamma t} dt - C_i(T_i), \tag{5.7}$$

$$U_i^f(T_i, T_{-i}) = \int_0^{T_c} u_i^0 e^{-\gamma t} dt + \int_{T_c}^{T_i} u_i^3 e^{-\gamma t} dt + \int_{T_i}^{T_{if}^{max}} u_i^4 e^{-\gamma t} dt + \int_{T_{if}^{max}}^{\infty} u_i^1 e^{-\gamma t} dt - C_i(T_i), \tag{5.8}$$

where $u_i^0 = u_i(q_i^0)$, $u_i^1 = u_i(q_i^0) + \epsilon_i(q_i^0)$, $u_i^2 = u_i(q_i^0 + \alpha q_i^0) + \epsilon_i(q_i^0 + \alpha q_i^0)$, $u_i^3 = u_i(q_i^0 - \beta q_i^0)$, and $u_i^4 = u_i(q_i^0 - \beta q_i^0) + \epsilon_i(q_i^0 - \beta q_i^0)$.

The optimal adoption time of ship operator i as a leader (T_i^l) or as a follower (T_i^f) can be obtained by solving $\max_{0 \le T_i \le T_c} U_i^l(T_i, T_{-i})$ and $\max_{T_c < T_i < \infty} U_i^f(T_i, T_{-i})$ respectively:

Lemma 1. *In the base model, the optimal adoption time of ship operator* i *as a leader is:*

$$T_i^l = \begin{cases} 0, & if\ r_i^l \ge 1, \\ \min\left(\frac{1}{\lambda - \gamma} ln \frac{\lambda C_i^0 + \frac{\lambda}{1 - e^{-\lambda}} C_i^a}{\epsilon_i(q_i^0)}, T_c\right), & if\ r_i^l < 1, \end{cases} \tag{5.9}$$

where $r_i^l = \frac{\epsilon_i(q_i^0)}{C_i^{'}(0)} = \frac{\epsilon_i(q_i^0)}{\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}} C_i^a}$ *(see the proof in APPENDIX A).*

The analytical solution of T_i^l indicates that as a leader, ship operator i would adopt blockchain immediately after shipper's announcement if it has blockchain leadership efficiency $\left(i.e.\ r_i^l \ge 1\right)$. Otherwise, it would adopt blockchain at a time of either $\frac{1}{\lambda-\gamma} \ln \frac{C_i^0 + \frac{\lambda}{1-e^{-\lambda}} C_i^a}{\epsilon_i(q_i^0)}$ or T_c, whichever is earlier.

Lemma 2. *In the base model, the optimal adoption time of ship operator* i *as a follower is:*

$$T_i^f = \begin{cases} T_c + \Delta\,, & if\ r_i^f \geq 1, \\ \max\left(\frac{1}{\lambda-\gamma} ln \frac{\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}} C_i^a}{\epsilon_i\left(q_i^0 - \beta q_i^0\right)}, T_c + \Delta\right), & if\ r_i^f < 1, \end{cases} \tag{5.10}$$

where $r_i^f = \frac{\epsilon_i(q_i^0-\beta q_i^0)}{C_i'(0)} = \frac{\epsilon_i(q_i^0-\beta q_i^0)}{\lambda C_i^0+\frac{\lambda}{1-e^{-\lambda}}C_i^a}$ *and* Δ *is a small positive real number to ensure that* $T_i^f > T_c$ *(see the proof in APPENDIX A).*

The analytical solution of T_i^f indicates that as a follower, ship operator i would adopt blockchain as early as possible within the constraints of $T_i^f > T_c$, if it has blockchain followership efficiency $\left(i.e.\ r_i^f \geq 1\right)$. Otherwise, it would adopt blockchain at time $\frac{1}{\lambda-\gamma}\ln\frac{\lambda C_i^0+\frac{\lambda}{1-e^{-\lambda}}C_i^a}{\epsilon_i(q_i^0-\beta q_i^0)}$ or a point of time soonest after T_c (i.e. $T_c + \delta$), whichever is later.

All ship operators would adopt blockchain at either T_i^l or T_i^f for $\forall i \in \{1,2,\ldots,n\}$. The final optimal adoption time of blockchain for ship operator i is $\underset{T_i\in\left\{T_i^l,T_i^f\right\}}{\operatorname{argmax}} U_i(T_i,T_{-i})$, which can be determined by comparing $U_i^l(T_i^l,T_{-i})$ and $U_i^f\left(T_i^f,T_{-i}\right)$. If the former is larger, T_i^l is the final optimal adoption time. If the latter is larger, T_i^f is the final optimal adoption time. However, after substituting T_i^l and T_i^f into U_i^l and U_i^f respectively, U_i^l and U_i^f are still dependent on the decisions of all other ship operators T_{-i}. This gives rise to:

Proposition 1. *(a) If the sign of* $U_i^l\left(T_i^l,T_{-i}\right) - U_i^f\left(T_i^f,T_{-i}\right)$ *is always positive for all possible combinations of* T_{-i}*, then* T_i^l *is the strictly dominant strategy and the optimal adoption time for ship operator* i*, which would be irrelevant to the adoption time of other ship operators in this case.*

(b) If the sign of $U_i^l\ \left(T_i^l,T_{-i}\right) - U_i^f\left(T_i^f,T_{-i}\right)$ *is always negative for all possible combinations of* T_{-i}*, then* T_i^f *is the strictly dominant strategy and the optimal*

adoption time for ship operator i, which would be irrelevant to the adoption time of other ship operators in this case.

(c) If the sign of $U_i^l\ (T_i^l, T_{-i}) - U_i^f(T_i^f, T_{-i})$ varies at different possible combinations of T_{-i}, then ship operator i does not have a strictly dominant strategy. Its optimal adoption time varies between T_i^l and T_i^f as a response to the adoption time of other ship operators.

Proposition 1 also applies to the extended models. The only difference is that the values of T_i^l and T_i^f are different in the extended models.

5.2.3 Nash equilibrium solution algorithm

This study develops a novel algorithm as below to obtain the numerical solutions of the Nash equilibrium of ship operators' adoption strategies. A pseudocode of the algorithm is presented in Table 5.2.

Table 5.2 Pseudocode of the Nash equilibrium solution algorithm.

```
Input:    $\beta, T_c, k, f, c, \gamma, \lambda, C_i^0, C_i^a, q_i^0$
Output:   $T_i^*$ and $s_i^*$
Step 1: Calculate the optimal adoption time as a leader and as a follower for ship operators
for $i = 1{:}n$
    1.1 Obtain $T_i^l$ and $T_i^f$.
end
Step 2: Get the best adoption strategies for ship operators
for $i = 1{:}n$
    2.1 Obtain $S_{-i}, \Psi_{-i}, T_{il}^{max}, T_{if}^{max}$ and $\alpha$;
    2.2 Calculate $g_i$;
    2.3 Obtain $T_i^*$ and $s_i^*$;
    2.4 Get the number of ship operators who do not have a strictly dominant strategy in this round and the index of them, represented by num_non_BS and index_non_BS accordingly.
end
Step 3: Iterated best strategies
while $num\_non\_BS > 0$
    Substitute known $T_i^*$ and $s_i^*$ for ship operator $i$ who has a strictly dominant strategy in the previous step;
    for $i = index\_non\_BS$
        3.1 Obtain $S_{-i}, \Psi_{-i}, T_{il}^{max}, T_{if}^{max}$ and $\alpha$;
```

```
        3.2 Calculate $g_i$;
        3.3 Obtain $T_i^*$ and $s_i^*$;
        3.4 Reassign $num\_non\_BS$ and $index\_non\_BS$ with the new value;
        3.5 Break if the loop exceeds the assigned maximum number of iterations.
    end
end
```

Step 1: Calculate the optimal adoption time as a leader and as a follower for all ship operators: $(\boldsymbol{T_1^l}, \dots, \boldsymbol{T_n^l})$ & $(\boldsymbol{T_1^f}, \dots, \boldsymbol{T_n^f})$.

Step 2: Determine if there exists a strictly dominant strategy $\boldsymbol{T_i^*}$ and $\boldsymbol{s_i^*}$ for all ship operators by comparing $\boldsymbol{U_i^l}$ with $\boldsymbol{U_i^f}$ for any possible combination strategies of other ship operators.

Let s_i denote the decision of ship operator i in terms of being a follower or a leader, s_i^* denote the strictly dominant strategy in this regard. T_i^* is the strictly dominant strategy of ship operator i in terms of optimal adoption time.

Let s_{-i_k} represent the k^{th} combination of decisions regarding being a follower or a leader for all ship operators other than ship operator i, where there are 2^{n-1} types of decision combinations in total.

$$s_{-i_k} = [s_1 \quad \cdots \quad s_{i-1} \quad s_{i+1} \quad \cdots \quad s_n], \text{for } k \in \{1,2,\dots,2^{n-1}\}, \tag{5.11}$$

where $s_j = \begin{cases} 0, & \text{if ship operator } i \text{ is a follower} \\ 1, & \text{if ship operator } i \text{ is a leader} \end{cases}$, for $j \in N/\{i\}$.

Let S_{-i} stand for all the possible s_{-i_k}, then $S_{-i} = \begin{bmatrix} s_{-i_1} \\ s_{-i_2} \\ \vdots \\ s_{-i_{(2^{n-1})}} \end{bmatrix}$.

Correspondingly, t_{-i_k} represents the k^{th} combination of decisions on adoption time for all ship operators other than ship operator i, where there are 2^{n-1} combinations in total.

$$t_{-i_k} = [T_1 \quad \cdots \quad T_{i-1} \quad T_{i+1} \quad \cdots \quad T_n], \text{for } k \in \{1,2,\dots,2^{n-1}\}, \tag{5.12}$$

where $T_j = \begin{cases} T_j^f, & \text{if } s_j = 0 \\ T_j^l, & \text{if } s_j = 1 \end{cases}$, for $j \in N/\{i\}$.

Let Ψ_{-i} denote all the possible t_{-i_k}, then $\Psi_{-i} = \begin{bmatrix} t_{-i_1} \\ t_{-i_2} \\ \vdots \\ t_{-i_{(2^{n-1})}} \end{bmatrix}$. With Ψ_{-i}, the maximum adoption time among all ship operators when ship operator i chooses to be a leader or follower is given by

$$T_{il}^{max} = \max\left(\Psi_{-i}, T_i^l\right). \tag{5.13}$$

$$T_{if}^{max} = \max\left(\Psi_{-i}, T_i^f\right). \tag{5.14}$$

Define $Q_{-i} = [q_1^0 \quad \cdots \quad q_{i-1}^0 \quad q_{i+1}^0 \quad \cdots \quad q_n^0]$, for $i \in \{1,2,\dots,n\}$. Therefore, the corresponding α for S_{-i} can be calculated by

$$\alpha = \frac{\beta\left[(1 - S_{-i}){Q_{-i}}^T\right]}{q_i^0 + S_{-i}{Q_{-i}}^T}. \tag{5.15}$$

Let $g_i\left(T_i^l, T_i^f, \alpha, \beta, T_{il}^{max}, T_{if}^{max}\right) = U_i^l\left(T_i^l, \alpha, T_{il}^{max}\right) - U_i^f\left(T_i^f, \beta, T_{if}^{max}\right)$. If the sign of all elements of g_i are the same, a strictly dominant strategy exists for ship operator i. Hence, the best strategy of ship operator i, can be provided as below:

$$(T_i^*, s_i^*) = \begin{cases} \left(T_i^l, 1\right), & \text{if all elements of matrix } g_i \text{ are positive,} \\ \left(T_i^f, 0\right), & \text{if all elements of matrix } g_i \text{ are negative,} \\ \text{does not exist,} & \text{otherwise.} \end{cases} \tag{5.16}$$

Step 3: Perform iterated dominant strategy, then Nash equilibrium $(\boldsymbol{T_1^*}, \dots, \boldsymbol{T_i^*}, \dots, \boldsymbol{T_n^*})$ and $(\boldsymbol{s_1^*}, \dots, \boldsymbol{s_i^*}, \dots, \boldsymbol{s_n^*})$ can be derived.

A strictly dominant strategy may not exist for all ship operators in step 2. Given this, a method of iterated dominant strategy can be used to get the s_i^* and T_i^* for all ship operators. It works by substituting confirmed s_i^* and T_i^* into equations and repeating the calculation of step 2 until all s_i^* and T_i^* are derived. A maximum number of iterations is assigned to avoid an infinite loop in case there is no Nash equilibrium for the game.

5.3 Model extension

5.3.1 The extended model 1 – Mixed pricing of blockchain

The base model assumes that the annual subscription fee is fixed. However, in real life, the annual fee could be dependent on the volume handled. Therefore, the base model is extended in the way that the annual fee of blockchain includes a fixed and a variable part.

Same as the base model, the fixed annual fee C_i^a is renewed at the beginning of every membership year. The variable fee is proportional to quantities handled at a coefficient of C_i^b and incurred every time when cargoes are being shipped. For simplicity, we assume the variable fee is paid continuously. With that, the total cost of blockchain adoption for ship operator i in the extended model is:

$$C_i(T_i) = C_i^0 e^{-\lambda T_i} + \sum_{t_1=T_i}^{\infty} C_i^a e^{-\lambda t_1} + \int_{t=T_i}^{\infty} C_i^b q_i^t e^{-\lambda t} dt, \tag{5.17}$$

where $t_1 = T_i, T_i + 1, T_i + 2, \cdots$.

By substituting the new blockchain adoption cost into the payoff functions, the new optimal adoption time of ship operators as a leader or a follower can be obtained:

Lemma 3. *In the extended model with a mixed pricing structure of blockchain, the optimal adoption time of ship operators as a leader is:*

$$T_i^l = \begin{cases} 0, & if\ r_i^l \geq 1, \\ \min\left(\frac{1}{\lambda - \gamma} \ln \frac{\lambda C_i^0 + \frac{\lambda}{1 - e^{-\lambda}} C_i^a + C_i^b q_i^0}{\epsilon_i\left(q_i^0\right)}, T_c\right), & if\ r_i^l < 1, \end{cases} \tag{5.18}$$

where $r_i^l = \frac{\epsilon_i(q_i^0)}{C_i'(0)} = \frac{\epsilon_i(q_i^0)}{\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}} C_i^a + C_i^b q_i^0}$ *(see the proof in APPENDIX A).*

Lemma 4. *In the extended model with a mixed pricing structure of blockchain, the optimal adoption time of ship operators as a follower is:*

$$T_i^f = \begin{cases} T_c + \Delta, & if\ r_i^f \geq 1, \\ \max\left(\frac{1}{\lambda - \gamma} \ln \frac{\lambda C_i^0 + \frac{\lambda}{1 - e^{-\lambda}} C_i^a + C_i^b (q_i^0 - \beta q_i^0)}{\epsilon_i (q_i^0 - \beta q_i^0)}, T_c + \Delta\right), & if\ r_i^f < 1, \end{cases} \quad (5.19)$$

where $r_i^f = \frac{\epsilon_i (q_i^0 - \beta q_i^0)}{C_i'(0)} = \frac{\epsilon_i (q_i^0 - \beta q_i^0)}{\lambda C_i^0 + \frac{\lambda}{1 - e^{-\lambda}} C_i^a + C_i^b (q_i^0 - \beta q_i^0)}$ *and* Δ *is a small positive real number to ensure that* $T_i^f > T_c$ *(see the proof in APPENDIX A).*

5.3.2 The extended model 2 – Impact of an exogenous disruption

Exogenous disruptions may change the business performance of ship operators and hence affect ship operators' strategies of blockchain adoption time. Changes could occur in shipping quantities, profit margin and the perception of blockchain solutions. This extension mainly analyses how an existing exogenous disruption would affect the blockchain adoption time of ship operators.

In the extension, we consider a mixed pricing structure of blockchain, which is more common in practice. The result of a fixed pricing structure of blockchain can still be obtained from this extension by setting the unit variable cost zero. This study analyses the situation where shipper's blockchain initiative is announced after an exogenous disruption takes place, which is very likely to happen in the real world. For instance, the outbreak of Covid-19 accelerates the need for digitalisation and companies started to prioritise blockchain projects because of the pandemic. The impact of the disruption is analysed by comparing the adoption time of ship operators with and without the disruption. The timeline of different events with and without a disruption is shown in Figure 5.1.

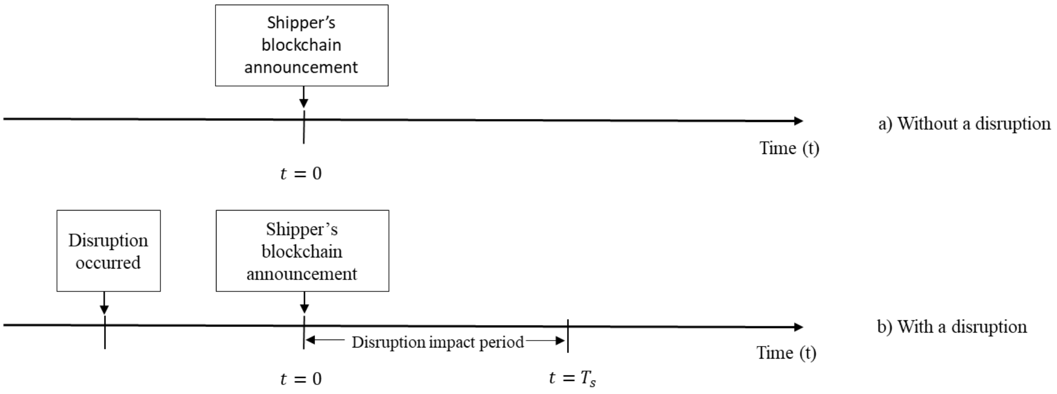

Figure 5.1 Timeline of events with and without a disruption.
Source: Drawn by author.

The impact duration of a disruption (hereinafter referred to as "disruption period") is denoted by T_s. The percentage change in shipping quantities of ship operators due to the disruption is denoted by δ. The shipping quantity of ship operator i during disruption impact period is hence given as $(1+\delta)q_i^t$ for $t \in [0, T_s]$. The change of ship operator i's profit margin is modelled by using a scaling parameter ϕ so that the profit flow during the disruption period becomes $\phi u_i(q_i^t)$ for $t \in [0, T_s]$. There are additional perceived benefits of using blockchain for shipping documents τ_i, as it provides an effective, traceable and secure way to process documents without human interaction, which becomes more important and more urgent in the context of Covid-19. In the model, $\tau_i = \omega q_i^t$, where ω is the additional perceived benefit of blockchain per unit shipping quantity (TEU). Therefore, the new unique benefits of adopting blockchain for ship operator i within the disruption period $t \in [0, T_s]$ are $\epsilon_i + \tau_i$, where ϵ_i is defined in Equation (5.3) representing the normal benefits of blockchain adoption regardless of exogenous disruptions. For ease of analysis, it is assumed that once the disruption period is over, the shipping quantities, profit flows and benefits of adopting blockchain will be immediately returned to the pre-disruption levels.

With that, if ship operator i is a leader, its payoff function in the extended model 2 is written as

$$U_i^l(T_i, T_{-i}) = \begin{cases} \int_0^{T_i} \hat{u}_i^0 e^{-\gamma t} dt + \int_{T_i}^{T_s} \hat{u}_i^1 e^{-\gamma t} dt + \int_{T_s}^{T_c} u_i^1 e^{-\gamma t} dt + \int_{T_c}^{T_{il}^{max}} u_i^2 e^{-\gamma t} dt \\ \quad + \int_{T_{il}^{max}}^{\infty} u_i^1 e^{-\gamma t} dt - C_i(T_i), \qquad \text{if } T_s < T_c \text{ and } T_i \le T_s, \\ \int_0^{T_s} \hat{u}_i^0 e^{-\gamma t} dt + \int_{T_s}^{T_i} u_i^0 e^{-\gamma t} dt + \int_{T_i}^{T_c} u_i^1 e^{-\gamma t} dt + \int_{T_c}^{T_{il}^{max}} u_i^2 e^{-\gamma t} dt \\ \quad + \int_{T_{il}^{max}}^{\infty} u_i^1 e^{-\gamma t} dt - C_i(T_i), \qquad \text{if } T_s < T_c \text{ and } T_i > T_s, \\ \int_0^{T_i} \hat{u}_i^0 e^{-\gamma t} dt + \int_{T_i}^{T_c} \hat{u}_i^1 e^{-\gamma t} dt + \int_{T_c}^{T_s} \hat{u}_i^2 e^{-\gamma t} dt + \int_{T_s}^{T_{il}^{max}} u_i^2 e^{-\gamma t} dt \\ \quad + \int_{T_{il}^{max}}^{\infty} u_i^1 e^{-\gamma t} dt - C_i(T_i), \qquad \text{if } T_s \ge T_c, \end{cases} \tag{5.20}$$

where $\hat{u}_i^0 = \phi u_i((1+\delta)q_i^0), \hat{u}_i^1 = \phi u_i((1+\delta)q_i^0) + \epsilon_i((1+\delta)q_i^0) + \tau_i((1+\delta)q_i^0)$ and $\hat{u}_i^2 = \phi u_i((1+\alpha)(1+\delta)q_i^0) + \epsilon_i((1+\alpha)(1+\delta)q_i^0) + \tau_i((1+\alpha)(1+\delta)q_i^0)$. $u_i^0, u_i^1,$ and u_i^2 have been defined in Equation (5.7).

If ship operator i is a follower, its payoff function in the extended model 2 is written as

$$
\begin{aligned}
&U_i^f(T_i, T_{-i}) \\
&= \begin{cases}
\int_0^{T_s} \hat{u}_i^0 e^{-\gamma t} dt + \int_{T_s}^{T_c} u_i^0 e^{-\gamma t} dt + \int_{T_c}^{T_i} u_i^3 e^{-\gamma t} dt + \int_{T_i}^{T_{if}^{max}} u_i^4 e^{-\gamma t} dt \\
\qquad + \int_{T_{if}^{max}}^{\infty} u_i^1 e^{-\gamma t} dt - C_i(T_i), \qquad \text{if } T_s < T_c\,, \\
\int_0^{T_c} \hat{u}_i^0 e^{-\gamma t} dt + \int_{T_c}^{T_i} \hat{u}_i^3 e^{-\gamma t} dt + \int_{T_i}^{T_s} \hat{u}_i^4 e^{-\gamma t} dt + \int_{T_s}^{T_{if}^{max}} u_i^4 e^{-\gamma t} dt \\
\qquad + \int_{T_{if}^{max}}^{\infty} u_i^1 e^{-\gamma t} dt - C_i(T_i), \qquad \text{if } T_s \geq T_c \text{ and } T_i \leq T_s, \\
\int_0^{T_c} \hat{u}_i^0 e^{-\gamma t} dt + \int_{T_c}^{T_s} \hat{u}_i^3 e^{-\gamma t} dt + \int_{T_s}^{T_i} u_i^3 e^{-\gamma t} dt + \int_{T_s}^{T_{if}^{max}} u_i^4 e^{-\gamma t} dt \\
\qquad + \int_{T_{if}^{max}}^{\infty} u_i^1 e^{-\gamma t} dt - C_i(T_i), \qquad \text{if } T_s \geq T_c \text{ and } T_i > T_s,
\end{cases}
\end{aligned}
\tag{5.21}
$$

where $\hat{u}_i^3 = \phi u_i\left((1-\beta)(1+\delta)q_i^0\right)$ and $\hat{u}_i^4 = \phi u_i((1-\beta)(1+\delta)q_i^0) + \epsilon_i((1-\beta)(1+\delta)q_i^0) + \tau_i((1-\beta)(1+\delta)q_i^0)$. $u_i^3$and u_i^4 have been defined in Equation (5.8).

The optimal adoption time of ship operator i as a leader (T_i^l) or as a follower (T_i^f) can be obtained by solving $\max\limits_{0 \leq T_i \leq T_c} U_i^l(T_i, T_{-i})$ and $\max\limits_{T_c < T_i < \infty} U_i^f(T_i, T_{-i})$, respectively:

Lemma 5. *In the extended model with an exogenous disruption under a mixed pricing structure of blockchain, the optimal adoption time of ship operators as a leader* (T_i^l) *is:*

(a) *If* $T_s \geq T_c$,

$$
T_i^l = \begin{cases}
0, if\ r_i^{l1} \geq 1, \\
\min(T_i^{l1}, T_c), if\ r_i^{l1} < 1.
\end{cases}
$$

(b) *If* $T_s < T_c$,

$$T_i^l = \begin{cases} \left\{\begin{array}{l} \underset{T_i \in \{0, T_i^{l2}\}}{argmax}\, U_i^l(T_i, T_{-i}), for\ T_s < T_i^{l2} < T_c \\ \underset{T_i \in \{0, T_c\}}{argmax}\, U_i^l(T_i, T_{-i}), for\ T_i^{l2} \geq T_c \\ 0, for\ T_i^{l2} \leq T_s \end{array}\right\}, if\ r_i^{l1} \geq 1, \\ \left\{\begin{array}{ll} \underset{T_i \in \{T_i^{l1}, T_i^{l2}\}}{argmax}\, U_i^l(T_i, T_{-i}), & for\ T_i^{l1} < T_s\ and\ T_s < T_i^{l2} < T_c \\ \underset{T_i \in \{T_i^{l1}, T_c\}}{argmax}\, U_i^l(T_i, T_{-i}), & for\ T_i^{l1} < T_s\ and\ T_i^{l2} \geq T_c \\ T_i^{l1}, & for\ T_i^{l1} < T_s\ and\ T_i^{l2} < T_s \\ T_i^{l2}, & for\ T_i^{l1} \geq T_s\ and\ T_s < T_i^{l2} < T_c \\ T_c, & for\ T_i^{l1} \geq T_s\ and\ T_i^{l2} \geq T_c \\ T_s, & for\ T_i^{l1} \geq T_s\ and\ T_i^{l2} \leq T_s \end{array}\right\}, if\ r_i^{l1} < 1, \end{cases}$$

where $T_i^{l_1} = \frac{1}{\lambda-\gamma} \ln \frac{1}{r_i^{l1}}$, $T_i^{l_2} = \frac{1}{\lambda-\gamma} \ln \frac{1}{r_i^{l2}}$, $r_i^{l1} = \frac{\epsilon_i\left((1+\delta)q_i^0\right) + \tau_i\left((1+\delta)q_i^0\right)}{\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}} C_i^a + C_i^b((1+\delta)q_i^0)}$, $r_i^{l2} = \frac{\epsilon_i(q_i^0)}{\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}} C_i^a + C_i^b q_i^0}$ *(see the proof in APPENDIX A).*

Lemma 6. *In the extended model with an exogenous disruption under a mixed pricing structure of blockchain, the optimal adoption time of ship operators as a follower* (T_i^f) *is:*

(a) *If* $T_s < T_c$,

$$T_i^f = \begin{cases} \mathrm{T}_\mathrm{i}^{f_2}, for\ \mathrm{T}_\mathrm{i}^{f_2} > T_c, \\ T_c + \Delta, for\ \mathrm{T}_\mathrm{i}^{f_2} \leq T_c, \end{cases}$$

(b) *If* $T_s \geq T_c$,

$$T_i^f = \begin{cases} \underset{T_i \in \{T_i^{f_1}, T_i^{f_2}\}}{\mathrm{argmax}}\ U_i^f(T_i, T_{-i}), & for\ T_i^{f_2} > T_s\ and\ T_c < T_i^{f_1} < T_s \\ \underset{T_i \in \{T_c + \Delta, T_i^{f_2}\}}{\mathrm{argmax}}\ U_i^f(T_i, T_{-i}), & for\ T_i^{f_2} > \mathrm{T_s}\ and\ \mathrm{T}_\mathrm{i}^{f_1} \leq \mathrm{T}_c \\ T_i^{f_2}, & for\ T_i^{f_2} > \mathrm{T_s}\ and\ \mathrm{T}_\mathrm{i}^{f_1} \geq \mathrm{T_s} \\ T_i^{f_1}, & for\ T_i^{f_2} \leq \mathrm{T_s}\ and\ \mathrm{T_s} < \mathrm{T}_\mathrm{i}^{f_1} < \mathrm{T_c} \\ T_c + \Delta, & for\ T_i^{f_2} \leq \mathrm{T_s}\ and\ \mathrm{T}_\mathrm{i}^{f_1} \leq \mathrm{T_c} \\ T_s, & for\ T_i^{f_2} \leq \mathrm{T_s}\ and\ \mathrm{T}_\mathrm{i}^{f_1} \geq \mathrm{T_s} \end{cases}$$

where $T_i^{f_1} = \frac{1}{\lambda-\gamma}\ln\frac{1}{r_i^{f1}}$, $T_i^{f_2} = \frac{1}{\lambda-\gamma}\ln\frac{1}{r_i^{f2}}$, $r_i^{f1} = \frac{\epsilon_i((1-\beta)(1+\delta)q_i^0)+\tau_i((1-\beta)(1+\delta)q_i^0)}{\lambda C_i^0+\frac{\lambda}{1-e^{-\lambda}}C_i^a+(1-\beta)(1+\delta)C_i^b q_i^0}$, $r_i^{f2} = \frac{\epsilon_i((1-\beta)q_i^0)}{\lambda C_i^0+\frac{\lambda}{1-e^{-\lambda}}C_i^a+(1-\beta)C_i^b q_i^0}$ *and* Δ *is a small positive real number to ensure that* $T_i^f > T_c$ *(see the proof in APPENDIX A).*

5.4 Numerical applications

5.4.1 The base model

5.4.1.1 Numerical setting

In this section, a practical case is applied to demonstrate the model developed in the study. The case considers one shipper and eight ship operators. The shipper imports cargoes from Shanghai to Los Angeles. Table 5.3 shows a list of parameters with assigned values in this study. Since the values of these parameters are assigned, sensitivity analysis will be performed for each parameter except Δ, which is just a small real number to ensure $T_i^f > T_c$. In this application, $\Delta = 1/12$ indicating that the earliest possible time that a follower would join the blockchain system is one month later than the cut-off time.

Table 5.3 List of parameters with an assigned value.

Parameter	Value	Unit
Cut-off time set by the shipper (T_c)	2	years
The substitution ratio imposed by the shipper on followers (β)	5%	
The reduction in company i's verification efforts per container (e_i)	8	/TEU
A small real number (Δ)	1/12	year

Table 5.4 tabulates other parameters used in the application case with values from industry or literature. It is assumed that the initial setup cost and annual fee are the same for all ship operators. The discount rate used for future normal business profits is the average weighted average cost of capital of big container carriers including CMA CGM and Hapag-Lloyd.

Table 5.4 List of parameters with industry data.

Parameter	Value	Unit	Reference
Container freight rate from Shanghai to Los Angeles (f)	1110	USD/TEU	From www.searates.com[1]
Marginal costs per container (c) (Sum of terminal handling charge in Shanghai and Los Angeles)	589	USD/TEU	From https://www.hapag-lloyd.com
Discount rate for the revenues/costs from normal businesses (γ)	8.1%	/year	(CMA CGM, 2019; Hapag-Lloyd, 2019)
Discount rate for the cost of the blockchain system (λ)	16%	/year	(Forrester Research, 2018)
Initial setup cost for ship operator i to join the blockchain system as soon as the shipper announces it $\left(C_i^0\right)$	7500	USD	(Forrester Research, 2018)
Annual fee for ship operator i to maintain in the blockchain network (C_i^a).	12000	USD/year	(Forrester Research, 2018)
The probability of cargoes being delivered upon forged bills of lading (θ)	4%	-	(UK Fraud Costs Measurement Committee, 2018)[2]
The average value of cargoes transported for the shipper per container (v)	10058	USD/TEU	(IHS Markit, 2017)[3]

Notes: [1]The freight is based on the rate on 30th Jul 2019. [2]The probability is assumed based on the general insurance fraud rate. [3]The cargo value is based on the value of Machinery and Mechanical Appliances, which are common cargoes shipped in the China-US route.

Among the eight ship operators, some are the shipper's regular sea freight suppliers with long-term contracts. They usually transport a large volume of cargoes for the shipper. Others are chosen in the spot market for special occasions when the regular ship operators cannot fulfil. The original annual container volumes of ship operators with the shipper are set in Table 5.5 so that enough different situations of blockchain cost-effectiveness can be covered.

Table 5.5 Ship operators' container volumes and blockchain cost-effectiveness.

Ship Operators	Shipping Volume (TEU)	Leadership Blockchain Cost-effectiveness	Followership Blockchain Cost-effectiveness
Ship Operator 1	30000	Efficient	Efficient
Ship Operator 2	10000	Efficient	Efficient
Ship Operator 3	5000	Efficient	Efficient
Ship Operator 4	500	Efficient	Efficient
Ship Operator 5	50	Efficient	Efficient
Ship Operator 6	34	Efficient	Inefficient
Ship Operator 7	20	Inefficient	Inefficient
Ship Operator 8	10	Inefficient	Inefficient

Source: Author.

5.4.1.2 Result analysis

This section analyses the results of the base model application regarding ship operators' optimal adoption time and corresponding payoffs. It also discusses sensitivity analysis of several important parameters.

Table 5.6 shows the Nash equilibrium of the baseline application case. The result reveals that ship operators with either leadership or followership blockchain cost-effectiveness would adopt blockchain earlier, while those without blockchain cost-effectiveness would do so later. A possible explanation is that ship operators without blockchain cost-effectiveness are usually very small ship operators and the small shipping volume limits the benefits that they can enjoy from blockchain adoption. Therefore, they have to wait for a long time until the costs of technology reduce to a sufficiently low level for them to adopt the technology. It is also interesting to note that even though blockchain is not cost-effective to ship operator 7, it would adopt blockchain within the cut-off time. This suggests that the presence of the substitution policy could form a credible threat to some small ship operators such that they would be worse off if joining the network later than cut-off time. However, for even smaller ship operators (like ship operator 8), the threat of substitution policy may not be severe enough to induce them to adopt blockchain within the cut-off time.

Table 5.6 Nash equilibrium of the baseline application case.

Ship Operators	Shipping Volume (TEU)	T_i^* (in year)	s_i^*	Net Payoff (in million USD)	β_i^*
Ship Operator 1	30000	0	Leader	353.74	NA
Ship Operator 2	10000	0	Leader	117.86	NA
Ship Operator 3	5000	0	Leader	58.89	NA
Ship Operator 4	500	0	Leader	5.81	NA
Ship Operator 5	50	0	Leader	0.51	NA
Ship Operator 6	34	0	Leader	0.32	NA
Ship Operator 7	20	2	Leader	0.16	0.03
Ship Operator 8	10	16	Follower	0.07	0.46

5.4.1.2.1 Sensitivity analysis of substitution ratio

Figure 5.2 and Figure 5.3 present the results of ship operators' adoption time and corresponding leadership or followership decisions at different substitution ratios (β).

At first, a special case is analysed when there is no penalty on followers (i.e., $\beta = 0$). The Nash equilibrium of the special case shows that ship operators 1-6 would adopt the blockchain system immediately. This indicates that without externalities like the substitution policy, ship operators with leadership blockchain cost-effectiveness are self-motivated to adopt blockchain and their optimal adoption time is not sensitive to β. But for ship operators who are lack of self-motivation, i.e., followers when $\beta = 0$, their optimal adoption time would increase in β until a critical point (β_i^*) is reached beyond which they would adopt blockchain within the cut-off time. This suggests that a severe enough substitution ratio (i.e., $\beta \geq \beta_i^*$) could force a follower to become a leader, like the case of ship operators 7 and 8 ($\beta_7^* = 0.03$ and $\beta_8^* = 0.46$).

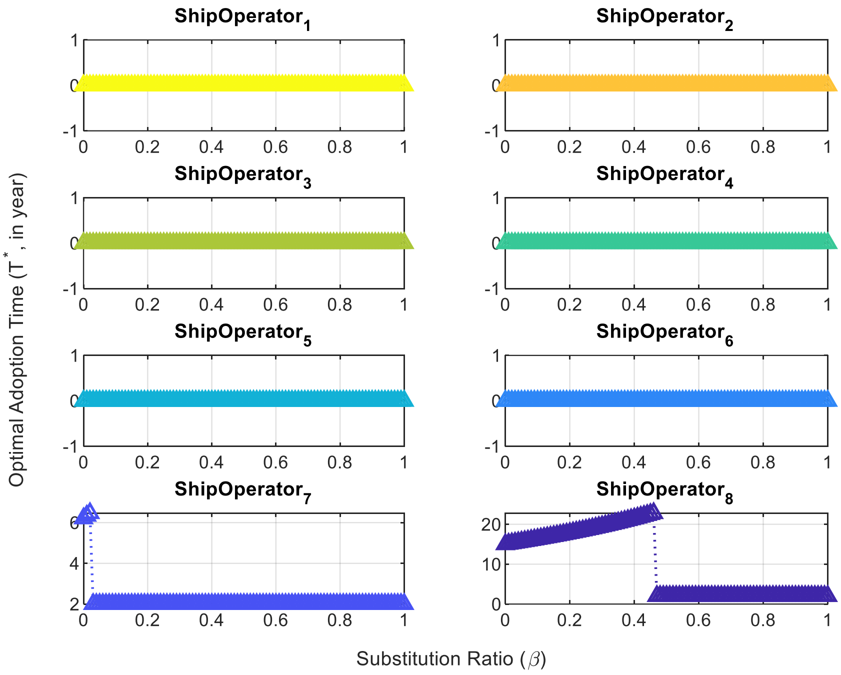

Figure 5.2 Sensitivity of optimal adoption time to substitution ratio.

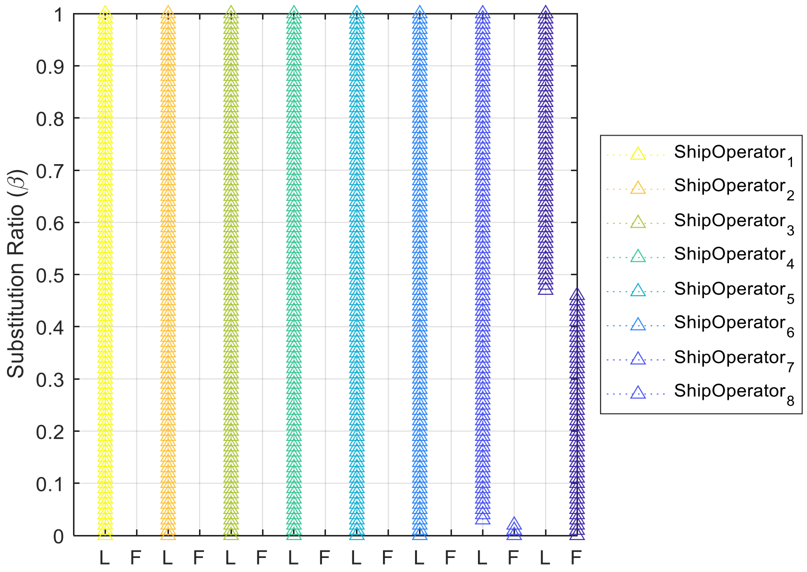

Figure 5.3 Sensitivity of leadership (L) or followership (F) decisions to substitution ratio.

5.4.1.2.2 Sensitivity analysis of shipper's cut-off time

Figure 5.4 and Figure 5.5 show the impact of cut-off time (T_c) on ship operators' strategies on optimal adoption time and corresponding leadership or followership decisions. The results indicate that the adoption strategies are generally not sensitive to cut-off time for ship operators that are leaders when $T_c = 0$. The intuitive explanation is that if ship operators are willing to adopt blockchain early at the strictest time condition (i.e., $T_c = 0$), they are highly likely to do so too at a looser condition (i.e., $T_c > 0$). However, for ship operators that are followers when $T_c = 0$, the increase of cut-off time could induce them to convert to leaders if a threshold $T_c^{i^*}$ is reached like the case of ship operators 7 and 8 ($T_c^{7^*} = 0.92$ and $T_c^{8^*} = 11.42$). Therefore, increasing T_c beyond a certain level can promote blockchain adoption among small ship operators that are followers when $T_c = 0$.

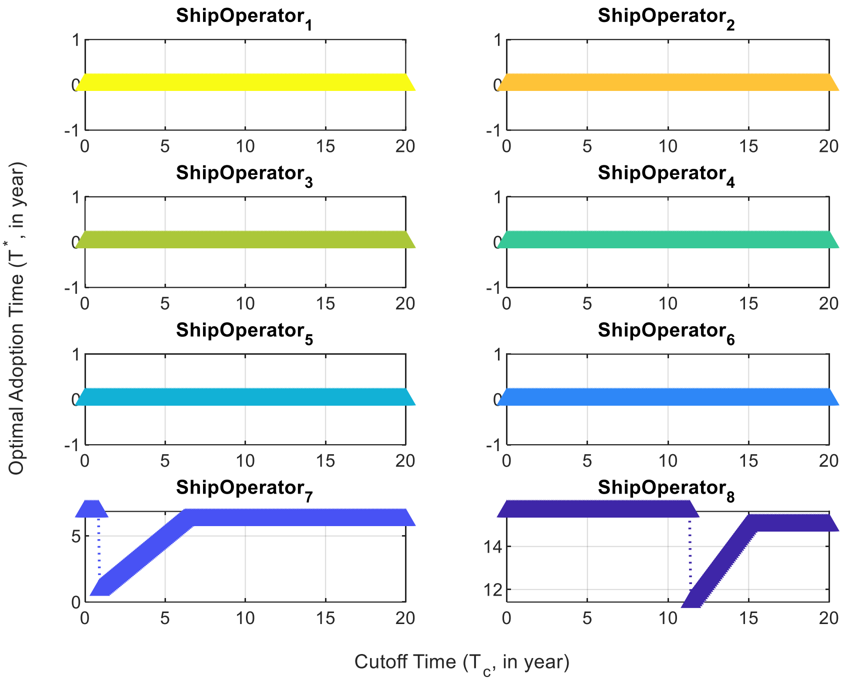

Figure 5.4 Sensitivity of optimal adoption time to cut-off time.

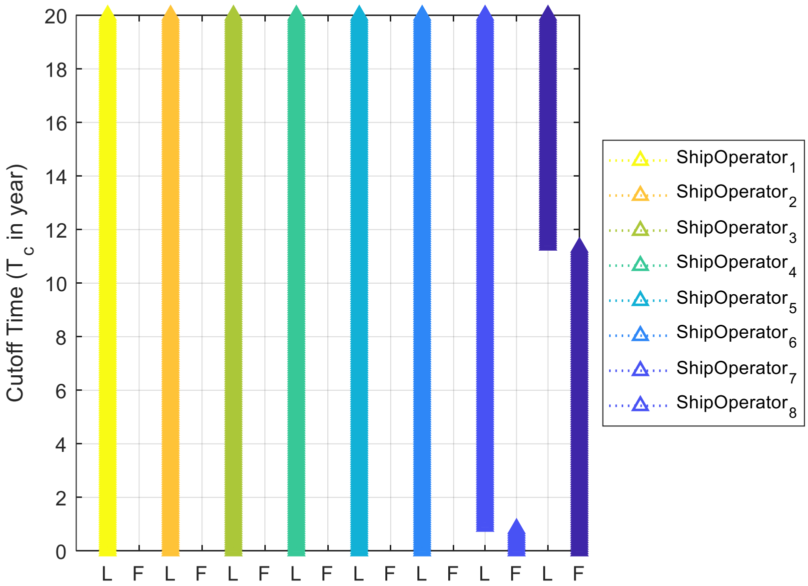

Figure 5.5 Sensitivity of leadership (L) or followership (F) decisions to cut-off time.

5.4.1.2.3 Sensitivity analysis of blockchain benefits

Figure 5.6, Figure 5.7 and Figure 5.8 depict the sensitivity of adoption time to parameters which determine blockchain benefits, namely reduced verification efforts (e_i), cargo value (v) and probability of BL fraud (θ). An overall trend is that the larger these parameters, the earlier the optional adoption time. This can be explained by the intuition that companies would like to adopt a technology faster if its benefits are more significant. In addition, smaller ship operators (like ship operators 5-8) are generally more sensitive to e_i, v and θ than bigger ship operators (like ship operators 1-4). For instance, small ship operators would adopt blockchain early if e_i is big, but may not do so if e_i is small. However, big ship operators would always adopt blockchain early even if e_i is small because they can obtain enough savings from reduced BL fraud due to their large shipping volume.

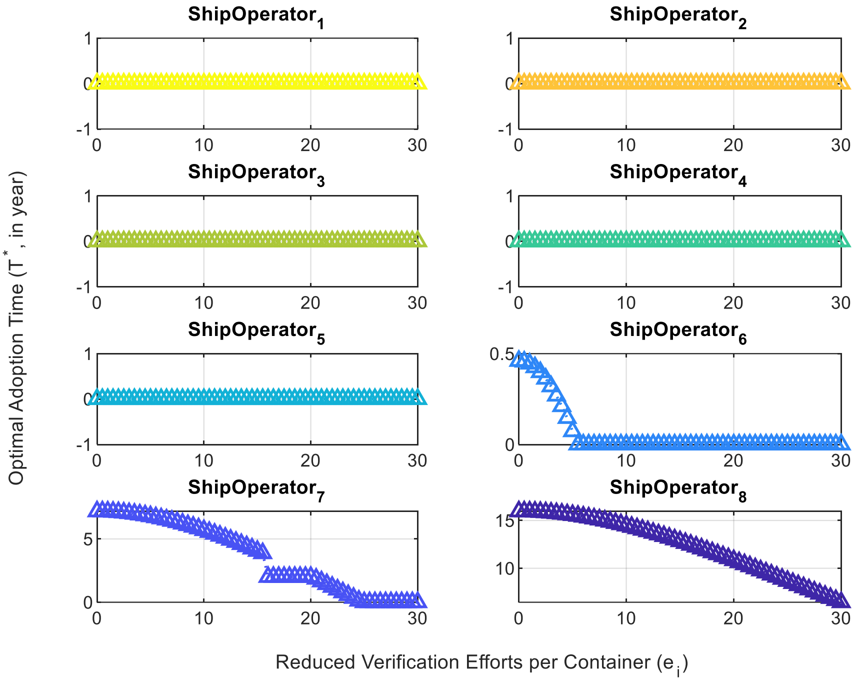

Figure 5.6 Sensitivity of optimal adoption time to reduced verification efforts.

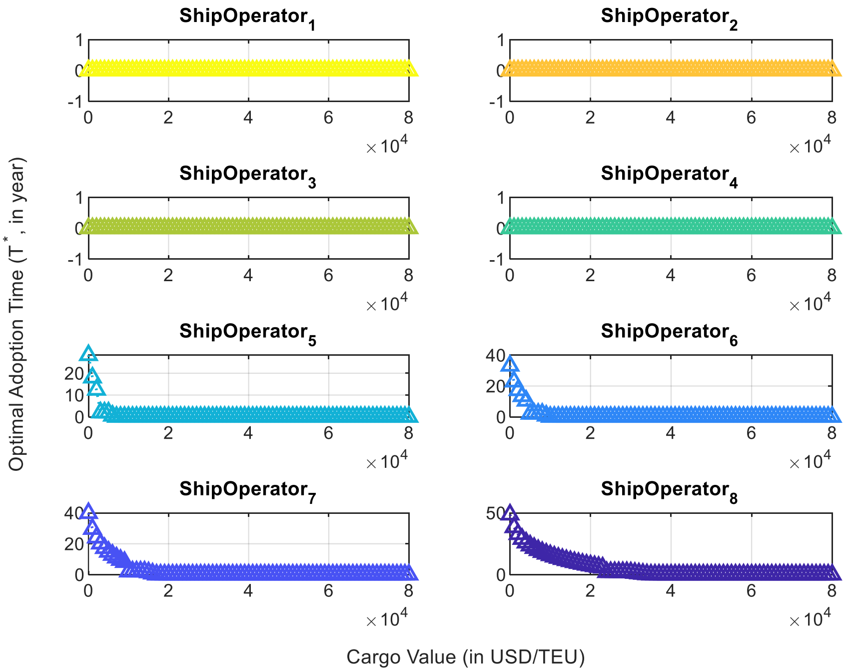

Figure 5.7 Sensitivity of optimal adoption time to cargo value.

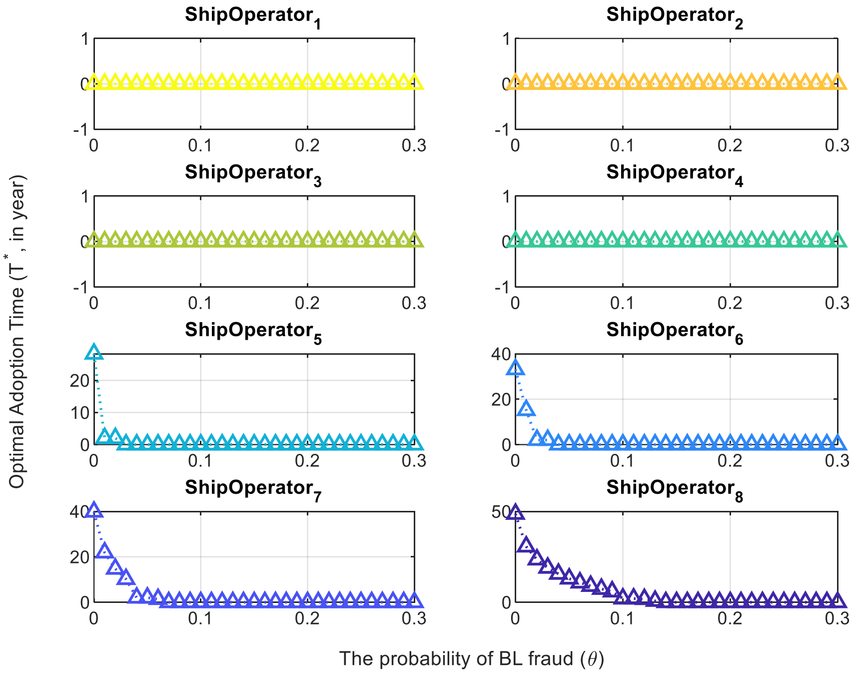

Figure 5.8 Sensitivity of optimal adoption time to probability of BL fraud.

5.4.2 The extended model 1

5.4.2.1 Numerical setting

In order to be comparable to the base model, the extended model sets the fixed annual fee (C_i^a) and unit variable fee (C_i^b) of the blockchain system in a way that the yearly total costs of all ship operators are the same in both models. As such, by assuming the fixed annual fee being US$2000, the unit variable price of using blockchain is 1.7538 US$/TEU. Other parameters are the same as the base model application.

5.4.2.2 Result analysis

This section discusses the numerical results of the extended model and sensitivity analysis of different parameters. Table 5.7 shows the Nash equilibrium of the extended model. Blockchain becomes cost-effective for all ship operators and they would adopt blockchain immediately after the shipper's announcement. This indicates that a mixed pricing structure of blockchain is more suitable than a fixed pricing structure for accelerating blockchain adoption as it allows more companies especially small ones to enjoy blockchain cost-effectiveness.

Table 5.7 Nash equilibrium of the extended model 1.

Ship Operators	Shipping Volume (TEU)	Blockchain Cost-effectiveness	T_i^* (in year)	s_i^*	Net Payoff (in million USD)
Ship Operator 1	30000	Yes$^{\#}$	0	Leader	353.44
Ship Operator 2	10000	Yes	0	Leader	117.80
Ship Operator 3	5000	Yes	0	Leader	58.89
Ship Operator 4	500	Yes	0	Leader	5.87
Ship Operator 5	50	Yes	0	Leader	0.57
Ship Operator 6	34	Yes	0	Leader	0.38
Ship Operator 7	20	Yes	0	Leader	0.21
Ship Operator 8	10	Yes	0	Leader	0.10

Notes: $^{\#}$Yes means that the corresponding ship operator has both leadership and followership blockchain cost-effectiveness.

5.4.2.2.1 Sensitivity analysis of substitution ratio, cut-off time and reduced verification efforts

Figure 5.9, Figure 5.10 and Figure 5.11 reveal that all ship operators would always adopt blockchain immediately regardless of the changes of substitution ratio, cut-off time and reduced verification efforts. This has two implications. First, substitution policy is not necessary in the extended model 1 since the adoption decisions are not sensitive to the policy (i.e., substitution ratio and cut-off time). This suggests that shippers with smaller bargaining power can also invite their shipping vendors to adopt blockchain without a substitution policy. A good adoption rate can still be expected if the blockchain benefits are well known by the shipping vendors. Second, the insensitivity of optimal adoption time to these parameters means that the adoption of blockchain is more robust with a mixed pricing structure than a fixed pricing structure.

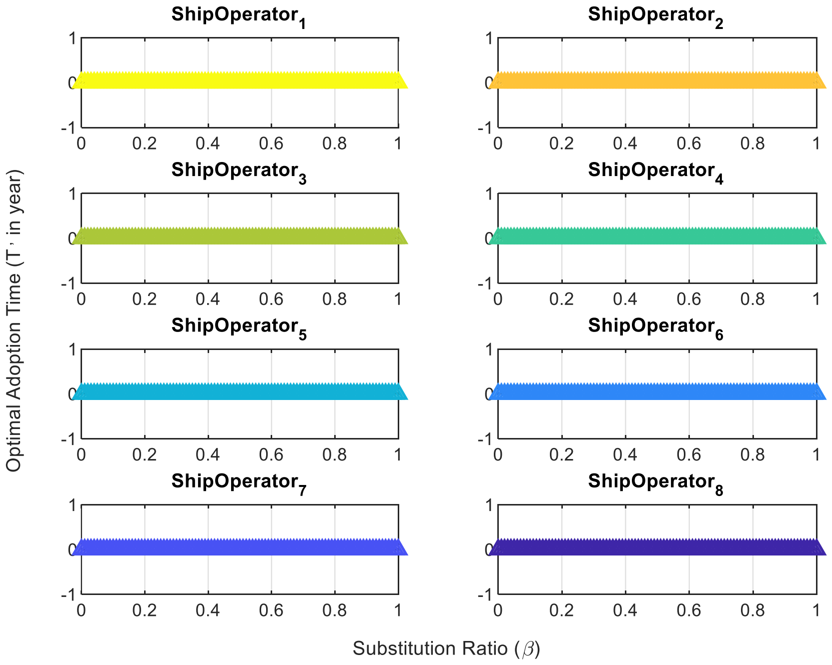

Figure 5.9 Sensitivity of optimal adoption time to substitution ratio in extended model 1.

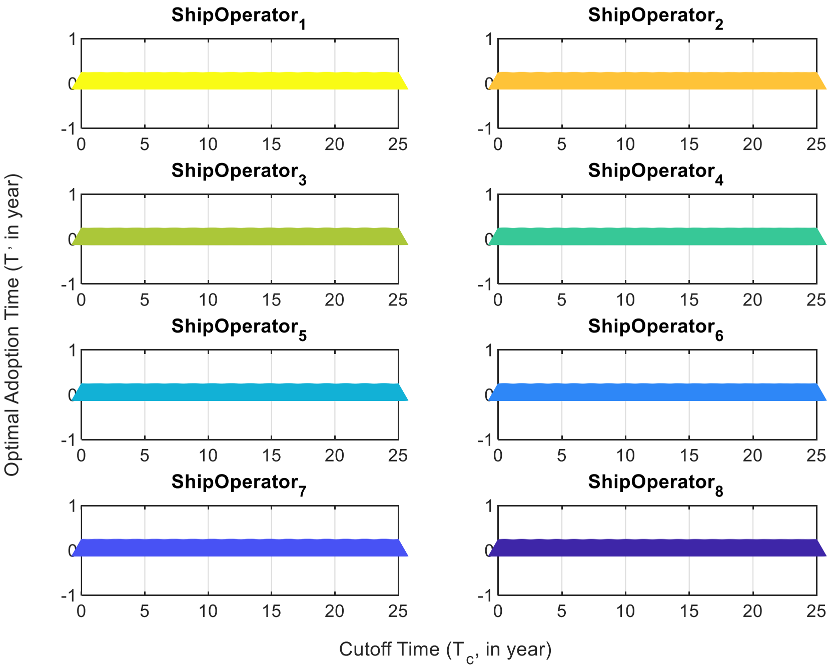

Figure 5.10 Sensitivity of optimal adoption time to cut-off time in extended model 1.

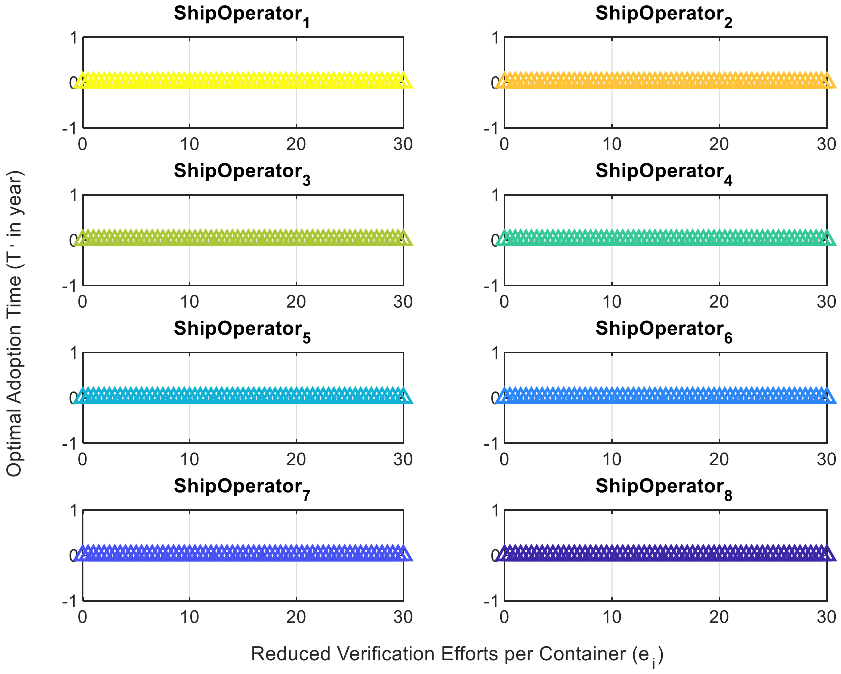

Figure 5.11 Sensitivity of optimal adoption time to reduced verification efforts in extended model 1.

5.4.2.2.2 Sensitivity analysis of cargo value and probability of BL fraud

Figure 5.12 and Figure 5.13 show the sensitivity of optimal adoption time to cargo value and probability of BL fraud in the extended model. The result shows that ship operators are generally less sensitive to the two parameters when compared with the base model. This suggests that a more robust blockchain adoption decision can be achieved when a mixed pricing structure is applied. In addition, at the same level of cargo value or probability of BL fraud, the optimal adoption time of ship operators in the extended model is shorter than or at least equal to that in the base model. In these regards, a mixed pricing structure is more suitable than a fixed pricing structure to promote blockchain adoption.

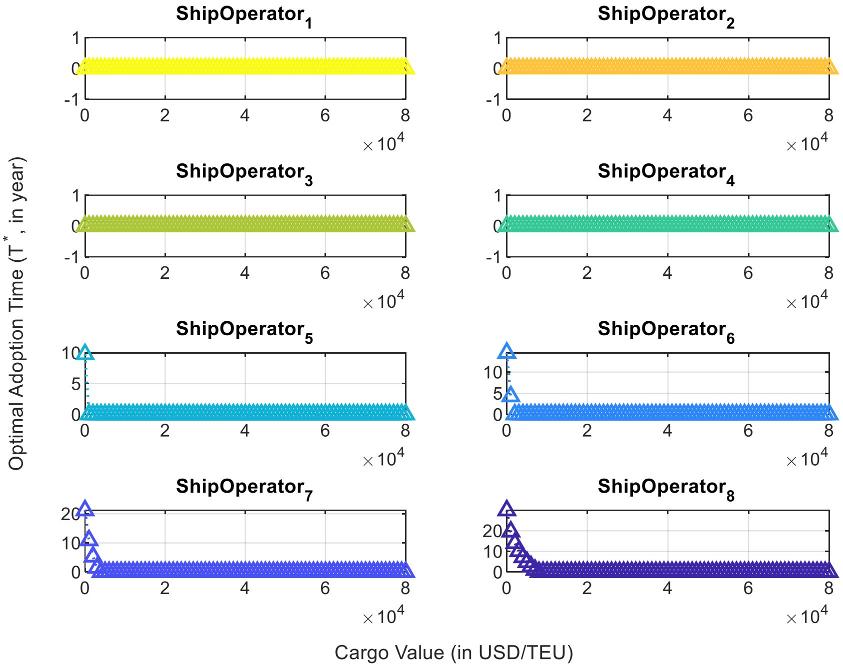

Figure 5.12 Sensitivity of optimal adoption time to cargo value in extended model 1.

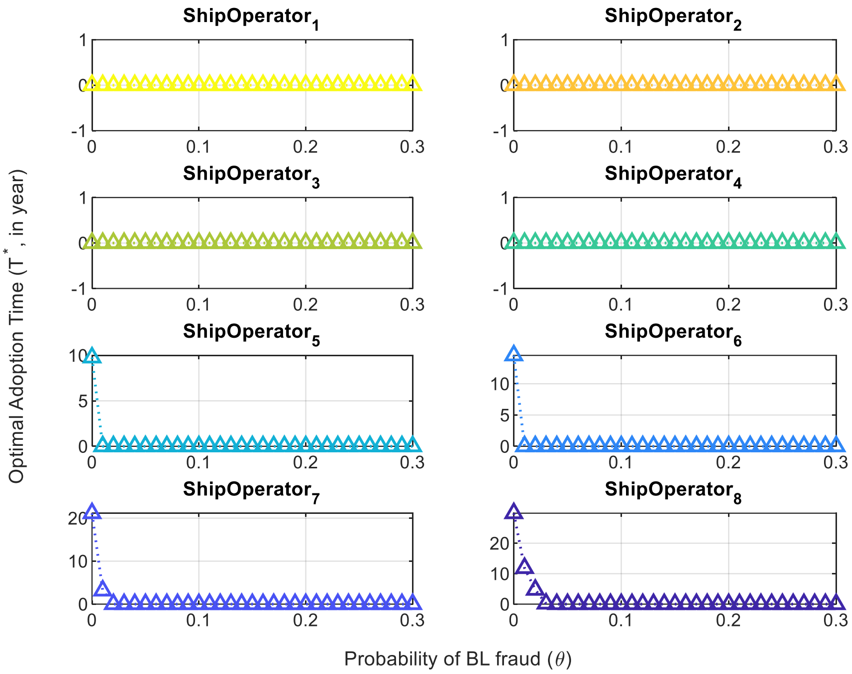

Figure 5.13 Sensitivity of optimal adoption time to probability of BL fraud in extended model 1.

5.4.3 The extended model 2

5.4.3.1 Numerical setting

In order to compare the impacts of an exogenous disruption at different pricing structures of blockchain, this section considers both fixed and mixed pricing structures using the base model and the extended model 1 as references, respectively. The outbreak of Covid-19 is used as an example. McKinsey (2020) estimates that it is most likely to take about 3 years to reach full US GDP recovery after Covid-19. Affected by Covid-19, there is an increase in container freight rate and hence profit margin for ship operators. According to Maersk's annual report (2021), its profit margin in 2020 increased by about 45% from 2019. Based on the bills of lading data from Bloomberg database, the shipping quantity from Shanghai to Los Angeles (the trading route selected for the numerical application) reduced by about 20% in the first half year of 2020 compared with the same period of 2019. The shipping volume has gradually recovered in the second half year of 2020. Hence, we set $T_s = 3,\ \phi = 1.45,$ and $\delta = -20\%$, where δ is set on a conservative basis. In addition, the additional perceived benefit of blockchain per shipping quantity ω is assumed to be

USD120/TEU due to unavailable market data. Other parameters are the same as the corresponding reference model so that the results with and without Covid-19 are comparable.

5.4.3.2 Result analysis

This section discusses the numerical results of the extended model 2, the impact of misestimation in the disruption period and sensitivity analysis of different parameters.

Table 5.8 shows the Nash equilibrium of extended model 2. Under a fixed pricing structure, only one ship operator (ship operator 8) would adopt blockchain later than the cut-off time. Under a mixed pricing structure, all ship operators would adopt blockchain immediately after the shipper's announcement. By comparing the results with those in the corresponding reference model (i.e., fixed pricing in extended model 2 vs the base model and mixed pricing in extended model 2 vs extended model 1), the impact of Covid-19 can be observed. The result shows that Covid-19 does not affect ship operators' optimal adoption time of blockchain in the case under both fixed and mixed pricing structures. It is also noted that Covid-19 generally increases the net payoffs of ship operators. This is mainly due to the increased profit margin and additional perceived benefits of blockchain as a consequence of Covid-19.

Table 5.8 Nash equilibrium of extended model 2.

Ship Operators	New Shipping Volume during the Disruption (TEU)	Fixed Pricing of Blockchain			Mixed Pricing of Blockchain		
		T_i^* (in year)	s_i^*	Net Payoff (in million USD)	T_i^* (in year)	s_i^*	Net Payoff (in million USD)
Ship Operator 1	24000	0	Leader	366.24	0	Leader	365.97
Ship Operator 2	8000	0	Leader	122.02	0	Leader	121.98
Ship Operator 3	4000	0	Leader	60.97	0	Leader	60.98
Ship Operator 4	400	0	Leader	60.17	0	Leader	60.78
Ship Operator 5	40	0	Leader	0.52	0	Leader	0.59
Ship Operator 6	27	0	Leader	0.33	0	Leader	0.39
Ship Operator 7	16	2	Leader	0.16	0	Leader	0.22
Ship Operator 8	8	16	Follower	0.07	0	Leader	0.10

5.4.3.2.1 The impact of misestimating disruption period

While the impact of Covid-19 on container shipping in terms of profit margin and shipping quantities can be observed from the shipping market, the disruption period remains uncertain and has to be estimated. In this section, we focus on the misestimation of the disruption period. For each problem instance, it is assumed that the actual disruption period would last 3 years after the launch of shipper's blockchain initiative. All ship operators are assumed to have the same estimated disruption period, which could differ from the actual one by as much as ±50%. The actual and estimated blockchain adoption time is then calculated. The impact of misestimating the disruption impact duration can therefore be measured by the percentage change in blockchain adoption time. A full-factorial study is conducted for the parameters provided in Table 5.9.

Table 5.9 Parameter value used in the misestimation analysis.

Parameter	Value used in the study				
Percentage change in shipping quantities, δ	-40%	-20%	0	20%	40%
Scaling parameter of profit margin, ϕ	0.85	1.05	1.25	1.45	1.65
Additional perceived benefits of blockchain per unit shipping quantity, w	80	100	120	140	160

Table 5.10 presents the change in each ship operator's optimal adoption time of blockchain due to misestimation of disruption period. The overall results suggest that the model is robust to the parameter misestimation. Misestimation generally does not affect ship operator's blockchain adoption time except for ship operator 8, whose blockchain adoption time is reduced by as high as 90% (equivalent to 1.9 years) when the disruption period is underestimated. This indicates that for very small ship operators, underestimation could have a more significant impact on blockchain adoption time than overestimation. It is hence recommended that very small ship operators should be more conservative in estimating the disruption period to reduce the impact of misestimation of disruption period.

Table 5.10 Average and biggest percentage change in optimal blockchain adoption time due to misestimation of disruption period

	Estimation error										
	-50%	-40%	-30%	-20%	-10%	0%	10%	20%	30%	40%	50%
Ship operator 1											
Average	0	0	0	0	0	0	0	0	0	0	0
Biggest	0	0	0	0	0	0	0	0	0	0	0
Ship operator 2											
Average	0	0	0	0	0	0	0	0	0	0	0
Biggest	0	0	0	0	0	0	0	0	0	0	0
Ship operator 3											
Average	0	0	0	0	0	0	0	0	0	0	0
Biggest	0	0	0	0	0	0	0	0	0	0	0
Ship operator 4											
Average	0	0	0	0	0	0	0	0	0	0	0
Biggest	0	0	0	0	0	0	0	0	0	0	0
Ship operator 5											
Average	0	0	0	0	0	0	0	0	0	0	0
Biggest	0	0	0	0	0	0	0	0	0	0	0
Ship operator 6											
Average	0	0	0	0	0	0	0	0	0	0	0
Biggest	0	0	0	0	0	0	0	0	0	0	0
Ship operator 7											
Average	0	0	0	0	0	0	0	0	0	0	0
Biggest	0	0	0	0	0	0	0	0	0	0	0
Ship operator 8											
Average	-8.2%	-8.2%	-0.7%	0	0	0	0	0	0	0	0
Biggest	-90.9%	-90.9%	-90.9%	0	0	0	0	0	0	0	0

5.4.3.2.2 Sensitivity analysis of disruption related parameters

Figure 5.14 - Figure 5.17 present the sensitivity of optimal adoption time to disruption related parameters under mixed and fixed pricing of blockchain. These parameters include disruption period T_s, percentage change in shipping quantities δ, additional perceived benefit of blockchain per unit shipping quantity ω, and scaling parameter of business profit flow ϕ.

Under mixed pricing of blockchain, ship operators' optimal adoption time is the most sensitive to shipping quantities, compared with other disruption-related parameters. If ship operators' shipping quantities are reduced to a large extent (about 40%-100%), their optimal adoption time of blockchain will be delayed until the pandemic period is over. In contrast, their optimal adoption time of blockchain remains the same in general, when changes happen in each of the other three disruption-related parameters, respectively. Therefore, with a mixed pricing structure of blockchain, the impact of a disruption on ship operators' blockchain adoption time is mainly manifested through its impact on shipping quantities.

Under fixed pricing of blockchain, the blockchain adoption time of small ship operators appears more sensitive to disruption related parameters than big ship operators. For instance, the adoption time of ship operators 5-7 changes with shipping quantities, while the adoption time of big ship operators 1-4 will only change if their shipping quantities are reduced by 100%. When ω is less than 100, the optimal adoption time of ship operators 6 and 7 increases with ω , while bigger ship operators are insensitive to ω. When ϕ is less than 1.3, ship operator 7 will delay its adoption time, while the adoption time of other ship operators remains the same regardless of the change in ϕ. Among those small ship operators, ship operator 8 the smallest ship operator is relatively insensitive to disruption-related parameters than others. This may be because its shipping quantity is too small so that blockchain adoption is always unattractive to it unless the disruption could bring tremendous changes to it (e.g., more than 115% increase in shipping quantities as shown in Figure 5.15). The results indicate that small ship operators' blockchain adoption time is generally more sensitive to the Covid-19 disruption than that of big operators, under fixed pricing of blockchain.

When comparing the two pricing structures, it is noted that ship operators appear more insensitive to disruption related parameters under a mixed pricing structure than under a fixed pricing structure. Under a mixed pricing structure, the variation in blockchain adoption time is narrower and the adoption time is not sensitive in a wider range of disruption related parameters. This implies that in view of Covid-19, a mixed pricing structure provides blockchain better resilience to the disruption as ship operators' optimal adoption time of blockchain is not significantly affected by the severity of the disruption.

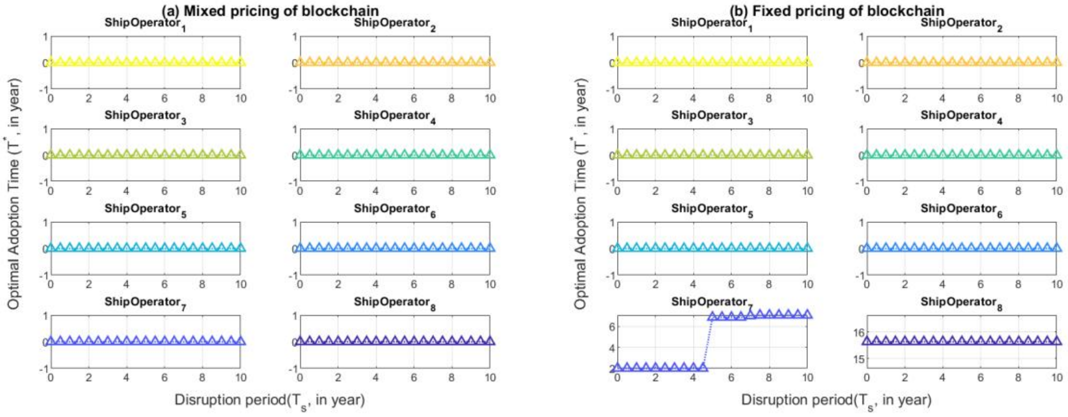

Figure 5.14 Sensitivity of optimal adoption time to disruption period.

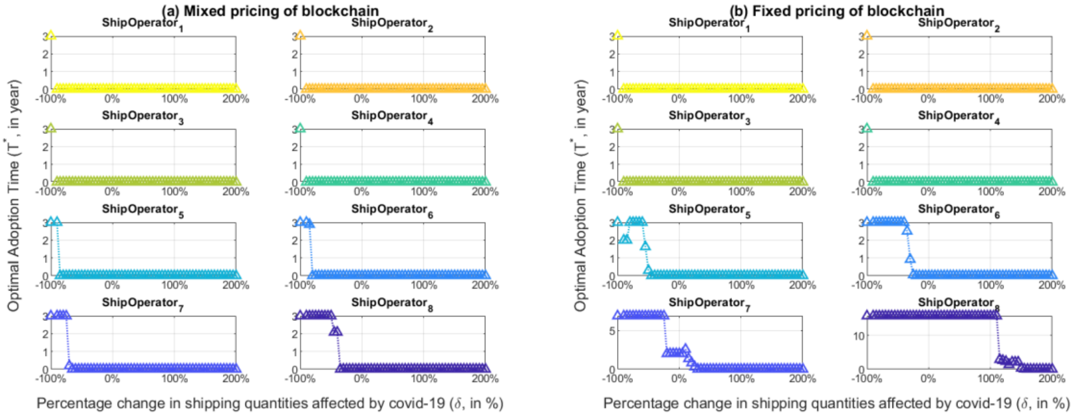

Figure 5.15 Sensitivity of optimal adoption time to percentage change in shipping quantities caused by Covid-19.

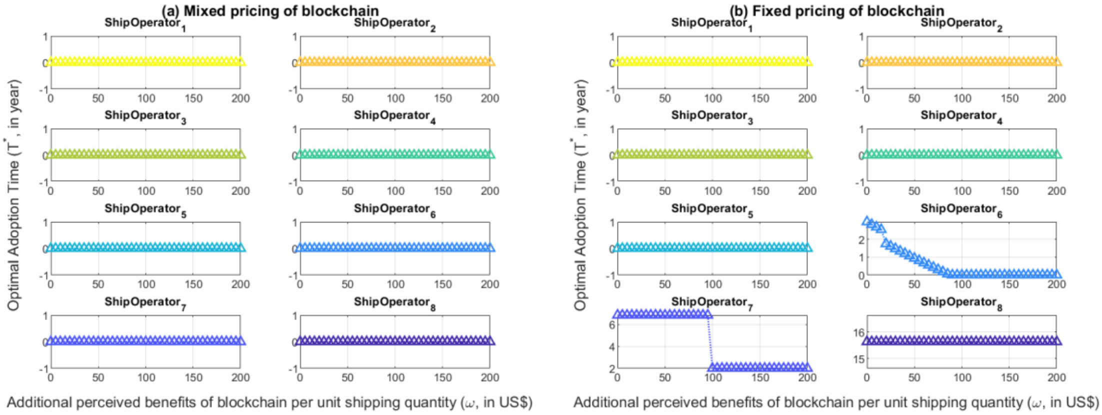

Figure 5.16 Sensitivity of optimal adoption time to additional perceived benefit of blockchain per unit shipping quantity.

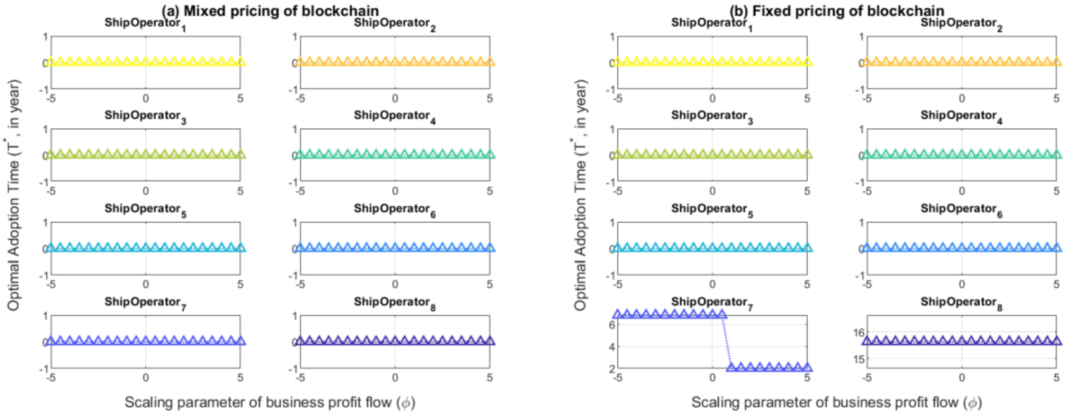

Figure 5.17 Sensitivity of optimal adoption time to scaling parameter of business profit flow.

5.4.3.2.3 Sensitivity analysis of non-disruption related parameters

This section analyses the sensitivity of ship operators to non-disruption related parameters regarding when to adopt blockchain, illustrated in Figure 5.18 - Figure 5.22. These parameters include cargo value V, probability of BL fraud θ, reduced verification efforts e_i, substitution ratio β and cut-off time T_c.

Comparison between mixed pricing and fixed pricing

By comparing the difference in sensitivity results between mixed pricing and fixed pricing, two key observations are worth highlighting. Firstly, ship operators under mixed pricing are less sensitive to these non-disruption related parameters than under fixed pricing. This can be reflected in three ways: 1) There are more ship operators who are not sensitive to these parameters under mixed pricing than under fixed pricing. 2) For the same ship operator, the variation in blockchain adoption time is narrower under mixed pricing. 3) For the same ship operator, there is a wider parameter range under mixed pricing where its blockchain adoption time is not sensitive. Secondly, the adoption time of ship operators under mixed pricing is generally shorter than that under fixed pricing for the same parameter value. These observations affirm the advantages of a mixed pricing structure for blockchain as it ensures an earlier adoption of the technology and provides better robustness of such a decision considering changes in non-disruption related parameters.

Impact of Covid-19

Under a mixed pricing structure, the impact of Covid-19 can be observed by comparing the results in extended model 2 (with Covid-19) and the extended model 1 (without Covid-19). Significant differences are observed when there are changes in cargo value V or probability of BL fraud θ. At the same level of V or θ, the blockchain adoption time of ship operators 5-8 with Covid-19 is generally earlier than that without Covid-19 when the parameter value is very small. The results indicate that for small ship operators, Covid-19 has a positive impact on accelerating blockchain adoption when V or θ is small.

Under a fixed pricing structure, the impact of Covid-19 can be observed by comparing the results in extended model 2 (with Covid-19) and the base model (without Covid-19). The result shows that Covid-19 has a mixed impact on blockchain adoption time of small ship operators. For instance, Covid-19 could cause a reduction in blockchain adoption time for ship operator 5 when $V \in [3000,7000]$ and for ship operator 6 when $e_i \in [0,5.5]$. It could also cause an increase in blockchain adoption time for ship operator 7 when $e_i \in [0,7] \cup [19.5, 26.5], \beta \in [0.02, 0.05]$ or $T_c \in [0.83, 2.08]$, and for ship operator 8 when $V \in [23000, 40000], \theta \in [0.09, 0.16]$, $\beta \in [0.46, 0.53]$, $T_c \in [11.33, 13.08]$. There are more scenarios where Covid-19 could have a negative effect instead of a positive effect on accelerating blockchain adoption when a fixed pricing scheme is applied.

The analysis shows that small ship operators' blockchain adoption time could be affected differently by Covid-19 under the two pricing structures of blockchain. Under a mixed pricing structure Covid-19 generally has a positive impact on accelerating blockchain adoption when cargo value and probability of BL fraud are low. However, under a fixed pricing structure Covid-19 has a mixed effect on accelerating blockchain adoption with a negative effect being observed in more scenarios. The results again suggest that blockchain developers should employ a mixed pricing structure in the context of Covid-19 to better advance blockchain adoption.

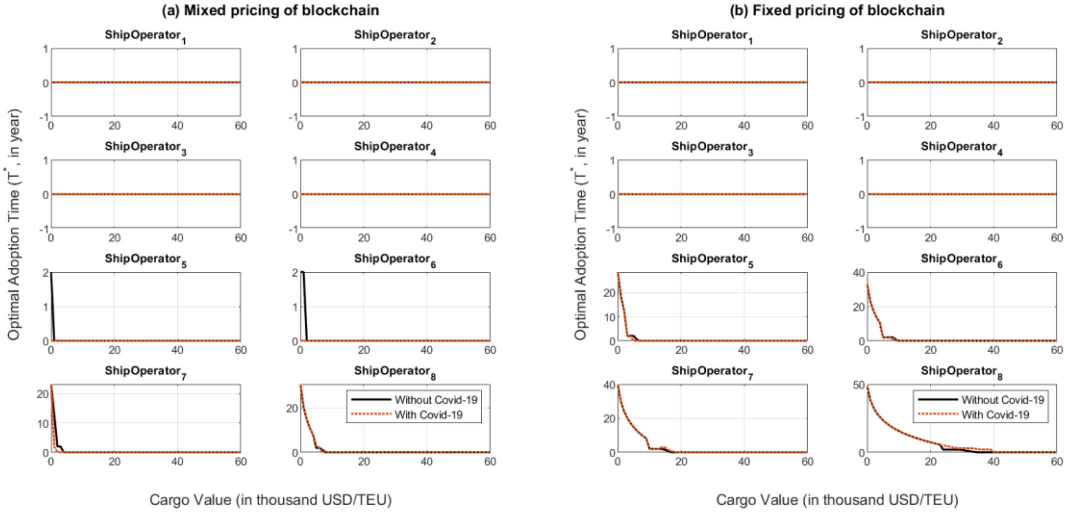

Figure 5.18 Sensitivity of optimal adoption time to cargo value with and without Covid-19.

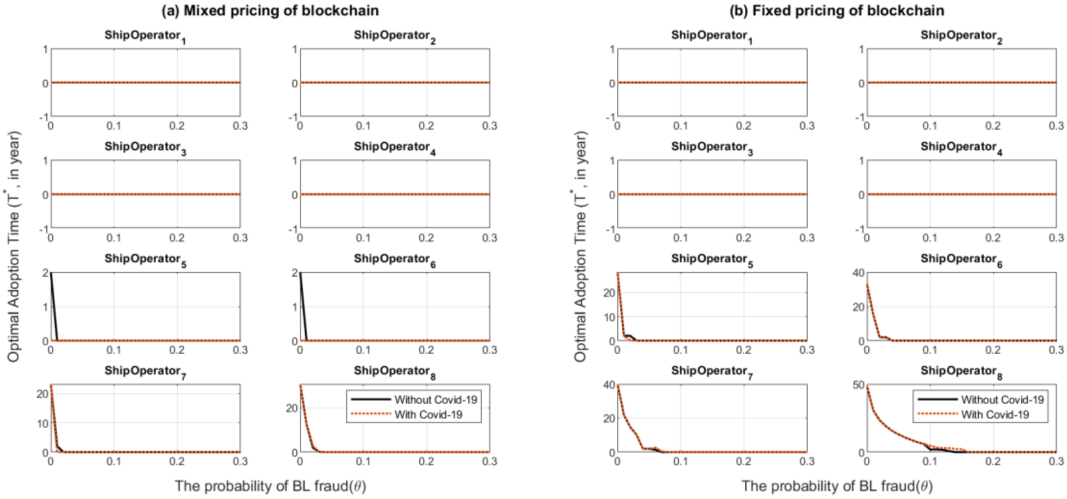

Figure 5.19 Sensitivity of optimal adoption time to the probability of BL fraud with and without Covid-19.

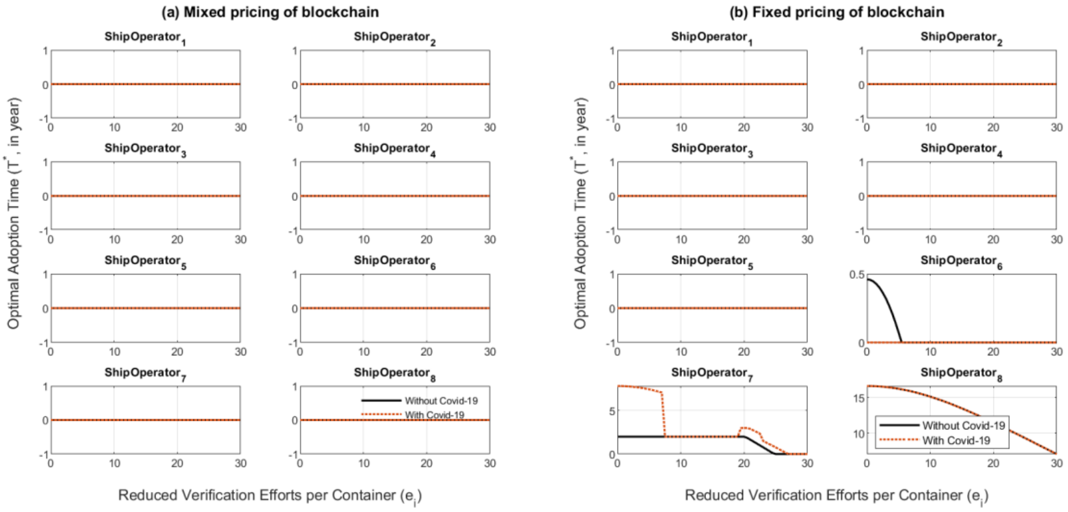

Figure 5.20 Sensitivity of optimal adoption time to reduced verification efforts with and without Covid-19.

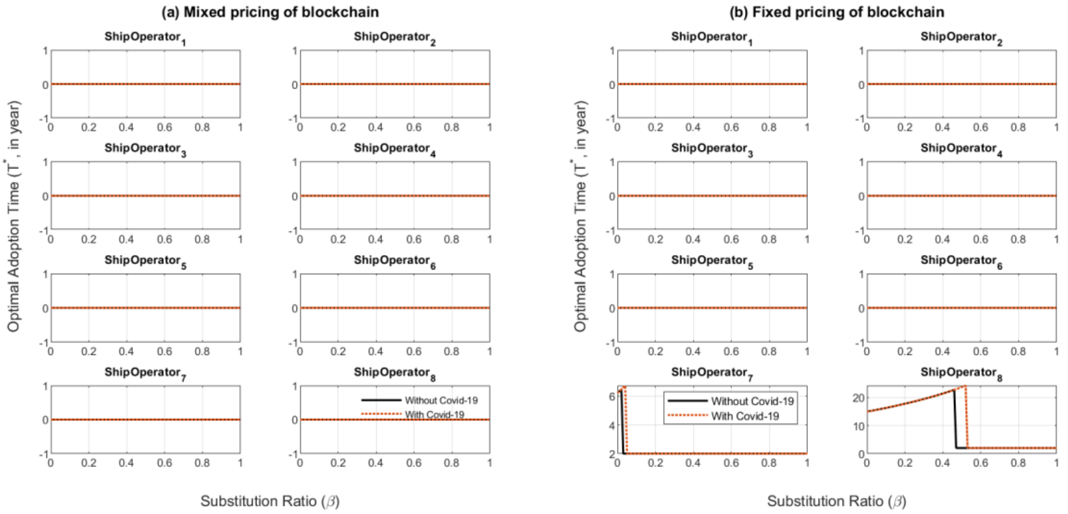

Figure 5.21 Sensitivity of optimal adoption time to substitution ratio with and without Covid-19.

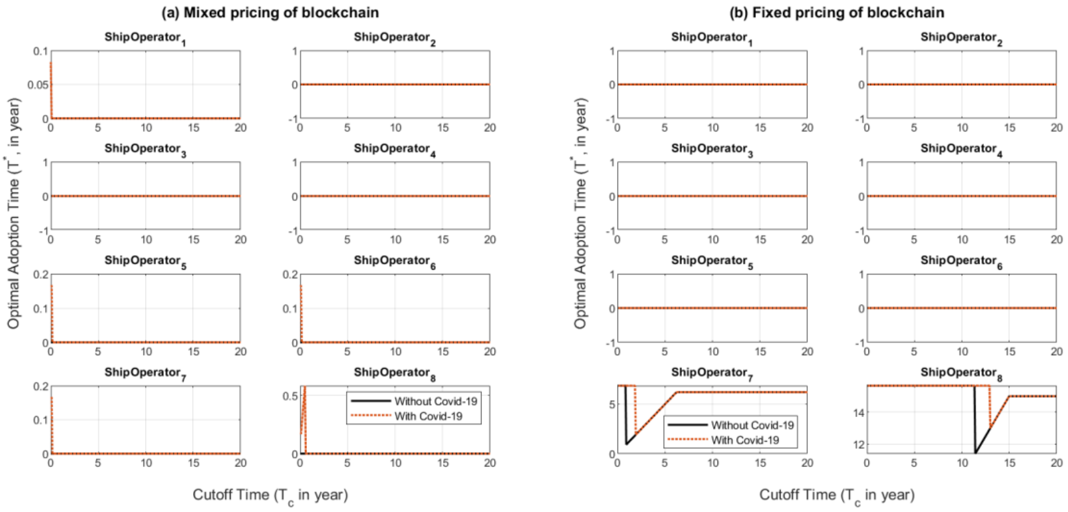

Figure 5.22 Sensitivity of optimal adoption time to cut-off time with and without Covid-19.

5.5 Implications

The results above have several implications for facilitating blockchain adoption from five perspectives: 1) substitution policy, 2) blockchain cost-effectiveness, 3) pricing strategy of blockchain, 4) impact of Covid-19 and 5) knowledge of blockchain.

The substitution policy from a big shipper, including a substitution ratio and cut-off time, is only effective to small ship operators under a fixed pricing model of blockchain. Big ship operators are self-motivated to adopt blockchain regardless of the substitution ratio and cut-off time. Imposing a higher substitution ratio or a longer cut-off time can induce small ship operators to join the blockchain network earlier. However, the two factors need to exceed a threshold to be effective in promoting blockchain adoption among small ship operators.

An intrinsic factor driving the adoption of blockchain among companies is its cost-effectiveness. Only when the cost-effectiveness is low, externalities like substitution policies may be needed to influence the adoption decisions. However, these policies are only effective when adopted by large customers with strong bargaining power. Therefore, blockchain initiators should not heavily rely on externalities to promote blockchain adoption. Instead, they should focus more on ways to improve the cost-effectiveness of the technology.

For blockchain developers, the pricing strategy of blockchain could affect the adoption decisions of potential users. Our analysis suggests that a mixed pricing structure is better than a fixed pricing structure in facilitating blockchain adoption in four ways. Firstly, with a mixed pricing structure, blockchain is cost-effective to more companies especially small-sized companies. Secondly, substitution policy is not necessary under a mixed pricing structure as the adoption time is not sensitive to the policy in this case. It implies that companies with smaller bargaining power can also invite their vendors to adopt blockchain without any substitution policy and expect a good adoption rate. Thirdly, under the same condition (e.g., the same cargo value or probability of BL fraud), a company's optimal adoption time with a mixed pricing structure is shorter than or at least equal to that with a fixed pricing structure. Lastly, a mixed pricing structure provides blockchain better resilience to an exogenous disruption in the way that potential users always have an earlier adoption time of blockchain and are less sensitive to changes in disruption and non-disruption related parameters under mixed pricing than fixed pricing. Hence, blockchain developers should consider employing a mixed pricing structure to better promote blockchain adoption.

Covid-19 has a positive effect on ship operators to accelerate blockchain adoption under a mixed pricing structure of blockchain. The effect can be seen for small ship operators and when blockchain benefits are low. This is because the additional blockchain benefits and increased profit margin caused by Covid-19 make an earlier blockchain adoption more affordable for small ship operators. It is noted that when blockchain benefits are high, the adoption time of ship operators is already at time 0. Hence, Covid-19 could not further hasten the blockchain adoption time of big ship operators who usually enjoy high blockchain benefits due to large shipping quantities. This study provides a positive signal to blockchain promoters or developers that more small potential maritime users would become willing to adopt blockchain earlier due to the Covid-19 pandemic, if a proper pricing structure (i.e., mixed pricing structure) is employed. The positive impact of Covid-19 to forward blockchain adoption has also been observed in other industries (Hoek and Lacity, 2020). Many blockchain initiatives and applications were launched and adopted particularly to address the problems amplified by the pandemic. Therefore, blockchain promoters or developers should turn the Covid-19 crisis into an opportunity to promote a wider use of blockchain by focusing on the right groups, employing a proper pricing scheme, introducing necessary incentive programmes and developing new use cases to address Covid-19 associated problems.

Our analysis shows a promising future of blockchain adoption in situations where a big customer requests its vendors to use blockchain and its resilience to exogenous disruptions under a mixed pricing structure. However, in real life, not many vendors adopt blockchain in such a case. The difference between the analysis and real-life situation could be because companies do not sufficiently understand blockchain especially about its benefits and how to quantify the benefits. This differs from our model setting where the knowledge of blockchain benefits is available to all players.

Therefore, blockchain promoters including industry initiators, technology developers and governments should endeavour to publicise blockchain benefits in a more quantitative way with specific case studies. Once companies have more concrete knowledge of blockchain benefits, the blockchain adoption rate is expected to increase.

5.6 Conclusion

This study develops a game theoretical model to analyse the optimal adoption time of blockchain for companies using ship operators as a case. A novel algorithm is developed to attain the numerical Nash equilibrium of companies' optimal adoption time. The model is extended with a mixed pricing structure and the impact of an exogenous disruption like Covid-19. The results suggest that substitution policy is only necessary for a fixed pricing structure of blockchain, where it could induce small companies to join the blockchain system earlier by imposing a higher substitution ratio and longer cut-off time. The study also shows that a mixed pricing structure of blockchain is better than a fixed pricing structure to facilitate blockchain adoption in terms of robustness, speed and scope. In addition, blockchain adoption time of ship operators is more resilient to exogenous disruptions such as Covid-19 if a mixed pricing structure is employed. Lastly, our analysis reveals the importance of blockchain cost-effectiveness and knowledge of blockchain for a wider scale of adoption.

CHAPTER 6 ASYMMETRIC EVOLUTIONARY GAME ANALYSIS OF BLOCKCHAIN ADOPTION: A CASE OF ELECTRONIC BILLS OF LADING

This chapter investigates the evolution of blockchain adoption in intelligent transportation systems (ITS) using blockchain electronic bills of lading (eBLs) as an example. An asymmetric evolutionary game model is developed to analyse the co-evolution of players from different populations (carriers and shippers) based on their dynamic interactions. The potential impact of incumbent systems on blockchain adoption in this area is captured by including the paper and electronic data interchange (EDI) systems in the model. The results are analysed in two situations depending on who pays the blockchain eBL transaction fee – carriers or shippers. The results provide practical implications for blockchain promoters and policymakers on how to facilitate and accelerate blockchain adoption.[4]

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[4] The following paper is published based on this chapter:

Pu, S., and Lam, J.S.L. (2017). "Blockchain Adoption in Electronic Bills of Lading: An Evolutionary Game Approach". Proceedings of 10th Asian Logistics Round Table (ALRT) Conference. 618-624.

6.1 Difference between blockchain and EDI eBL

Depending on the supporting technology, eBL systems are classified into two groups: EDI and blockchain. Although EDI eBL systems are able to address the problems of paper BL systems including instant delivery, reduced costs and higher security, the EDI solutions have some limitations and risks. Firstly, Takahashi (2016) and Pagnoni and Visconti (2010) claim that the existing EDI eBL systems are vulnerable to problems of single point of failure, insider fraud, and confidentiality issues. These systems depend on a central party to manage and transmit BLs. All messages are decrypted and read by the central platform before being transferred to the recipient, thus exposed to insider fraud. Thus, even though the BL fraud can be reduced by using EDI eBL systems, it is still possible to happen. Secondly, Takahashi (2016) and Goldby (2008) mention that the close-membership system of the current EDI eBL solutions limits their adoption. In the system, there is a committee to set the membership criteria and determine if an applicant can be approved as a member. Although this is necessary for security, it is disadvantageous to smaller companies. Lastly, Todd (2019) argues that the EDI eBL systems are not a true replacement of the paper BL system because the EDI systems are closed ones while the paper system is an open one.

Blockchain technology, providing a distributed ledger platform with a high level of confidentiality and security, is considered a new promising direction of eBL development (Takahashi, 2016; UK P&I Club, 2017; Saive, 2019; Todd, 2019). It could not only address the limitations and risks of current EDI eBL systems but also provide value-added services which cannot be realised in the current EDI eBL systems. First, being a decentralised system, blockchain has no concerns of single point of failure (Berke, 2017). Even if a node is down, the data is still accessible in a 24/7 manner via other nodes within the network. Then, it could mitigate the risks of insider fraud by providing direct peer to peer transmission without going through a central party (Berke, 2017). Besides, it ensures privacy and confidentiality for users as the blockchain service provider is not the principal of transactions and does not have access to the transaction information (UK P&I Club, 2020). Lastly, blockchain could provide value-added services to improve the efficiency of the whole supply chain through providing real-time cargo information, data transparency and easy verification for external parties. Real-time continuous cargo information (e.g., location and temperature of cargoes) from IoT systems can be fed into the blockchain eBL platform, which is not possible for EDI platforms allowing only discrete information (IBM, 2019). Besides, the information recorded in blockchain is immutable (Berke, 2017) which provides a reliable history of ownership and a trustful source for verification. In addition, due to the features of asymmetric cryptography, the authenticity of documents can be easily verified by any parties without releasing the document information (Christidis and Devetsikiotis, 2016).

Based on the above analysis, the differences among blockchain, EDI and paper BL systems are summarised in Table 6.1. This forms a knowledge base for the payoff calculations of the three BL systems, which will be explained later in Section 6.2.2.

Table 6.1 Comparison of three types of bills of lading systems.

Aspects	Blockchain eBL systems	EDI eBL systems	Paper BL system
Centralised System	Decentralised	Centralised	Decentralised
BL Fraud risks	Very low	Low	High
Cyber risks	No single point of failure	Single point of failure	-
Validation	Multiple sources to validate eBLs	Single central party to validate eBLs	Based on handwriting signature
Confidentiality	Yes	Depends on system design	No
BL charge	Could be lower	Could be lower	Higher
Courier cost	No	No	Yes
Time to transfer title	Instant	Instant	Days or weeks
Requirement for discharging cargoes without original BL	No	No	Sometimes
Value-added services*	Yes	No	No

Notes: the comparison is based on the EDI and blockchain eBL systems approved by the International Group of P&I Clubs by June 2020: EDI-based systems are Bolero, e-title^{TM} and essDOCs; blockchain-based systems are edoxOnline, Wave and CargoX. The results may be different when new systems or new features are added.

*Examples of value-added services provided by blockchain are real-time continuous cargo information, data transparency, and easy verification of external parties.

Source: Compiled by author, based on (Pagnoni and Visconti, 2010; Takahashi, 2016; CargoX, 2018; Economic Commission for Europe, 2019).

6.2 The evolutionary game model

With respect to blockchain adoption, the decision problem of potential users is whether they will be better off with blockchain adoption. The decision problem of blockchain developers is to whom and at what price they should charge to motivate companies to participate in the system. The answers to these problems are dependent on the choices of other sectors, as the strategies of players from different sectors co-evolve under the mutual influence with each other. In this research, eBL is used as a blockchain case to analyse these problems with an evolutionary game model. Since the current blockchain eBL systems approved by P&I Clubs are permissioned blockchain, the blockchain eBL system discussed in the study are assumed permissioned blockchain.

6.2.1 Basic model setup

In a simple BL, typical players are carriers, shippers and receivers, where carrier refers to the owner of a vessel. One set of BLs refers to one shipment. Whenever engaged in a shipment, players in each population can adopt one of the following three BL systems: blockchain eBL system (B), EDI eBL system (E), and the paper BL system (P). The majority of these eBL systems are web-based and hence do not require an initial investment in hardware and software. In practice, only a transaction fee per BL is charged to either carriers or shippers, not receivers. As such, adopting blockchain eBL systems is assessed a dominant strategy for receivers regardless of other populations' strategies because they can always enjoy the additional benefits of blockchain eBLs without incurring investment or transaction costs. Therefore, the BL game is simplified to cover two populations only: carriers and shippers, where a population in this study refers to a group of players playing the same business role.

In the evolutionary game, the BL game is conducted repeatedly by randomly pairing the players from each population and a stable or dynamic state may be reached eventually. The notations of symbols are provided in Table 6.2. A few assumptions are made in this model as follows: 1) players from the same population have the same willingness to pay for the value-added services provided by blockchain. This assumption allows us to focus on the differences among the two populations rather than individuals; 2) the different blockchain eBL systems are treated the same. Similarly, the different EDI eBL systems are also treated the same. The two assumptions allow us to focus on the competition between blockchain and EDI eBL systems; 3) the exogenous scaling parameter to measure the intensity of network effects is the same for all players. This allows us to focus on the differences in companies' willingness to pay for the value-added services of blockchain.

Table 6.2 Notations.

Notations	Definitions
N	Sets of populations. $N=\{\text{carriers}(x),\text{shippers}(y)\}$
i, j	Index of a player from a population, where $i \in N$ and $j \in N \setminus \{i\}$
S	Strategy set, where $S \in \{B, E, P\}$
s_i	A strategy chosen by player i, where $s_i \in S$ and $i \in N$.
$p_i^{s_i}$	The current proportion of population i choosing strategy s_i
θ_b	The probability of encountering BL fraud
V	The total cargo value per BL
a_i	The administrative cost of player i about handling a set of paper BL in a shipment, where $i \in N$
d_i	A binary parameter to indicate if player i needs to pay for the transaction fee of eBL systems, $d_i = 1$ or 0, referring to Yes or No respectively
c_{bl}	Original BL fee which is charged by the carrier to the shipper for issuing one set of paper BL
c_{li}	The costs of player i about preparing and checking LOI for discharging cargoes without original BLs, where $i \in N$
r_i	The willingness of population i to pay for the value-added services provided by blockchain, $r \in [0,1]$
q^{s_i}	The quality level of value-added services provided by strategy s_i, where $s_i \in S$
v_i	Player i's valuation of blockchain's value-added services
e	An exogenous scaling parameter to measure the intensity of network effects
c_{ts_i}	The transaction fee charged by system providers under strategy s_i, where $s_i \in S$
β_B	The percentage reduction in BL fee when blockchain eBL is used
φ_{s_i}	The percentage reduction in the probability of encountering BL fraud when strategy s_i is used

Note: BL – Bills of lading; LOI - Letter of indemnity.

6.2.2 The payoff

A blockchain or EDI eBL system will be used in the shipment if and only if both players choose the same system. For example, blockchain eBLs will be used if and only if both players choose to use the blockchain eBL system. Any mismatch of selected BL systems among the players will lead to the use of paper BL, which is the current norm in the industry. Let $s_x s_y$ denote the final strategy adopted in a BL game under the strategy combination of s_x and s_y. Therefore, $s_x s_y = B$, if $s_x = s_y = B$; $s_x s_y = E$, if $s_x = s_y = E$; $s_x s_y = P$, otherwise.

When formulating the payoff functions, we consider only the revenues and costs affected by using different BL systems because the inclusion of other unaffected revenues or costs has no impact on the results. The payoff to the carrier and the shipper in the BL game can be presented by equations (6.1) and (6.2) respectively:

$$\pi_x(s_x,s_y) = b(s_x,s_y)d_x + v_x(s_x,s_y) - a_x(s_x,s_y) - f(s_x,s_y) - t(s_x,s_y)d_x, \tag{6.1}$$

$$\pi_y(s_x,s_y) = v_y(s_x,s_y) - b(s_x,s_y)(1-d_y) - a_y(s_x,s_y) - t(s_x,s_y)d_y, \tag{6.2}$$

where $b(s_x,s_y)$ denotes the BL fee charged by carriers for a particular pair of strategies. $v_i(s_x,s_y)$ denotes player i's valuation of value-added services. $a_i(s_x,s_y)$ denotes player i's administrative costs of processing paper BLs. $f(s_x,s_y)$ denotes the shipper's expected loss from BL fraud. $t(s_x,s_y)$ denotes the transaction fee of eBL systems charged by eBL service provider. d_i is a binary parameter to indicate if player i needs to pay for the transaction fee of eBL systems. $d_i = 1$ or 0, referring to Yes or No respectively. $d_x + d_y = 1$ because only one player needs to pay the fee based on industry practice.

In practice, the eBL system providers impose a transaction fee on either carriers or shippers. Other parties involved in the shipment can use the system for free. Let $c_{ts_x s_y}$ denote the transaction fee of an eBL when strategies s_x and s_y are used by the two players in the shipment. When paper BLs are used in a shipment, no transaction fee of eBL is incurred, i.e., $c_{tP} = 0$. Based on the currently available market information, among the three EDI eBL systems approved by the International Group of P&I Clubs (IG), only shippers are charged the transaction fee. Among the three blockchain eBL systems approved by IG, two situations exist - either carriers or shippers are charged the transaction fee (UK P&I Club, 2020). Therefore, it is assumed that when an EDI eBL is used, the transaction fee of eBL is paid by shippers only. When a blockchain eBL is used, the transaction fee can be paid by either carriers or shippers. Hence, the transaction fee of eBL systems payable for a particular pair of strategies is given by

$$t(s_x, s_y) = \begin{cases} c_{tB}, \text{ if } s_x = s_y = B \text{ (payable by either carriers or shippers)}, \\ c_{tE}, \text{ if } s_x = s_y = E \text{ (payable by shippers only)}, \\ c_{tP} = 0, \text{ otherwise.} \end{cases} \tag{6.3}$$

In the paper BL system, a carrier imposes a BL fee c_{bl} to a shipper for issuing and releasing original BLs. The fee may be reduced when eBL systems are used. It is assumed that if a shipper already pays the eBL transaction fee to the service provider, it does not need to pay the BL fee to its carrier to avoid double payment. As such, when EDI eBLs are used, shippers do not pay for the BL fee as they pay for the eBL transaction fee already. Let β_B denote the percentage reduction in BL fee when blockchain eBLs are used. Then, the BL fee charged by carriers for a particular pair of strategies is given by

$$b(s_x, s_y) = \begin{cases} (1-\beta_B)c_{bl}, \text{ if } s_x = s_y = B, \\ 0, \text{ if } s_x = s_y = E, \\ c_{bl}, \text{ otherwise.} \end{cases} \tag{6.4}$$

As discussed in section 6.1, blockchain eBLs could provide value-added services, such as real-time cargo information, data transparency and easy verification for external parties, to improve the efficiency of the whole maritime supply chain. The perceived benefit of the value-added services depends on users' willingness to pay for the services and the network effects. Since the value-added services pertain to the creation of a BL, player i's valuation of the value-added services provided by blockchain eBL systems is formulated as follows based on Bhargava and Choudhary (2004),

$$v_i(s_x, s_y) = r_i q^{s_x s_y} e[1-(1-p_j^{s_i})^2], \text{ for } i \in \{x, y\}, \tag{6.5}$$

where r_i is player *i*'s willingness to pay for the value-added services following a uniform distribution in [0,1]; $q^{s_x s_y}$ is the quality level of value-added services from the adopted BL system; e is an exogenous scaling parameter to measure the intensity of network effects based on the number of players from the other population; and $p_j^{s_i}$ is the proportion of the other population *j* adopting strategy s_i. Since the paper BL and EDI eBL systems cannot provide the value-added services that blockchain eBL systems provide, $q^P = q^E = 0$, and $q^B = 1$.

The administrative cost of player *i* about handling paper BLs includes courier fee c_{ci} and cost related to preparing and checking LOI for discharging cargoes without original bills of lading (OBL) c_{li}. These costs are incurred only when paper BLs are used in the shipment. Therefore, the administrative cost of player *i* for a particular pair of strategies is given by

$$a_i(s_x, s_y) = \begin{cases} 0, \text{ if } s_x = s_y = B \text{ or } s_x = s_y = E, \\ c_{ci} + c_{li}, \text{ otherwise.} \end{cases} \tag{6.6}$$

The expected loss of a shipment from BL fraud is modelled as the product of the probability of encountering BL fraud θ_b and the total cargo value in the shipment V. Based on Table 6.1, it is assumed that the probability of encountering BL fraud in a shipment can be reduced by φ_E from using EDI eBL systems and reduced by φ_B from using blockchain eBL systems, where $0 \le \varphi_E < \varphi_B \le 1$. Hence, the expected loss due to BL fraud for a particular pair of strategies can be presented by

$$f(s_x, s_y) = \begin{cases} (1-\varphi_B)V\theta_b, \text{ if } s_x = s_y = B, \\ (1-\varphi_E)V\theta_b, \text{ if } s_x = s_y = E, \\ V\theta_b, \text{ otherwise.} \end{cases} \tag{6.7}$$

Based on the above analysis, the payoff matrix is provided in Table 6.3 to show the payoffs to the two players when a particular pair of strategies is chosen. In each cell, the first equation is the payoff to the carrier, followed by the payoff to the shipper.

Table 6.3 Payoff matrix.

		Shipper		
		Blockchain eBL	EDI eBL	Paper BL
Carrier	Blockchain eBL	$r_x e[1-(1-p_y^B)^2]+(1-\beta_B)c_{bl}d_x-(1-\varphi_B)V\theta_b-c_{tB}d_x$, $r_y e[1-(1-p_x^B)^2]-(1-\beta_B)c_{bl}(1-d_y)-c_{tB}d_y$	$c_{bl}-a_x-V\theta_b$, $-c_{bl}-a_y$	$c_{bl}-a_x-V\theta_b$, $-c_{bl}-a_y$
	EDI eBL	$c_{bl}-a_x-V\theta_b$, $-c_{bl}-a_y$	$-(1-\varphi_E)V\theta_b$, $-c_{tE}$	$c_{bl}-a_x-V\theta_b$, $-c_{bl}-a_y$
	Paper BL	$c_{bl}-a_x-V\theta_b$, $-c_{bl}-a_y$	$c_{bl}-a_x-V\theta_b$, $-c_{bl}-a_y$	$c_{bl}-a_x-V\theta_b$, $-c_{bl}-a_y$

6.3 Evolutionary analysis of the game

To find the evolutionarily stable strategies of the game, we define $p_i^{s_i}$ as the proportions of population i choosing strategy s_i.

$$\sum_{s_i \in S} p_i^{s_i} = 1. \tag{6.8}$$

The expected payoff of player i by adopting strategy s_i is given by

$$\pi_i^{s_i} = \sum_{s_j \in S} p_j^{s_j} \pi_i(s_x, s_y), \text{ for } i \in N, j \in N/\{i\}. \tag{6.9}$$

The average payoff of population i is given by

$$\overline{\pi_i} = E(\sum_{s_i \in S} p_i^{s_i} \pi_i^{s_i}), \text{ for } i \in N. \tag{6.10}$$

The growth rate of strategy s_i in population i can be described based on replicator dynamics (Taylor and Jonker, 1978):

$$g_i^{s_i} = p_i^{s_i}(\pi_i^{s_i} - \overline{\pi_i}), \text{ where } s_i \in S. \tag{6.11}$$

For player i, if the expected payoff from adopting strategy s_i is higher (lower) than the population's average payoff, the population's share of adopting strategy s_i will increase (decrease).

Evolutionarily stable strategies (ESS) can be achieved when the following conditions are met (Taylor and Jonker 1978; Smith 1982; Apaloo, Brown, and Vincent 2009):

(1) the growth rates of different strategies in both populations are zero, i.e., $g_x^B = 0, g_x^E = 0, g_y^B = 0,$ and $g_y^E = 0.$ The corresponding solutions for $p_i^{s_i}$ are called fixed points; and (2) the neighbourhood of the fixed points should be stable.

6.3.1 Fixed points

With $g_x^B = 0, g_x^E = 0, g_y^B = 0,$ and $g_y^E = 0,$ the possible fixed points can be obtained by having:

$$\begin{cases} p_x^B = 0, \text{ or } (1 - p_x^B)(\pi_x^B - \pi_x^P) - p_x^E(\pi_x^E - \pi_x^P) = 0, \\ p_x^E = 0, \text{ or } (1 - p_x^E)(\pi_x^E - \pi_x^P) - p_x^B(\pi_x^B - \pi_x^P) = 0, \\ p_y^B = 0, \text{ or } (1 - p_y^B)(\pi_y^B - \pi_y^P) - p_y^E(\pi_y^E - \pi_y^P) = 0, \\ p_y^E = 0, \text{ or } (1 - p_y^E)(\pi_y^E - \pi_y^P) - p_y^B(\pi_y^B - \pi_y^P) = 0. \end{cases} \tag{6.12}$$

With different combinations of the above equations, a total of 26 possible fixed points $((p_x^B, p_x^E), (p_y^B, p_y^E))$ for the evolutionary game are obtained and presented in Table 6.4 (see the proofs in APPENDIX B).

Table 6.4 Solutions of fixed points.

No.	Solutions $((p_x^B, p_x^E), (p_y^B, p_y^E))$	Conditions
1	$((0,0),(0,0))$	Nil
2	$((0,1),(0,1))$	Nil
3	$((1,0),(1,0))$	Nil
4	$((w_{x1},0),(0,0))$ for $\forall w_{x1} \in [0,1]$	Nil
5	$((0,w_{x1}),(0,0))$ for $\forall w_{x1} \in [0,1]$	Nil
6	$((0,0),(w_{y1},0))$ for $\forall w_{y1} \in [0,1]$	Nil
7	$((0,0),(0,w_{y1}))$ for $\forall w_{y1} \in [0,1]$	Nil
8	$((0,w_{x1}),(w_{y1},0))$ for $\forall w_{x1}, w_{y1} \in [0,1]$	Nil
9	$((w_{x1},0),(0,w_{y1}))$ for $\forall w_{x1}, w_{y1} \in [0,1]$	Nil
10	$((0,w_{x1}),(0,1))$ for $\forall w_{x1} \in [0,1]$	$\pi_x^E = \pi_x^P$ and $\pi_y^E \neq \pi_y^P$
11	$((0,1),(0,w_{y1}))$ for $\forall w_{y1} \in [0,1]$	$\pi_x^E \neq \pi_x^P$ and $\pi_y^E = \pi_y^P$
12	$((0,w_{x1}),(0,w_{y1}))$ for $\forall w_{x1}, w_{y1} \in [0,1]$	$\pi_x^E = \pi_x^P$ and $\pi_y^E = \pi_y^P$
13	$((0,0),(w_{y1},w_{y2}))$ for $\forall w_{y1}, w_{y2} \in [0,1]$	$w_{y1} + w_{y2} \leq 1$
14	$((0,1),(w_{y1},w_{y2}))$ for $\forall w_{y1} \in [0,1]$	$w_{y1} + w_{y2} \leq 1$, $\pi_x^E \neq \pi_x^P$ and $\pi_y^E = \pi_y^P$
15	$((0,w_{x1}),(w_{y1},w_{y2}))$ for $\forall w_{x1}, w_{y1} \in [0,1]$	$w_{y1} + w_{y2} \leq 1$, $\pi_x^E = \pi_x^P$ and $\pi_y^E = \pi_y^P$

16	$((w_{x1}, w_{x2}), (0,0))$ for $\forall w_{x1}, w_{x2} \in [0,1]$	$w_{x1} + w_{x2} \le 1$
17	$((w_{x1}, 0), (1,0))$ for $\forall w_{x1} \in [0,1]$	$\pi_x^B = \pi_x^P$ and $\pi_y^B \ne \pi_y^P$
18	$((1,0), (w_{y1}, 0))$ for $\forall w_{y1} \in [0,1]$	$\pi_x^B \ne \pi_x^P$ and $\pi_y^B = \pi_y^P$
19	$((w_{x1}, 0), (w_{y1}, 0))$ for $\forall w_{x1}, w_{y1} \in [0,1]$	$\pi_x^B = \pi_x^P$ and $\pi_y^B = \pi_y^P$
20	$((w_{x1}, w_{x2}), (1,0))$ for $\forall w_{x1}, w_{x2} \in [0,1]$	$\pi_x^B = \pi_x^P$ and $\pi_y^B \ne \pi_y^P$
21	$((w_{x1}, w_{x2}), (w_{y1}, 0))$ for $\forall w_{x1}, w_{x2}, w_{y1} \in [0,1]$	$w_{x1} + w_{x2} \le 1$, $\pi_x^B = \pi_x^P$ and $\pi_y^B = \pi_y^P$
22	$((w_{x1}, w_{x2}), (0,1))$ for $\forall w_{x1}, w_{x2} \in [0,1]$	$\pi_x^E = \pi_x^P$ and $\pi_y^E \ne \pi_y^P$
23	$((w_{x1}, w_{x2}), (0, w_{y1}))$ for $\forall w_{x1}, w_{x2}, w_{y1} \in [0,1]$	$w_{x1} + w_{x2} \le 1$, $\pi_x^E = \pi_x^P$ and $\pi_y^E = \pi_y^P$
24	$((1,0), (w_{y1}, w_{y2}))$ for $\forall w_{y1}, w_{y2} \in [0,1]$	$\pi_y^B = \pi_y^P$ and $\pi_x^B \ne \pi_x^P$
25	$((w_{x1}, 0), (w_{y1}, w_{y2}))$ for $\forall w_{x1}, w_{y1}, w_{y2} \in [0,1]$	$w_{y1} + w_{y2} \le 1$, $\pi_y^B = \pi_y^P$ and $\pi_x^B = \pi_x^P$
26	$((w^*_{x1}, 1 - w^*_{x1}), (w^*_{y1}, 1 - w^*_{y1}))$ for $w^*_{x1}, w^*_{y1} \in [0,1]$	$\pi_x^B = \pi_x^E$ and $\pi_y^B = \pi_y^E$

Notes: w^*_{x1} and w^*_{y1} are the only solutions of p_x^B and p_y^B which solve $\pi_x^B = \pi_x^E$ and $\pi_y^B = \pi_y^E$ respectively.

6.3.2 Stability of fixed points

Based on Taylor and Jonker (1978), the neighbourhood of a fixed point is stable if the real parts of the eigenvalues of $\mathrm{J}(g_x^B, g_x^E, g_y^B, g_y^E)$ matrix at that point are all negative, where $\mathrm{J}(g_x^B, g_x^E, g_y^B, g_y^E)$ is the Jacobian matrix of the equations of replicator dynamics and is given by

$$\mathrm{J}(g_x^B, g_x^E, g_y^B, g_y^E) = \begin{pmatrix} \dfrac{\partial g_x^B}{\partial p_x^B} & \dfrac{\partial g_x^B}{\partial p_x^E} & \dfrac{\partial g_x^B}{\partial p_y^B} & \dfrac{\partial g_x^B}{\partial p_y^E} \\ \dfrac{\partial g_x^E}{\partial p_x^B} & \dfrac{\partial g_x^E}{\partial p_x^E} & \dfrac{\partial g_x^E}{\partial p_y^B} & \dfrac{\partial g_x^E}{\partial p_y^E} \\ \dfrac{\partial g_y^B}{\partial p_x^B} & \dfrac{\partial g_y^B}{\partial p_x^E} & \dfrac{\partial g_y^B}{\partial p_y^B} & \dfrac{\partial g_y^B}{\partial p_y^E} \\ \dfrac{\partial g_y^E}{\partial p_x^B} & \dfrac{\partial g_y^E}{\partial p_x^E} & \dfrac{\partial g_y^E}{\partial p_y^B} & \dfrac{\partial g_y^E}{\partial p_y^E} \end{pmatrix}. \tag{6.13}$$

The eigenvalues (λ) of the matrix $\mathrm{J}(g_x^B, g_x^E, g_y^B, g_y^E)$ at each fixed point can be found by setting $\mathrm{J}(g_x^B, g_x^E, g_y^B, g_y^E) - \lambda I = 0,$ where I is the identity matrix with the same dimensions as $\mathrm{J}(g_x^B, g_x^E, g_y^B, g_y^E)$. Then the conditions of evolutionary stability can be derived.

The eigenvalue analysis indicates that fixed points $((1,0),(1,0))$, $((0,1),(0,1))$, and $((w^*_{x1},1-w^*_{x1}),(w^*_{y1},1-w^*_{y1}))$ are possible to be evolutionarily stable strategies. Table 6.5 shows their eigenvalues and corresponding conditions to be ESS. Since the eigenvalues of $((w^*_{x1},1-w^*_{x1}),(w^*_{y1},1-w^*_{y1}))$ are quite complicated and does not provide much analytical significance, they are not analysed in detail in this section. For the fixed points not presented in Table 6.5, their stabilities cannot be determined by the signs of eigenvalues because at least one of their eigenvalues is zero. Considering they are not the targeted state of the game, further analysis of their stabilities is not conducted here.

Table 6.5 Possible evolutionarily stable strategies and conditions to be ESS.

Fixed points	Eigenvalues of $\mathrm{J}(g_x^B, g_x^E, g_y^B, g_y^E)$ $(\{\lambda_1,\lambda_2,\lambda_3,\lambda_4\})$	Conditions to be ESS
$((1,0),(1,0))$	$\left\{\begin{array}{l} \lambda_1 = \pi_x^P - \pi_x^B \\ = -a_x + c_{bl} - V\theta_b - er_x[-c_{tB}d_x + c_{bl}d_x(1-\beta_B) \\ -V\theta_b(1-\varphi_B)], \\ \lambda_2 = \pi_x^E - \pi_x^B \\ = -a_x + c_{bl} - V\theta_b - er_x[-c_{tB}d_x + c_{bl}d_x(1-\beta_B) \\ -V\theta_b(1-\varphi_B)], \\ \lambda_3 = \pi_y^P - \pi_y^B = -a_y - c_{bl} + c_{tB}d_y - er_y \\ +c_{bl}(1-d_y)(1-\beta_B), \\ \lambda_4 = \pi_y^E - \pi_y^B = -a_y - c_{bl} + c_{tB}d_y - er_y \\ +c_{bl}(1-d_y)(1-\beta_B). \end{array}\right\}$	In case 1[#]: $-a_x + c_{bl} - V\theta_b - er_x[-c_{tB} +$ $c_{bl}(1-\beta_B) - V\theta_b(1-\varphi_B)] < 0$ In case 2: $-a_x + c_{bl} - V\theta_b + er_x V\theta_b(1-\varphi_B)$ < 0 and $-a_y - c_{bl} + c_{tB} - er_y < 0.$
$((0,1),(0,1))$	$\left\{\begin{array}{l} \lambda_1 = \pi_x^B - \pi_x^E = -a_x + c_{bl} - V\varphi_E\theta_b, \\ \lambda_2 = \pi_x^P - \pi_x^E = -a_x + c_{bl} - V\varphi_E\theta_b, \\ \lambda_3 = \pi_y^B - \pi_y^E = -a_y - c_{bl} + c_{tE}, \\ \lambda_4 = \pi_y^P - \pi_y^E = -a_y - c_{bl} + c_{tE}. \end{array}\right\}$	In both cases: $-a_x + c_{bl} - V\varphi_E\theta_b < 0$ and $-a_y - c_{bl} + c_{tE} < 0.$

Notes: Case 1 is when carriers pay for the blockchain eBL transaction fee and case 2 is when shippers pay for the fee. Not all possible ESS are presented in this table. [#]Another condition for $((1,0),(1,0))$ to be an ESS in case 1 is $-a_y - er_y - c_{bl}\beta_B < 0$, which is not reflected in the table as it is always true based on the model setting.

According to Table 6.5, $((1,0),(1,0))$ can be an ESS (hereinafter referred to as “blockchain ESS”) if a player’s expected payoff from adopting blockchain eBLs is the highest among the three strategies when all other players choose to use blockchain eBLs. $((0,1),(0,1))$ can also be an ESS (hereinafter referred to as “EDI ESS”) if a player's expected payoff from adopting EDI eBLs is the highest among the three strategies when all other players choose to use EDI eBLs. In case 1 when carriers pay the blockchain eBL transaction fee, $d_x = 1$ and $d_y = 0$; in case 2 when shippers pay the fee, $d_x = 0$ and $d_y = 1$. By substituting the values of d_x and d_y into the equations of eigenvalues, the conditions for the fixed points to be ESS are derived and provided in Table 6.5.

6.4 Numerical applications

This section applies industry data to demonstrate the evolution of blockchain eBL adoption and the sensitivity of ESS to different parameters. The probability of a population selecting a specific strategy is updated based on the following equation:

$$p_i^{s_i}(t) = p_i^{s_i}(t-1) + \kappa p_i^{s_i}(t-1)(\pi_i^{s_i}(t) - \overline{\pi_i}(t)), \text{ for } s_i \in S, \tag{6.14}$$

where κ denotes the learning rate of populations, which is an exogenous parameter to show how fast players would move to the optimal solutions. If κ is too big, the optimal solutions may be skipped. If κ is too small, it takes more iterations to reach the optimal solutions. t denotes the number of stages, starting from 0.

For illustration purposes, some assumptions are made in the numerical application. First, carriers and shippers are assumed to have the same costs of preparing and checking LOIs for discharging cargoes without original BLs and the same courier fees for delivering paper BLs to another party. Then, carriers are assumed to have lesser willingness than shippers to pay for the value-added services of blockchain eBL systems, considering that carriers tend to focus on a particular transport phase while shippers normally have to consider the whole supply chain. Thus, for the base case analysis, we assign $r_x = 0.5$ and $r_y = 1$. The sensitivity analysis reported later shows that the final ESS is not sensitive to the two parameters. Lastly, the initial proportions of players choosing blockchain eBL and EDI eBL systems at stage 0 are assumed to be $p_x^B(0) = 0.02, p_x^E(0) = 0.2, p_y^B(0) = 0.1,$ and $p_x^E(0) = 0.2$ in the base case, in view of the current number of companies using blockchain eBL and EDI eBL. The values of other parameters are summarised in Table 6.6. Sensitivity analysis will be conducted for parameters with assumed value and other parameters like cargo value.

Table 6.6 Parameter value.

Notations	Value	Unit	References
The probability of encountering fraud (θ_b)	4%	-	(UK Fraud Costs Measurement Committee, 2018)[1]
Total cargo value per shipment (V)	2710	USD	(IHS Markit, 2017)[2]
The reduced costs of preparing and checking LOIs for discharging cargoes without OBLs ($c_{li},\ i \in N$)	36.34	USD	(essDOCS, 2020b)
Courier fee of paper bills of lading ($c_{ci},\ i \in N$)	46	USD	DHL[3]
Carrier's charge to the shipper for issuing paper OBLs (c_{bl})	126	USD per BL	OOCL Singapore price
Blockchain transaction fee per BL (c_{tB})	15	USD	(North P&I Club, 2019)
Percentage reduction in BL fee when blockchain eBLs are used (β_B)	27%	-	OOCL Singapore price[4]
The percentage reduction in BL fraud when EDI eBLs are used (φ_E)	85%	-	Assumed
The percentage reduction in BL fraud when blockchain eBLs are used (φ_B)	95%	-	Assumed
EDI transaction fee per BL (c_{tE})	50	USD	Assumed
An exogenous scaling parameter to measure the intensity of network effects (e)	100	USD	Assumed
Learning rate which determines how fast the players move to the ESS (κ)	0.001	-	Assigned

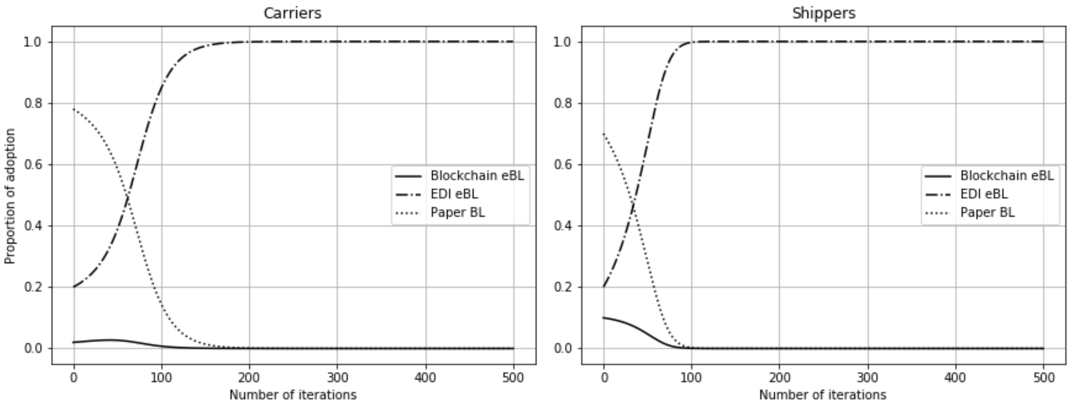
Notes: OBL – original bill of lading; LOI – letter of indemnity; ESS – evolutionary stable strategy. [1]The value is based on the general insurance fraud rate from the source. [2]The value is based on the value of wood & wood products which has the lowest value among the top 15 container commodities. [3]The value is based on the medium courier fee of DHL in all delivery zones. [4]The value is based on the price difference between telex release price of BLs and paper BL fee in OOCL Singapore.

6.4.1 Result analysis

As mentioned in previous sections, there are two cases of the game depending on who pays the blockchain eBL transaction fee. In case 1, carriers pay the fee, while in case 2 shippers pay the fee. The results of the evolution of blockchain adoption in case 1 and case 2, as illustrated in Figure 6.1, show that all carriers and shippers will reach EDI ESS, no matter who pays for the blockchain eBL transaction fee.

In the two cases, for the population of carriers, the expected payoffs from adopting blockchain eBLs and EDI eBLs are greater than the population's average payoff. Therefore, both p_x^B and p_x^E increase at the early stage of the evolution, where p_x^E grows at a much faster rate than p_x^B. However, with the influence of shippers' adoption strategies (gradual decrease of p_y^B and fast increase of p_y^E), p_x^B starts to decrease after a while and p_x^E continues to increase. The evolution of carriers' adoption strategies, in turn, strengthens the original evolutionary direction of shippers where p_y^B decreases and p_y^E increases. Eventually, all carriers and shippers will choose the EDI eBL system.

(a) Case 1 ($d_x = 1$ and $d_y = 0$)



(b) Case 2 ($d_x = 0$ and $d_y = 1$)

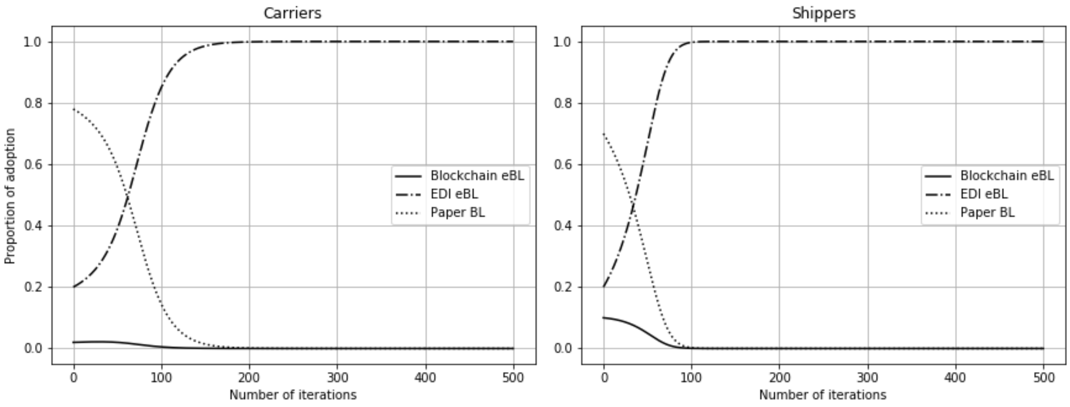


Figure 6.1 Evolution of the game.

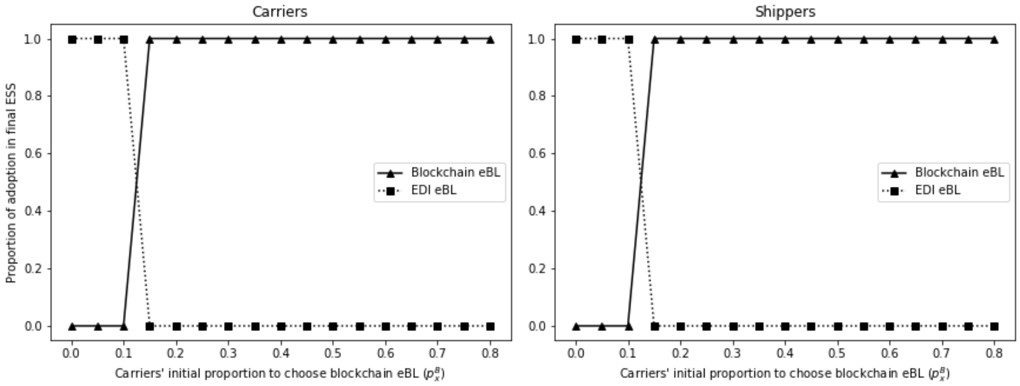
6.4.2 Sensitivity analysis

This section examines how ESS would be affected by the changes of a parameter while other parameters remain the same. It is noticed that the ESS is not sensitive to some parameters including populations' willingness to pay for value-added services of blockchain eBLs (r_x and r_y), transaction fee of EDI and blockchain eBL systems (c_{tE} and c_{tB}), scaling parameter of network effects (e), and percentage reduction in BL fee from using blockchain system (β_B). Therefore, these parameters are not discussed in this section.

6.4.2.1 Initial proportion of blockchain eBL adoption

Figure 6.2 and Figure 6.3 present the sensitivity of ESS to carriers' and shippers' initial proportions of choosing blockchain eBL systems (p_x^B and p_y^B), respectively. The result in terms of proportions of adopting paper BLs (p_i^P) is not explicitly shown in the sensitivity graphs as it can be obtained by $p_i^P = 1 - p_i^B - p_i^E$. The results indicate that a critical mass is required for blockchain ESS. The critical mass refers to a threshold, once reached, the more players choose a strategy, the more others will be inclined to do the same (Schelling, 1978). In this case, as long as the critical mass for a single population is reached, blockchain eBLs can achieve mass adoption in all populations. The critical mass required for carriers (about 15% in case 1 and about 16% in case 2) is lesser than that for shippers (about 39% in case 1 and about 58% in case 2). This indicates that it could be easier to achieve widespread blockchain eBL adoption by focusing more on carriers than shippers when promoting blockchain eBLs.

(a) Case 1 ($d_x = 1$ and $d_y = 0$)



(b) Case 2 ($d_x = 0$ and $d_y = 1$)

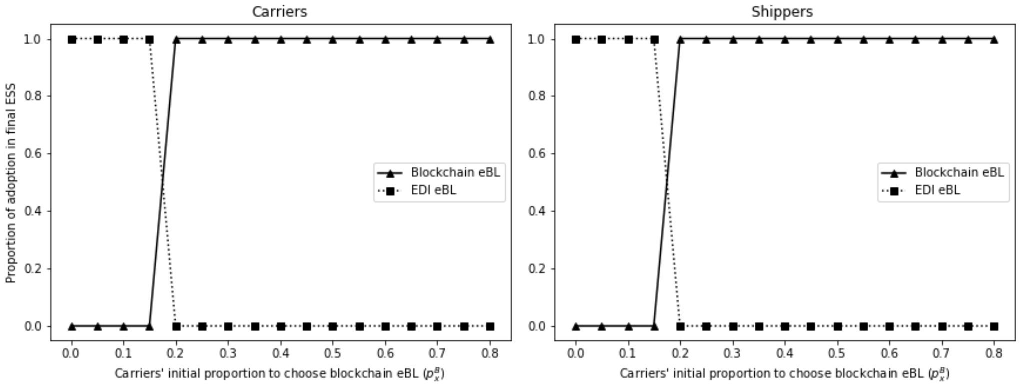
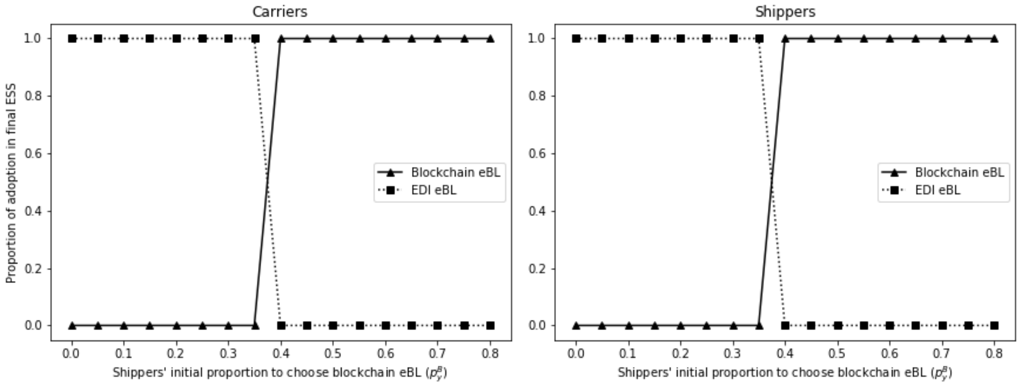


Figure 6.2 Sensitivity of ESS to carriers' initial proportion to choose blockchain eBLs.

(a) Case 1 ($d_x = 1$ and $d_y = 0$)



(b) Case 2 ($d_x = 0$ and $d_y = 1$)

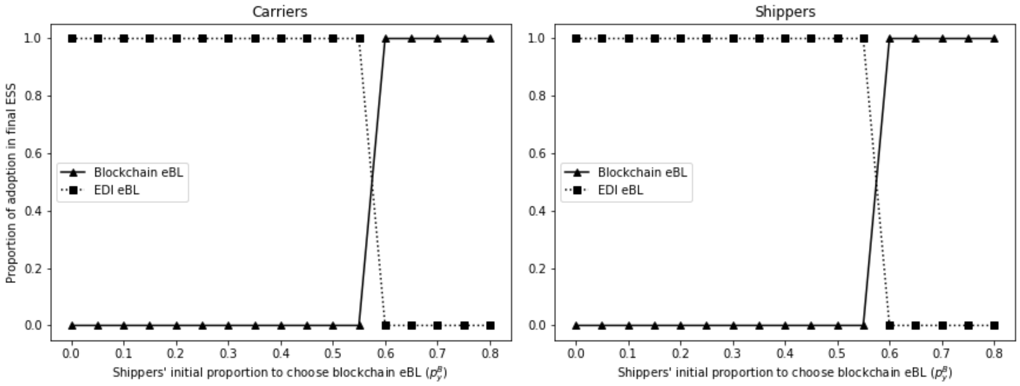


Figure 6.3 Sensitivity of ESS to shippers' initial proportion to choose blockchain eBLs.

6.4.2.2 Initial proportion of EDI eBL adoption

Figure 6.4 and Figure 6.5 depict the sensitivity of ESS to the initial proportions of EDI eBL adoption among carriers and shippers (p_x^E and p_y^E), respectively. Since the sensitivity results are the same in both cases, only the graph of case 1 is provided to avoid repetition. The results suggest that all carriers and shippers will eventually adopt EDI eBL systems, even when p_x^E and p_y^E are at a very low level (e.g., at 0.05). This implies the difficulties for blockchain eBLs to reach widespread adoption given the current user base of EDI eBL systems.

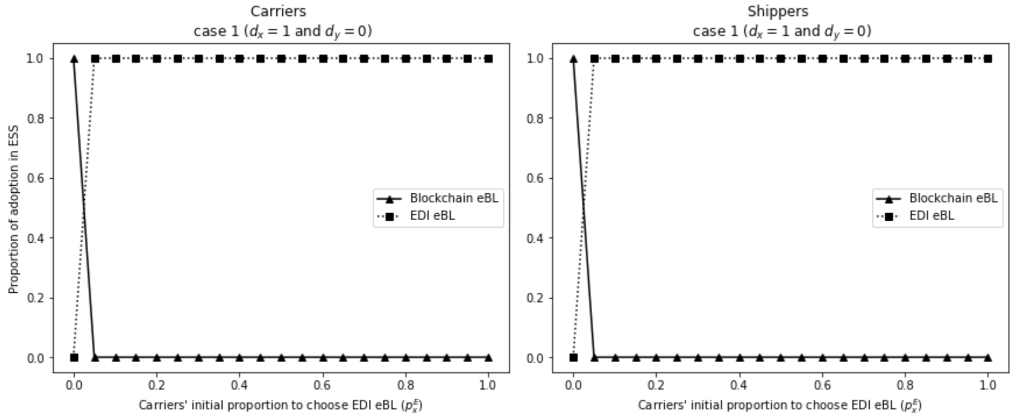


Figure 6.4 Sensitivity of ESS to carriers' initial proportion to choose EDI eBLs.

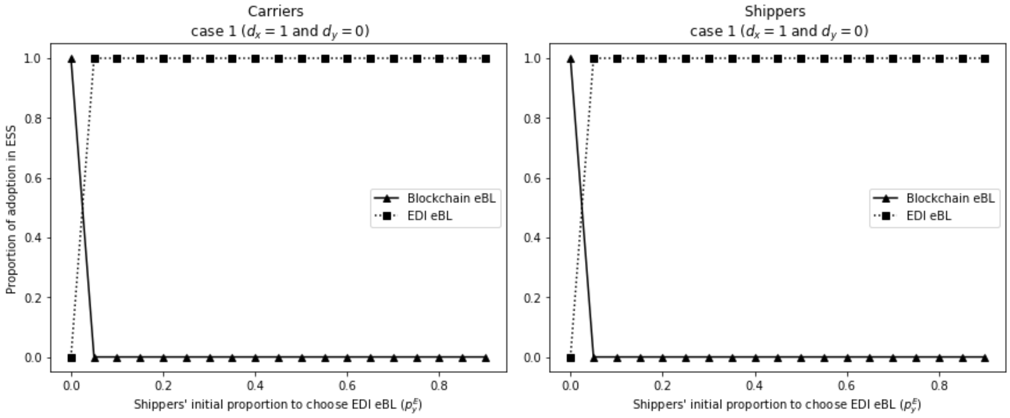
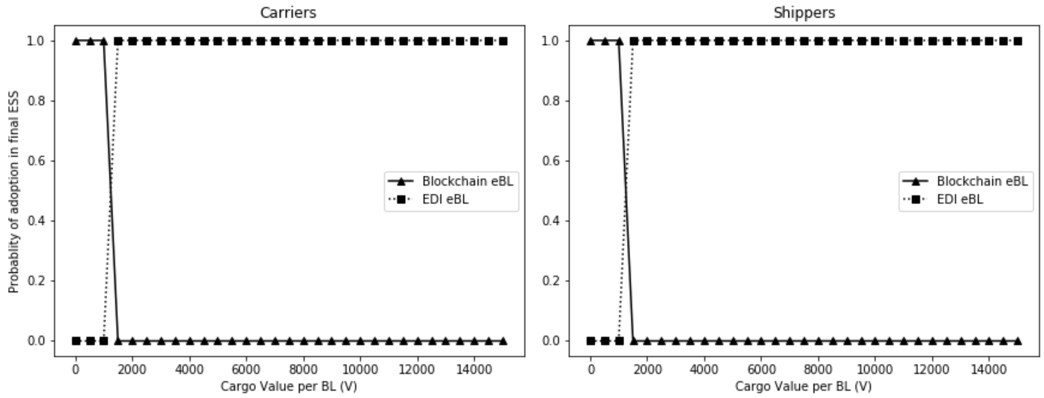


Figure 6.5 Sensitivity of ESS to shippers' initial proportion to choose EDI eBLs.

6.4.2.3 Cargo value per BL

Figure 6.6 suggests that ESS is sensitive to cargo value and blockchain is more preferred for low-value products by both populations. All players will eventually adopt blockchain if the cargo value is in a certain low range ($V \leq$ US\$1282 for case 1 and US\$392 $\leq V \leq$ US\$1279 for case 2). When the cargo value is very small in case 2 ($V <$ US\$392), only a small percentage of shippers would adopt blockchain systems and all carriers would adopt the paper BL system as the proportions of carriers choosing the other two systems are zero ($p_i^P = 1 - p_i^B - p_i^E$).

(a) Case 1 ($d_x = 1$ and $d_y = 0$)



(b) Case 2 ($d_x = 0$ and $d_y = 1$)

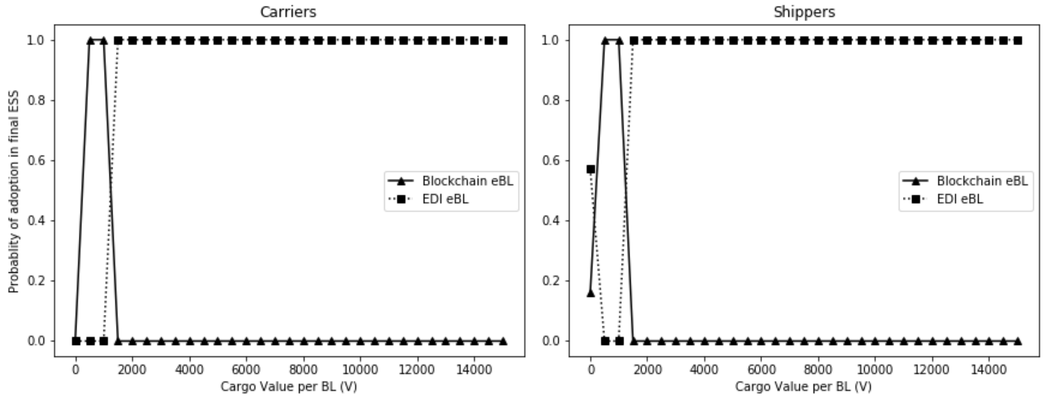


Figure 6.6 Sensitivity of ESS to cargo value per BL.

6.4.2.4 Percentage reduction in BL fraud from eBL System

Figure 6.7 and Figure 6.8 show the sensitivity of ESS to the percentage reduction in BL fraud from adopting EDI and blockchain eBL systems (φ_E and φ_B), respectively. Since the sensitivity results are the same in both cases, only the graph of case 1 is provided to avoid repetition. According to the analysis in Table 6.1, φ_B should be at least equal to φ_E . Hence, the sensitivity analyses of φ_E and φ_B are conducted in the range of [0, 95%] and [85%,1], respectively. The result shows that in order to achieve blockchain ESS, φ_E should be no more than 40% when φ_B is 95%, i.e., $\varphi_B - \varphi_E$ should be at least more than 55%. This indicates that widespread adoption of blockchain eBLs can only be realised if there is a big difference in the capabilities to reduce BL fraud between blockchain and EDI eBL systems. Otherwise, full EDI eBL adoption will be the final ESS. The finding is reasonable as the higher marginal benefits from blockchain eBL adoption, the higher willingness of populations to switch to blockchain eBLs.

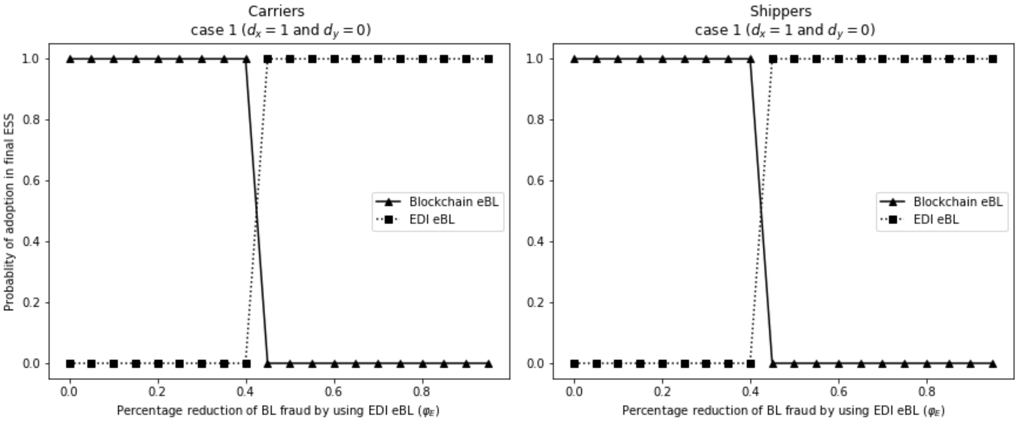


Figure 6.7 Sensitivity of ESS to percentage reduction in BL fraud by using EDI eBL systems (for φ_B = 95%).

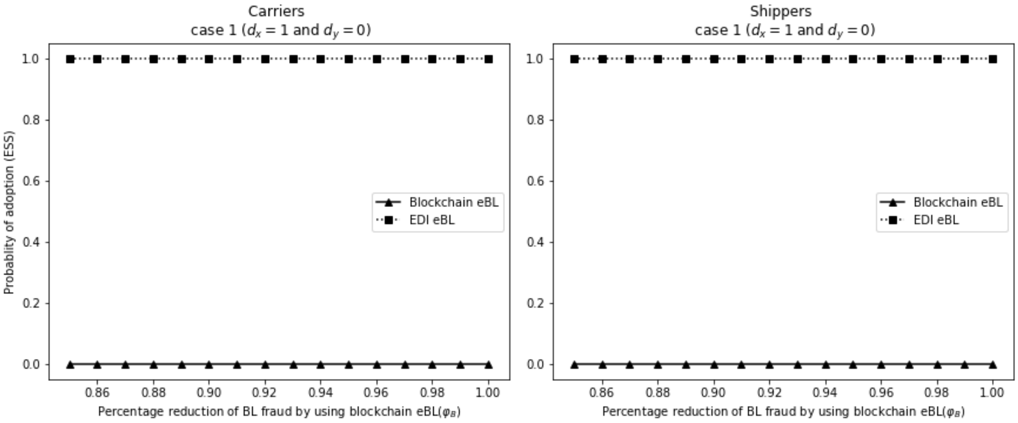
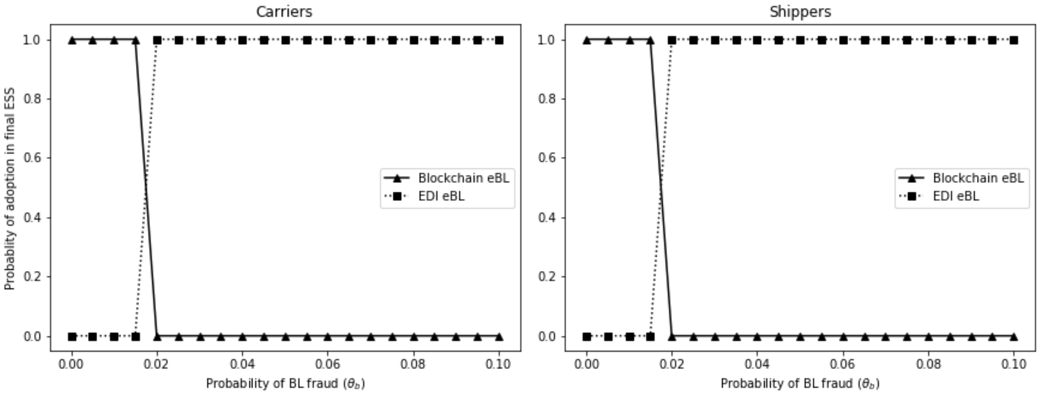


Figure 6.8 Sensitivity of ESS to percentage reduction in BL fraud by using blockchain eBL systems (for φ_E = 85%).

6.4.2.5 Original probability of BL fraud in paper BL system

Figure 6.9 shows that ESS is not sensitive to the original probability of BL fraud (θ_b) when it is big. When θ_b is bigger than 1.8%, EDI ESS remains. When $\theta_b \leq 1.8\%$ for case 1 and $0.6\% \leq \theta_b \leq 1.8\%$ for case 2, blockchain ESS is achieved. When θ_b is very small in case 2 ($\theta_b < 0.6\%$), only a small percentage of shippers would eventually use blockchain eBLs and all carriers would just use paper BLs as the proportions of carriers choosing blockchain and EDI eBLs are both zero ($p_i^P = 1 - p_i^B - p_i^E$).

(a) Case 1 ($d_x = 1$ and $d_y = 0$)



(b) Case 2 ($d_x = 0$ and $d_y = 1$)

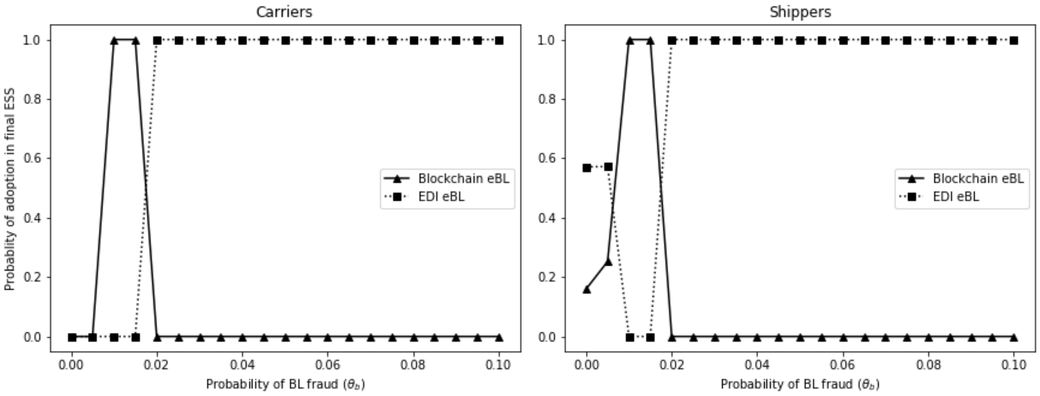


Figure 6.9 Sensitivity of ESS to the probability of BL fraud.

6.4.2.6 Time to reach ESS

Figure 6.10 illustrates the number of iterations needed to reach ESS for parameters to which the ESS is sensitive. It is discovered when blockchain ESS is achieved, case 1 always takes a shorter time to reach the stable state than case 2 for all these parameters. In addition, it is noticed that in case 1 there is a wider scope of p_x^B, p_y^B, V and θ_b that can reach blockchain ESS than in case 2, while the scopes of φ_E that can reach blockchain ESS in both cases are the same. The two findings collectively suggest that it is more efficient to charge carriers the blockchain eBL transaction fee than shippers for faster and wider adoption of blockchain.

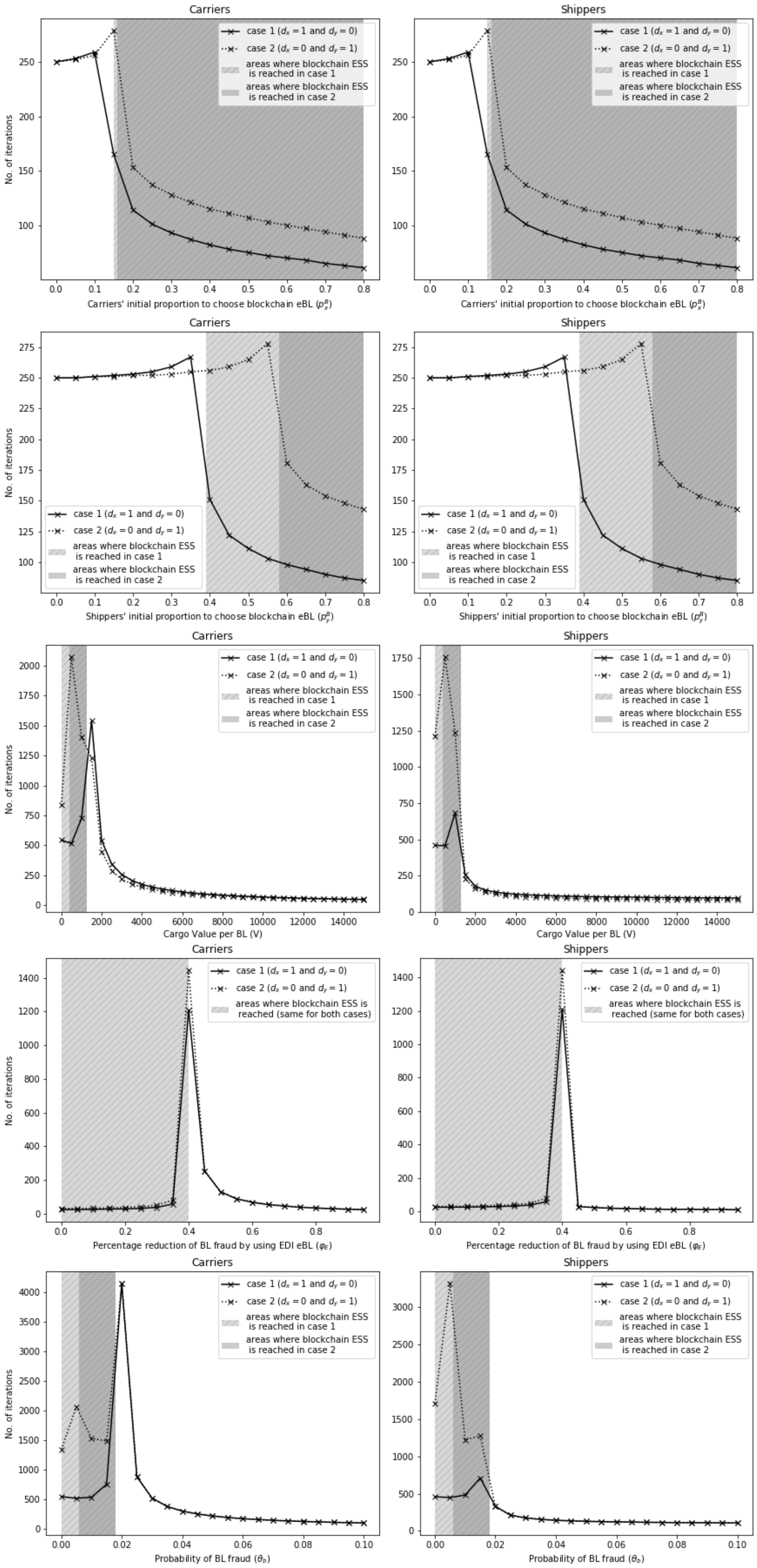


Figure 6.10 Number of iterations needed to reach ESS with changes in sensitive parameters.

6.4.3 Implications

The results of numerical applications and sensitivity analysis provide insights for blockchain eBL promoters and potential adopters. Firstly, the adoption of blockchain eBL systems is not guaranteed to be the evolutionarily stable strategy, even though they can provide value-added services and better security compared with EDI eBL systems. The result also shows that the populations' willingness to pay for the value-added services of blockchain does not have an impact on the final ESS. This indicates that the claimed value-added services are not sufficient to induce players to choose blockchain eBL. This is consistent with real cases seen in previous format wars like the videotape format war between Betamax and Video Home System (VHS) where technically superior products did not become widely adopted in the market.

Secondly, what truly differentiates blockchain from EDI eBL systems is the network effects reflected by the number of players. Given the current limited number of players adopting blockchain eBL systems and a fair number of players using EDI eBL systems, mainstream adoption of blockchain eBLs is hard to achieve. However, the result can be reversed if the number of players joining blockchain eBL systems could reach a critical mass. Our analysis reveals that a lower critical mass is required among carriers than shippers to reach blockchain ESS. Therefore, it is recommended that promoters of blockchain eBLs should focus more on carriers when encouraging the practice of blockchain eBLs.

Thirdly, mass adoption of blockchain eBL systems can still be reached for low-value products despite the current low proportion of players implementing blockchain eBLs. Hence, it is suggested that blockchain eBL promoters could first target companies engaged in shipping low-value products to expand the user base. Once the user base of blockchain eBLs reaches the critical mass, trading players for high-value products would switch to adopt blockchain eBL systems because players can expect more significant network effects and higher expected payoff from using blockchain eBLs with a larger user base.

Lastly, our analysis shows two positive effects when the blockchain eBL transaction fee is borne by carriers instead of shippers. First, it takes a shorter time to reach blockchain ESS. Second, it enables blockchain ESS to be reached in a wider scope for four parameters, namely initial proportions of carriers and shippers choosing blockchain eBL, cargo value and original probability of BL fraud in the paper system. For the rest of the parameters, the scope that can reach blockchain ESS is the same in both scenarios. Therefore, it is recommended that the blockchain eBL transaction fee should be charged to carriers instead of shippers to accelerate blockchain adoption and ensure blockchain ESS in a wider range of scenarios. Our results also imply how much the fee should be charged. Since ESS is not sensitive to the fee, the fee can be set at any level as long as the conditions for blockchain ESS (in Table 6.5) are met.

6.5 Conclusion

This chapter makes a novel attempt to investigate the evolution of blockchain adoption in terms of adoption rate by developing an asymmetric evolutionary game model, which includes the interactions from different populations and the impact of incumbent systems. Using electronic bills of lading as a blockchain adoption case, the possible evolutionarily stable strategies and their corresponding conditions are analytically identified. The numerical application results suggest that given the current proportions of companies adopting EDI eBLs and blockchain eBLs, it is unlikely to realise widespread blockchain eBL adoption in the long run unless a critical mass is reached. The critical mass of carriers is about 15% (16%) when carriers (shippers) pay the blockchain eBL transaction fee and the critical mass of shippers is about 45% (65%) when carriers (shippers) pay the fee. The results also unveil some mechanisms to foster mass adoption of blockchain eBLs. When promoting blockchain eBLs, focusing more on carriers is more efficient than shippers since the population of carriers requires a lower critical mass. Blockchain eBL promoters could first target organisations involved in shipping low-value cargoes as the current market tends to implement blockchain eBLs for low-value products. After reaching a critical mass, blockchain eBLs could become favourable for high-value products too. Lastly, imposing the blockchain eBL transaction fee on carriers is better than shippers to accelerate blockchain adoption.

CHAPTER 7 GREENHOUSE GAS IMPACT OF DIGITALISING SHIPPING DOCUMENTS: BLOCKCHAIN VS. CENTRALISED SYSTEMS

This chapter quantifies the potential greenhouse gas reductions from digitalising shipping documents at the national level. First, it develops an estimation framework with concrete methods to quantify the greenhouse gas reductions from digitalising shipping documents. Then it applies the proposed framework to the cases of Singapore and China. In the applications, the study compares the greenhouse gas impact between blockchain and centralised digital systems, and between separate platforms and an integrated platform. The results provide useful insights on how to digitalise shipping documents and which technology or platform to go for.[5]

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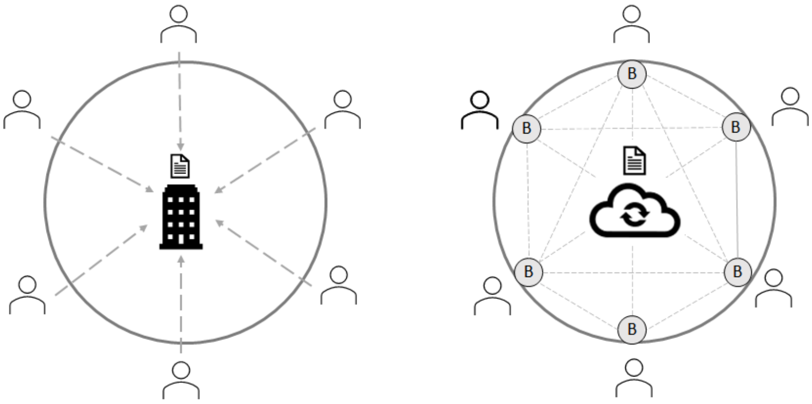
[5] The following paper is published based on this chapter:

Pu, S., and Lam, J. S. L. (2021), "Greenhouse gas impact of digitalizing shipping documents: blockchain vs. centralised systems", Transportation Research Part D: Transport and Environment. DOI: 10.1016/j.trd.2021.102942.

7.1 Background

Currently, centralised systems are commonly used to process digital documents. In centralised systems, all digital documents and transactions are compiled and controlled by a single party (Nair and Sebastian, 2017). Users can submit data to the central party, but they have limited information on the status of their upstream or downstream partners. Centralised systems are subject to a single point of failure, where a cyberattack on a central party could affect all users of its centralised system. These limitations of centralised systems could be addressed by blockchain technology. Blockchain provides a decentralised system which can ensure all participants a secure and synchronised record of transactions (Dhillon et al., 2017). No single party controls the data (Berke, 2017). The updated data are automatically synchronised among all whitelisted parties. All parties keep a full copy of data. Even if a party is down, the data are still accessible in a 24/7 manner via other parties (Abeyratne and Monfared, 2016). The differences in structure between centralised systems and blockchain systems are demonstrated in Figure 7.1. This study will consider both technologies for digitising shipping documents and compare their performance in GHG reductions.



Centralized system

Blockchain system

Figure 7.1 The network structures of centralised and blockchain systems.

Source: Drawn by author adapted from (Puthal et al., 2018).

Apart from the technology used, the platform structure of digital systems relating to the level of integration with other organisations is also an important area to be considered, particularly for maritime supply chains as various government authorities and business partners are involved in a single shipping event. When designing a digital system for shipping documentation, two types of platform structures can be considered regardless of the technology used, namely an integrated platform or separate platforms. In an integrated system, a single window is provided to link all government authorities and business partners so that each user does not need to submit the same documents repeatedly to different organisations. In separated systems, different organisations have their own platforms which are not inter-connected which lead to repeated submission of the same documents. This research will also compare the two structures from the environmental aspect.

7.2 Developing a GHG emission estimation framework for shipping documents

7.2.1 GHG Protocol for project accounting

GHG protocol is one of the most widely accepted standards for GHG accounting with more than 90% of Fortune 500 companies using it (GHG Protocol, 2020). It was published with the joint efforts of multiple organisations lead by World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) (GHG Protocol, 2020). It provides general guidelines on effective calculation of GHG at either corporate-level, production-level or project-level. Based on the nature of this study, the project-level guideline from the GHG protocol for project accounting is chosen. The guideline suggests procedures for quantifying the emission reductions from a project, as depicted in Figure 7.2. Following the procedures, the study aims to measure the potential impact of digitalising shipping documents on GHG emissions.

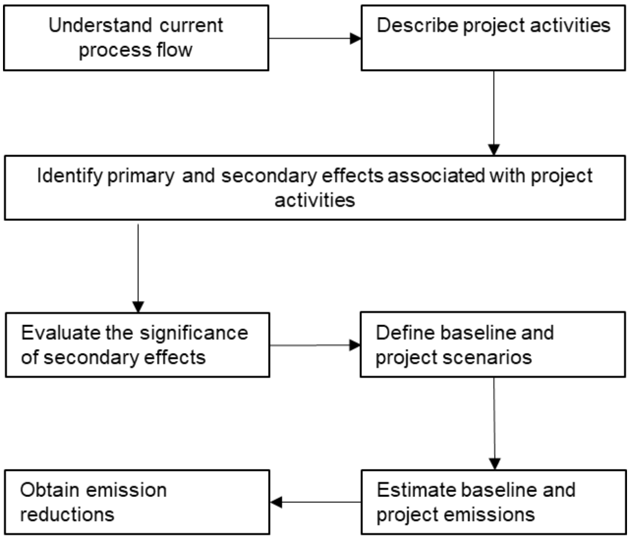


Figure 7.2 Procedures to quantify emission reductions from a project.
Source: Drawn by the author according to GHG protocol for project accounting.

7.2.2 Shipping document flow in the current paper system

Maritime supply chains are operated through interaction and coordination among related but separated players, such as shippers, freight forwarders, ocean carriers, agents, terminal operators, government agencies and banks. During the process, a series of documents have to be passed through a long chain of procedures for processing payments, securing slots, obtaining approvals, or clearing customs. Figure 7.3 illustrates the document flow in a typical simple maritime supply chain and the associated GHG emissions in the current paper system. It is identified that emissions relating to paper documents across a maritime supply chain mainly come from paper printing, transportation and storage.

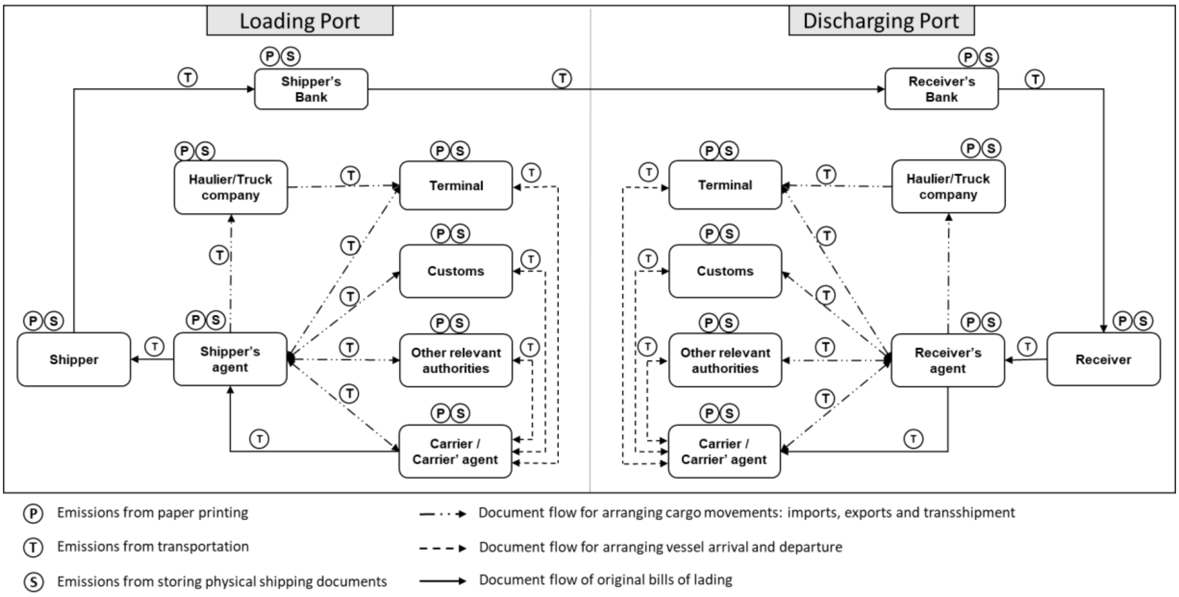


Figure 7.3 Document flow in a typical maritime supply chain in the current paper system. Source: Drawn by author.

Shippers usually appoint a local agent to represent themselves to arrange necessary applications and coordinate with various organisations for ensuring cargoes being legally and safely loaded onboard a ship for export. Meanwhile, shippers communicate with their banks for ship financing via letter of credit. Documents are created at every step along the chain. For example, after receiving cargoes onboard a vessel, carriers will issue original bills of lading (BLs) to shippers, which enables shippers to exchange original BLs for payment from banks via the letter of credit process. In terms of import, receivers need to communicate and exchange documents with carriers, customs office, discharge port terminals and their banks for taking delivery of cargoes. Some documents required like original BLs are created at previous stages at loading ports, while some others like import permits are newly generated at discharge ports.

Along the process, different modes of transport are used to transfer shipping documents across maritime supply chains, depending on the distance, urgency and availability of each case. At a relatively short distance, van transport (VT) is usually used in a less urgent case, while car transport (CT) is usually used in a more urgent case. In this study, car transport includes taxi. At a relatively long distance, rail transport (RT) is usually used in a less urgent case and airfreight transport (AT) are usually used in a more urgent case.

Apart from printing and transportation, maritime stakeholders need to keep their paper documents in a suitable place like an internal or external warehouse for sufficient time. This is because most countries require organisations to keep accounting records and supporting documents in physical format for a certain period, usually 5-10 years (PwC, 2019).

7.2.3 Digitalising shipping documents across maritime supply chains

This study focuses on national emission reductions from digitalising shipping documents using a blockchain or centralised digital system. The proposed project involves switching current paper document operations to a digital platform, where all shipping documents can be uploaded or created and shared among authorised parties. By implementing this digitalisation project, shipping documents are no longer printed or physically transported or stored.

In GHG protocol for project accounting, primary effect (PE) is defined as the intended change in GHG emissions, removals or storage caused by a project (WBCSD and WRI, 2005). Secondary effect (SE) is defined as unintended change in GHG emissions, removals or storage by a project, consisting of one-time effect from activities such as installation and termination of the project and upstream and downstream effect associated with inputs to and outputs from the project (WBCSD and WRI, 2005). The primary and secondary effects associated with the digitalisation project are identified in Table 7.1. Through an initial estimation using the proposed calculation methods in Section 7.2.4 and parameter values in Section 7.4 (see the supplementary material in Appendix C), the emission of each primary and secondary effect can be obtained. SE2 and SE3 are assessed insignificant secondary effects as they contribute less than 0.005% of the total emissions. In addition, SE2 is not applicable to organisations that have in-house warehouses to store documents. Hence, SE2 and SE3 are not included in the study.

Table 7.1 Primary and secondary effects of digitalising shipping documents across maritime supply chains.

Symbol	Primary effects	Included in the study
PE1	Reduction in emissions resulting from eliminated paper printing	Yes
PE2	Reduction in emissions resulting from eliminated transport to transfer documents	Yes
PE3	Increase in emissions resulting from the use of digital platforms	Yes
Symbol	**Secondary effects**	**Included in the study**
SE1	Reduction in emissions from storing paper shipping documents	Yes
SE2	Reduction in emissions from transporting shipping documents to warehouses	No
SE3	Reduction in emissions from disposed paper waste	No

Source: Author.

The baseline scenario refers to the situation where paper documents are required for processing ocean shipments and vessel calls. This complies with the current practice in a paper system of maritime supply chains. Blockchain and traditional centralised digital systems are considered as project candidates in the research for comparison. Since the study focuses on emission reductions at the national level, the scope of GHG assessment is defined within the national territory of a country (IPCC, 2006).

7.2.4 A GHG emission estimation framework

This section develops an estimation framework with concrete methods to obtain GHG emissions relating to shipping documents (hereinafter referred to as "emissions"), as shown in Figure 7.4. Shipping documents are generated by various shipping events including import shipment, export shipment, transshipment and vessel call. Because of different procedures, the framework addresses individual shipping events separately. The main idea is to first obtain the unit emissions of shipping events in a country and then estimate the associated national emissions based on the number of shipping events incurred in the country. The remaining section describes the detailed calculation methods mentioned in the framework for each applicable emission source.

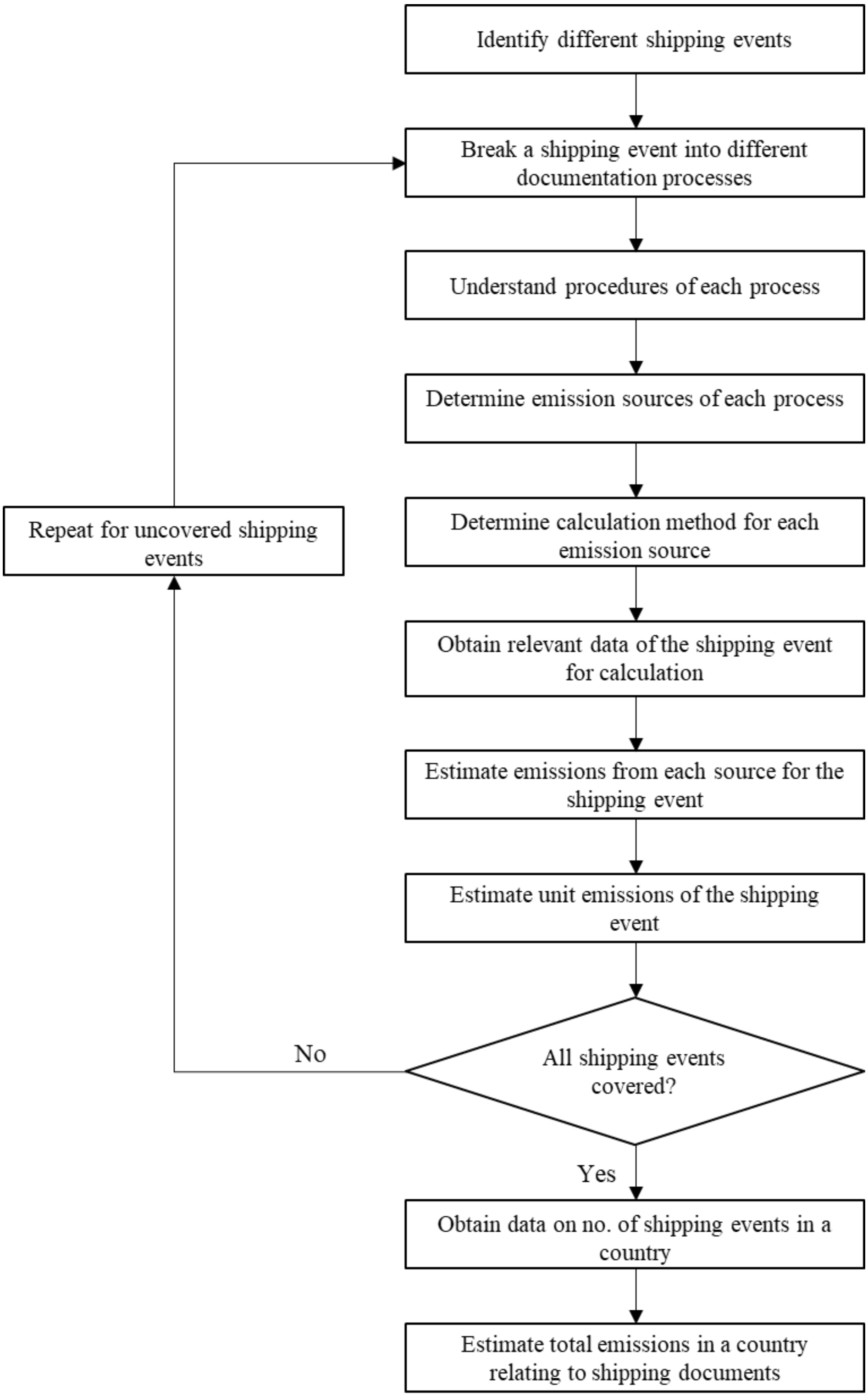


Figure 7.4 A GHG emission estimation framework for shipping documents.

Source: Drawn by author.

Let k denote the types of shipping events, including import shipment (i), export shipment (e), transshipment (r) and vessel call (v). Let s denote the types of emission sources, including paper printing (p), warehouse storage (w), transport (t), electricity (el), digital operations (d). Let E_k^s denote the emissions per shipping event k from source s.

The emissions from printing documents per shipping event k depend on the total sheets of printed documents and hence can be obtained by

$$E_k^p = EF^p \times \phi_k, \tag{7.1}$$

where EF^p is the emission factor of printing a sheet of A4 paper, including the emissions of papers from cradle to consumers (in kg CO_2e/sheet). ϕ_k is a printing multiplier, representing the total sheets of printed documents in a single event k.

Similarly, the emissions from storing physical documents per shipping event k can be calculated by

$$E_k^w = EF^w \times \gamma_k \times T, \tag{7.2}$$

$$EF^w = EF^{el} \times EUI^w, \tag{7.3}$$

where EF^w is the emission factor of storing one sheet paper in one year in warehouses (in kg CO_2e/sheet-year); γ_k is a storage multiplier, representing the total sheets of documents that need to be stored in a single event k; T is the required retention period of records in a country (in years); EF^{el} is the emission factor of electricity (in kg CO_2e/kWh); EUI^w is the energy use intensity (in kWh/sheet-year) for storing one sheet of paper in one year.

For each shipping event k, the emissions from transporting documents in mode t are derived as

$$E_k^t = \begin{cases} EF^t \times \eta_k^t \times \mu \times D^t, \text{for } t \in \{VT, RT, AT\} \\ EF^t \times n_k \times D^t, \text{for } t \in \{CT\} \end{cases}, \tag{7.4}$$

where EF^t is the emission factor of transportation t (in kg CO$_2$e/ton-km for VT, RT and AT, and in kg CO$_2$e/km for CT); η_k^t is a transport multiplier in mode t per event k (in sheets), representing the total sheets of documents that are carried in transportation mode t; μ is the unit weight per paper sheet (in g/sheet); D^t is the average travel distance per trip in transport mode t (in km); n_k is the number of passenger trips generated per event k.

Additional emissions come from handling shipping documents in digital systems, which can be derived by

$$E_k^d = EF^d \times \varphi_k, \tag{7.5}$$

where EF^d is the emission factor of digital systems (in kg CO$_2$e/transaction) and φ_k is a transaction multiplier per event k, which depends on the number of document issuance and transfer. Each issuance or transfer is considered a transaction in this study. In a digital system, a document needs to be uploaded or issued only once and can be visible to relevant parties without additional transfer. One exception is the original bills of lading (BLs), which need to be intentionally transferred with a digital signature for the transfer of title of goods. Hence the number of distinct documents plus the times of BLs transfer is used as a proxy for the number of document transactions in digital systems for shipping documents.

The unit emission of shipping event k is defined as the document-related emissions in a single event k. It can be written as

$$UE_k = \sum_{s \in S_k} E_k^s\,, \tag{7.6}$$

where S_k denotes the set of emission sources in shipping event k. It is worth mentioning that paper documents may not be fully eliminated in some digital systems, hence paper-related emissions may still exist in digital systems.

Finally, the yearly national emissions from handling shipping documents in a country can be written as

$$E = \sum_{k} UE_k \times N_k \, , \tag{7.7}$$

where N_k denotes the yearly number of shipping event k.

7.3 Applications to Singapore and China

This study applies the proposed framework to the cases of Singapore and China for illustration as they vary significantly in shipping process complexity, geographical size, and governance structure. Singapore is one of the pioneer countries which digitalised the documentation process relating to maritime trade and port services in the 1980s-1990s. Singapore launched TradeNet in 1989, which was the world's first national single window at that time, to digitalise and streamline trade documentation (Singapore Customs, 2014). The Maritime and Port Authority of Singapore (MPA) launched MARINET in 1999 (MPA, 1999), an internet-based digital system for port and shipping-related applications and transactions. In August 2020, MPA further launched a new digital platform digitalPORT@SG to replace MARINET by providing one-stop clearance for vessel arriving in and departing from Singapore (MPA, 2020). The new platform integrates the documentation processes of three government agencies – MPA, the Immigration and Checkpoints Authority (ICA) and the National Environment Agency (NEA).

China started digitalisation in maritime and trade documentation in the late 1990s with the launch of E-Port in 1998 as a national single window for trade documents (UNESCAP, 2015). The system realised full coverage of all the provincial capitals and municipalities of China at the end of 2010. Besides, China carried out a pilot reform of paperless customs clearance in selected districts in 2012 (KPMG, 2012). Big Chinese ports such as Shanghai, Shenzhen and Dalian also made efforts to realise full paperless processes for port clearance. However, differences exist among different ports of China regarding the progress of digitalisation. Not all Chinese ports have achieved full paperless port clearance at the time of research.

The documentation process of individual shipping event and corresponding data in both countries were collected from circulars issued by relevant government agencies and interviews with local shipping agents. The documentation data on the paper system is based on the paper submission processes in both countries respectively before digitalisation was introduced. The documentation data in a centralised system is based on the current systems used in the two countries respectively. The documentation data in a blockchain system is assumed the same as those in a centralised system as they have the same capability to reduce paper printing, storage and transportation. The number of individual shipping events in Singapore is based on the statistics provided by Singapore Customs and MPA.

There are a few assumptions made in the applications. Firstly, in practice, duplicate processes may exist in cities like Dubai (PwC, 2018) which require documents to be submitted in both digital and paper formats. This study assumes digital systems are truly effective so that paper submissions are no longer required. Secondly, based on the current situation in Singapore and China, both countries use centralised systems with an integrated platform so that a single window is provided to process documents among various stakeholders including government agencies and business partners. For consistency, it is assumed that an integrated platform is also used under a blockchain system. Thirdly, although electronic BLs are available in the market either in EDI or blockchain format, most ocean shipments still prefer paper BLs which may be mainly due to concerns of legal recognition of electronic BLs (Reed Smith, 2016; Clyde&Co LLP, 2018). It is expected that the situation will remain the same in the near future. Hence it is assumed that original BLs are still handled in paper format under centralised and blockchain digital systems in this study. Lastly, depending on the openness of network, blockchain can be classified into two types, namely permissioned and permissionless (Xu et al., 2016). The former restricts consensus to pre-selected validators and limit the rights to write and read only to whitelisted organisations. The latter opens consensus and rights to write and read to the public. Since shipping processes need to be restricted only to whitelisted organisations involved in a shipping event, this study assumes that permissioned blockchain will be used for digitalising shipping documents.

The data of handling shipping documents in different systems are summarised in Table 7.2 (Please refer to D-I for details). The documentation data in a centralised system and a blockchain system are the same as they have the same capability to reduce paper printing, storage and transportation. CT is the most frequently used transportation mode in both countries to deliver shipping documents, especially for customs clearance and vessel call. This is mainly because government agencies usually require document submission and collection in person. The number of distinct documents in each country reflects that China has a more bureaucratic and complex shipping process than Singapore, especially for vessel call.

The values of other applicable parameters in both countries are summarised in Table 7.3. Some parameters are assumed equal for the two countries because no differentiated data were available at the time of research. It is noted that the emission factor of a centralised system is at least three orders of magnitude lower than that of a blockchain system. The emission factor of a blockchain system in Singapore is about three orders of magnitude lower than that in China mainly because blockchain's energy consumption increases with network size (Sedlmeir et al., 2020) and the amount of users in China is significantly higher than that in Singapore.

Table 7.2 Data on shipping documents across maritime supply chains in Singapore and China.

Parameter	Singapore			China		
	Paper system	Centralised system	Blockchain system	Paper system	Centralised system	Blockchain system
Printing multiplier per import shipment	20	0	0	35	0	0
Storage multiplier per import shipment	23	3	3	38	3	3
Printing multiplier per export shipment	23	3	3	37	3	3
Storage multiplier per export shipment	20	0	0	34	0	0
Printing multiplier per transshipment	20	0	0	25	0	0
Storage multiplier per transshipment	20	0	0	25	0	0
Printing multiplier per vessel call	18	0	0	100	0	0
Storage multiplier per vessel call	18	0	0	100	0	0
No. of CT trips per import shipment	5	0	0	6	0	0
No. of VT trips per import shipment	4	4	4	4	4	4
No. of CT trips per export shipment	3	0	0	3	0	0
No. of VT trips per export shipment	3	3	3	3	3	3
No. of CT trips per transshipment	5	0	0	6	0	0
No. of CT trips per vessel call	6	0	0	13	0	0
No. of distinct documents per import shipment	18	18	18	28	28	28
No. of distinct documents per export shipment	18	18	18	27	27	27
No. of distinct documents per transshipment	18	18	18	18	18	18
No. of distinct documents per vessel call	27	27	27	63	63	63

Note: Each vessel call includes the processes of both vessel arrival and departure.
Source: Compiled by author.

Table 7.3 Values of other applicable parameters.

Parameter	Unit	Singapore	China	Reference
Emission factor of electricity (EF^{el})	kg CO2e/kWh	0.4210	0.5500	(EMA, 2020), (Stoll et al., 2019)
Emission factor of printing papers (EF^{p})	kg CO2e/sheet	4.6761×10^{-3}	4.7127×10^{-3}	Derived by author†
Energy use intensity of warehouse storing papers (EUI^{w})	kWh/sheet/year	1.2565×10^{-3}	1.2565×10^{-3}	Derived by author*
Required retention period of records (T)	years	5	10	(PwC, 2019)
Weight per sheet (μ)	g/sheet	5	5	Measured by author
Average distance per passenger trip (d^{CT})	km/trip	4.3	15.1	(LTA, 2017), (Wang et al., 2015)
Emission factor of van transport (EF^{VT})	kg CO2e/ton-km	0.2155	0.2155	(EPA, 2018)
Emission factor of car transport (EF^{CT})	kg CO2e/km	0.1258	0.1258	(EPA, 2018)
Emission factor of a centralised digital system with 2 backups (EF^{c})	kg CO2e/ transaction	2.339×10^{-8}	3.0556×10^{-8}	Derived by author#
Emission factor of a blockchain system (EF^{b})	kg CO2e/ transaction	3.5083×10^{-5}	1.0144×10^{-2}	Derived by author§

Note: When two references are provided, the first and second ones are the data source for Singapore and China, respectively. When only one reference is provided, it is the common source for Singapore and China data.

† EF^{p} is obtained based on the following assumptions: 1) the average emission factor of papers from cradle-to-consumer is 4.56 kg CO2e/sheet (Dias and Arroja, 2012); 2) the power consumption of printing is 970 watts and 57 pages can be printed per minute based on a normal Enterprise printer.

* EUI^{w} is obtained based on the following assumptions: 1) papers are stored in document carton boxes with a dimension of 39cm x 39cm x 26cm; 2) maximum height of storage is 1.8m; 3) one carton box can store 2500 sheets of paper; 4) the energy use intensity of warehouses for documents is 160 kWh/m^2/year (BCA, 2018).

EF^{c} is obtained based on the estimation from Sedlmeir et al. (2020) that the energy consumption of a centralised system with one backup is 0.1 J per transaction.

§ EF^{b} is obtained based on the following assumptions: 1) energy consumption of a permissioned blockchain with 10 nodes is 1 J per transaction (Sedlmeir et al., 2020); 2) the estimated number of users of digital systems is about 3000 nodes in Singapore (Singapore Customs, 2014) and 664,000 nodes in China (UNESCAP, 2015); 3) the energy consumption of a permissioned blockchain is proportional to the network size (Sedlmeir et al., 2020).

7.4 Result analysis and implications

This section presents the application results in terms of unit emissions of shipping events relating to shipping documents and the total emission reductions from digitalising shipping documents.

7.4.1 Unit emissions of shipping events in Singapore and China

The unit emissions of various shipping events in Singapore and China are provided in Table 7.4. Next, we will discuss the results from the following perspectives: the paper system, digital systems, separate and integrated platforms.

Table 7.4 Documents-related emissions per shipping event in different documentation systems.

Document-related emissions per shipping event (g CO2e/shipping event)	Singapore			China		
	Paper system	Centralised system	Blockchain system	Paper system	Centralised system	Blockchain system
Per import shipment (total)	2859.6736	7.9910	8.6221	11827.5998	20.9287	233.9613
Emissions from printing documents	93.5215	0	0	164.9431	0	0
Emissions from physical storage of documents	60.8351	7.9350	7.9350	262.6155	20.7328	20.7328
Emissions from VT	0.0556	0.0556	0.0556	0.1952	0.1952	0.1952
Emissions from CT	2705.2615	0	0	11399.8460	0	0
Emissions from digital systems	0	0.0004	0.6315	0	0.0006	213.0333
Per export shipment (total)	1783.6622	14.0842	14.7153	6109.4584	14.3338	217.2221
Emissions from printing documents	107.5497	14.0282	14.0282	174.3685	14.1380	14.1380
Emissions from physical storage of documents	52.9001	0	0	234.9717	0	0
Emissions from VT	0.0556	0.0556	0.0556	0.1952	0.1952	0.1952
Emissions from CT	1623.1569	0	0	5699.9230	0	0
Emissions from digital systems	0	0.0004	0.6315	0	0.0006	202.8889
Per transshipment (total)	2851.6830	0.0004	0.6315	11690.4359	0.0005	152.1667
Emissions from printing documents	93.5215	0	0	117.8165	0	0
Emissions from physical storage of documents	52.9001	0	0	172.7733	0	0
Emissions from VT	0	0	0	0	0	0
Emissions from CT	2705.2615	0	0	11399.8460	0	0
Emissions from digital systems	0	0.0004	0.6315	0	0.0005	152.1667
Per vessel call (total)	3378.0931	0.0006	0.9122	25862.0258	0.0013	436.2111
Emissions from printing documents	84.1693	0	0	471.2661	0	0
Emissions from physical storage of documents	47.6100	0	0	691.0933	0	0
Emissions from VT	0	0	0	0	0	0
Emissions from CT	3246.3138	0	0	24699.6664	0	0
Emissions from digital systems	0	0.0006	0.9122	0	0.0013	436.2111

Note: CT - car transport; VT- van transport.

Source: Author.

7.4.1.1 Paper system

The results in the paper systems of the two countries are generally consistent. Among various emission sources, CT is the largest source for all shipping events in both countries. The associated emissions are 91-98% of the total emissions per shipping event. A possible explanation is that CT has a larger emission factor compared with paper printing and storage. Another reason could be that VT is shared among different types of cargoes, so its emissions are partially attributed to shipping documents, but CT in discussion is solely for moving shipping documents so its emissions are fully attributed to shipping documents. The results also indicate that the GHG impact of printing and storing paper documents is not significant, compared with that of transportation generated by paper documents. The results suggest the importance of reducing CT to reduce GHG emissions associated with shipping documents.

Regarding country-wide comparison, Singapore has lower unit emissions than China for all types of shipping events. This could be attributed to three reasons, namely fewer documents required, fewer government agencies involved, and shorter retention period of records required. Singapore requires fewer documents for both cargo and vessel clearance, which can be reflected by the number of distinct documents as shown in Table 7.2. Involvement of fewer government agencies means fewer transportation trips and repeated submissions. A shorter retention period of records contributes to lower storage emissions. Regarding emission sources, the emissions from CT in China are much higher than those in Singapore. This is because China has a longer average travel distance as a large country and incurs more CT trips per shipping event with more complex processes.

Among various types of shipping events, vessel call generates the largest unit emissions in both countries, followed by import shipment, transshipment and export shipment. This is because the procedures of vessel call are more tedious than other shipping events, requiring more CT trips and paper documents.

7.4.1.2 Digital system

Table 7.5 illustrates the percentage reduction in GHG emissions of digitalising shipping documents with a centralised system and a blockchain system. More than 96% of unit emissions of shipping events can be reduced by changing from a paper system to a digital one for both technologies. This represents a significant positive environmental impact of digitalising shipping documents in maritime supply chains.

In terms of absolute values (See Table 7.4), the emissions of handling shipping documents in a blockchain system are much higher than those in a centralised system. This is because the energy consumption of blockchain is generally significantly higher than that of centralised systems due to backups and natural redundancy of the systems (Sedlmeir et al., 2020). The difference between Singapore and China in unit emissions for a blockchain system is much larger than that in a centralised system. This is because blockchain's emission factor is much higher than that of a normal centralised system, which amplifies the impact of difference in the number of document transactions between the two countries.

Table 7.5 Percentage reduction in unit emissions by digitalising shipping documents.

Percentage reduction in unit emissions of shipping event	Singapore		China	
	Centralised system	Blockchain system	Centralised system	Blockchain System
Per import shipment	99.72%	99.70%	99.82%	98.02%
Per export shipment	99.21%	99.17%	99.77%	96.44%
Per transshipment	100.00%	99.98%	100.00%	98.70%
Per vessel call	100.00%	99.97%	100.00%	98.31%

Source: Author.

7.4.1.3 Separate platforms vs an integrated platform

The major difference between the two formats of platforms in this study is that separate platforms may incur repeated transactions, as a digital document may have to be submitted repeatedly in different platforms. In this regard, a comparative analysis of the two formats is conducted, as shown in Table 7.6.

The marginal GHG benefits shifting from separate platforms to an integrated platform are nearly negligible, even though the latter has slightly higher emission reductions than the former in certain cases. Under a centralised digital system, the effects of the two formats on emission reductions are similar. The emission factor of a centralised system is so small that the impact of additional transactions caused by repeated submissions in separate platforms is negligible. Under a blockchain system, the difference in emissions between an integrated platform and separate platforms in China is much larger than in Singapore. This is because of the high emission factor of blockchain in China. However, both formats can reduce more than 97% of emissions from the paper system. There is no significant difference between the two formats in terms of their capability to reduce document-related emissions.

Table 7.6 Unit emissions of shipping events from paper systems to digital systems: separate platforms vs an integrated platform.

Country	Unit emissions of shipping events*	Centralised system			Blockchain system		
		Separate platform	Integrated platform	Difference	Separate platform	Integrated platform	Difference
Singapore	Per import shipment	7.9910	7.9910	0	8.6221	8.6221	0
	Per export shipment	14.0842	14.0842	0	14.7153	14.7153	0
	Per transshipment	0.0004	0.0004	0	0.6315	0.6315	0
	Per vessel call	0.0006	0.0006	0	0.9473	0.9122	0.0351
China	Per import shipment	20.9289	20.9287	0.0002	296.4169	233.9613	62.4556
	Per export shipment	14.3340	14.3338	0.0002	279.9832	217.2221	62.7611
	Per transshipment	0.0006	0.0005	0.0001	177.1000	152.1667	24.9333
	Per vessel call	0.0019	0.0013	0.0006	619.8500	436.2111	183.6389

Note: The unit emissions are in g CO2e/shipping event.
Source: Author.

7.4.2 Total GHG impact: an example of Singapore

The national total GHG reductions by digitalising shipping documents are calculated based on available data in Singapore for 2017. As shown in Table 7.7, both digital systems can reduce the total GHG emissions relating to paper-based shipping documents by more than 99% in Singapore. A centralised system performs slightly better than a blockchain system in terms of GHG reductions, as the former saves about 1,658.85 kg CO_2e per annum more than the latter. In practice, the difference is nearly negligible. This indicates that the GHG impact of blockchain and centralised systems to digitalise shipping documents are very similar.

When digitalising shipping documents, the most significant reduction comes from the elimination of CT, which contributes the largest emissions (93%) of the paper system in Singapore. The result further confirms the importance of CT to reduce GHG emissions associated with shipping documents.

Table 7.7 GHG emissions relating to shipping documents in Singapore.

Emission (kg CO_2e)	Paper system	Centralised system	Blockchain system
Emissions from VT	124.91	124.91	124.91
Emissions from CT	5,584,135.91	0	0
Emissions from physical storage of documents	142,210.40	7,337.74	7,337.74
Emissions from printing documents	256,990.33	18,550.33	18,550.33
Emissions from digital systems	0	1.11	1,659.96
Grand Total	5,983,461.56	26,014.10	27,672.94
GHG reductions from paper system	-	5,957,447.47	5,955,788.62
Percentage reduction from paper system	-	99.57%	99.54%

Note: CT- car transport; VT – van transport.
Source: Author.

Table 7.8 shows the total emissions by shipping event in the paper system of Singapore. Import and export shipments account for about 44% and 39% of total emissions relating to handling shipping documents across stakeholders in the country, respectively. This indicates the importance of focusing on digitalising customs clearance in the country. The result affirms the digitalisation decisions of Singapore which digitalised its customs clearance procedures much earlier than its port clearance procedures (1989 vs 1999). Emissions from documents relating to transshipment only constitute 8% of the total emissions in the country, although Singapore is a transshipment hub port of which 85% of container throughput are transshipment cargoes. This suggests that in Singapore each transshipment usually handles very large cargo quantities. These results provide insights to stakeholders on where to focus when digitalising shipping documents.

Table 7.8 Document-related GHG emissions by shipping events in the paper system of Singapore.

Emission source	Export	Import	Transshipment	Vessel call	Row Total
CT	2,146,394.74	2,501,635.76	464,912.71	471,192.70	5,584,135.91
Printing documents	142,219.20	86,482.08	16,072.13	12,216.92	256,990.33
Physical storage of documents	69,952.82	56,255.99	9,091.14	6,910.46	142,210.40
VT	73.51	51.41	-	-	124.91
Column Total	2,358,640.27	2,644,425.23	490,075.98	490,320.08	5,983,461.56

Note: CT- car transport; VT – van transport.
Source: Author.

7.4.3 Implications

The results have several institutional and practical implications. Firstly, the difference in GHG impact between blockchain and centralised systems to digitalise shipping documents is nearly negligible, despite the concerns of low energy efficiency of blockchain. It suggests that blockchain's low energy efficiency should not be an issue to hinder its wide adoption. This together with blockchain's technical advantages implies a promising potential of blockchain to be applied in the digitalisation processes of the maritime industry.

Secondly, car transport is the key to reducing the carbon footprint associated with shipping documents, especially for countries with large land areas. Geographical proximity among maritime stakeholders can assist in reducing GHG emissions significantly. When transforming to digital systems and designing relevant procedures, government agencies and business decision-makers should prioritise eliminating or at least minimising car transport of paper documents. Duplicate processes for documents submission in both digital and paper formats should also be avoided to minimise car transport.

Thirdly, there is no significant difference between separate platforms and an integrated platform in terms of their impact on emission reductions. When investing in a digital system for maritime supply chains, it is suggested that stakeholders adopt a gradual approach by starting with separate platforms which usually require less financial support and inter-organisational coordination and have less technical complexity. After gaining the technology know-how, an integrated platform that consolidates both business to government (B2G), government to government (G2G) and business to business (B2B) procedures in a single window can be developed later. The history of digitalisation development in Singapore’s vessel clearance process is a good example. In the early stage, separate platforms are provided by three government agencies in Singapore for vessel port clearance. Some common data need to be filled repeatedly in these platforms. However, in June 2020, which is about 11 years later than the introduction of separate platforms, Singapore replaced the original systems with a one-stop port clearance portal which integrates the interactions across the three regulatory bodies.

Fourthly, the comparison between Singapore and China implies that simplified government procedures and a leaner government structure help to reduce document-related emissions. Governments could consider simplifying their procedures by removing dispensable documents requirement. They could also restructure governments by integrating or merging functions from different agencies. This aligns with past relevant policies in China. For instance, along the process of digitalisation, China has also cancelled the submission requirement of a few documents such as the certificate of inspection for goods inward (outward) and declaration form for export goods (used for export tax refund only). China Inspection and Quarantine Bureau (CIQ) was merged into China Customs in 2018 to simplify trade procedures.

Lastly, digital transformation cannot be truly effective without the establishment of a relevant legal framework. In Singapore, the re-enacted Electronic Transactions Act in 2010 provides a legal foundation for the use of electronic contracts and digital signatures (IMDA, 2019). With the act, paper documents and electronic ones are generally treated equally. In China, the revised China Customs Law in 2000 not only allows digital declaration but also adopts international practices for the use of information and communication technology (UNESCAP, 2015). Besides, the E-signature Law in China provides a legal foundation of digital signature (UNESCAP, 2015). Thus, a country’s legal framework should be updated to keep up with the pace of its digital development. Jurisdictions could consider adopting the United Nations Commission on International Trade Law (UNCITRAL) Model Law on Electronic

Transferable Records (Clyde&Co LLP, 2018) to facilitate the use of digital documents.

7.5 Conclusion

This chapter evaluates the GHG impact of digitising shipping documents across maritime supply chains and compares the difference in GHG performance in a blockchain system and a centralised system. A process analysis-based estimation framework with concrete methods is proposed according to the conceptual guidelines of GHG protocol for project accounting. Taking Singapore and China as examples, the research estimates the unit emissions of different shipping events in a paper system and a digital system. Then the potential emission reductions from digitalisation are obtained. The results show that digitalising shipping documents can reduce more than 99% of total emissions relating to paper documents in Singapore in either a blockchain or centralised system. Blockchain systems have a comparable capability to reduce GHG emissions with centralised systems as a digital solution for shipping documents. It suggests that blockchain's low energy efficiency should not be a concern for potential adopters when they consider deploying the technology. Car transport of paper documents is the key area to focus on when digitalising shipping documents as it is the largest emission source constituting over 90% of document-related emissions per shipping event in both countries. There is no significant difference between separate platforms and an integrated platform in terms of emission reductions when digitalising shipping documents. These results provide implications on the key areas to focus on, which digital technology is more suitable, and which kind of platform to start with (separate one or integrated one).

CHAPTER 8 CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

This chapter concludes the thesis with a summary of main research findings and research contributions. It also presents the limitations of the research and proposes future research directions.

The primary goal of this thesis is to analyse blockchain adoption in the maritime industry. It starts with an in-depth literature review on blockchain technology in general and its adoption in general and in various industries. Then the focus is zoomed into the maritime industry. It was found that there is a lack of thorough analysis of blockchain adoption in the maritime industry covering various sectors of the industry. There are no studies on analysing whether and when to adopt blockchain in an industry. There is no research on studying the evolution of blockchain adoption in terms of adoption rate in an industry. There are scarce studies to analyse the GHG impact relating to blockchain adoption in a non-financial use case. In order to address these research gaps, studies in chapters 4-7 are then developed using the methods described in chapter 3. With that, the proposed research objectives are thereby fulfilled.

8.1 Summary of main findings

This section summarises the main findings relating to achieving the research objectives listed in chapter 1.

1) To thoroughly analyse current and emerging blockchain applications from the perspectives of different sectors in the maritime industry

This objective has been met in chapter 4 with an extensive review of existing literature and online sources like newspapers and magazines on blockchain adoption in the maritime industry. A method of content analysis and an inductive approach are employed to thoroughly analyse blockchain applications in different sectors of the maritime industry. The analysis not only answers where but also explains why to adopt blockchain in these potential application areas. The result shows that the major current blockchain applications in the industry fall into four areas: 1) electronic bills of lading, 2) ship operations, 3) ship finance and 4) marine insurance, with an emerging trend to be integrated with other technologies such as IoT, smart grid and 3D printing. The analysis indicates that the majority of maritime blockchain applications is to achieve a lean process from three aspects, namely reducing paperwork, enhancing information sharing, and automating processes.

2) To develop a conceptual framework of blockchain adoption in the maritime industry in a holistic view and guide future research.

This objective has been achieved in chapter 4 too. On top of the findings relating to objective 1, a conceptual framework is developed, integrating Moon and Ngai's (2008) framework, TAM and TOE model. The conceptual framework consists of five dimensions: technical features, commercial benefits, applicable areas, major stakeholders in each application, and potential adoption challenges. With the five dimensions, the conceptual framework provides a holistic view of blockchain adoption in the maritime industry. It answers the fundamental questions of why, how and who regarding blockchain's adoption in the maritime industry. Ample future research opportunities are also identified based on the framework.

3) To analyse ship operators' optimal adoption time of blockchain when facing an adoption request from a big customer, using a big shipper and multiple ship operators as a case.

Chapter 5 has fulfilled this objective by developing a game theoretical model. Analytical results are derived from the study. In addition, an algorithm is also developed to obtain the numerical results. The model is extended from a fixed pricing structure to a mixed pricing structure of blockchain (i.e., the blockchain fee consists of fixed and variable parts). It is further extended to consider the impact of Covid-19 on blockchain adoption time. Using industry data, numerical applications are conducted. The result suggests that (i) the substitution policy only matters to small companies and is only necessary under fixed pricing structure (i.e. the blockchain fee is fixed regardless of volume handled); (ii) there is a threshold of substitution ratio and cut-off time for them to effectively induce small companies to adopt blockchain early; (iii) blockchain developers should consider a mixed pricing structure instead of fixed pricing structure for faster and wider blockchain adoption; (iv) blockchain initiators should focus more on improving the technology's cost-effectiveness rather than relying heavily on externalities like substitution policies to promote the adoption of the technology; (v) Covid-19 shows a positive effect on accelerating blockchain adoption for small players and when blockchain benefits are very small.

4) To analyse the evolution of blockchain adoption in the maritime industry in terms of adoption rate, using electronic bills of lading as a case.

This objective has been achieved in Chapter 6 by developing an asymmetric evolutionary game model. Using industry data, the potential dynamic change among shippers and carriers is examined in two situations depending on who pays the blockchain eBL transaction fee (carriers – case 1, shippers – case 2). The key findings are: (i) blockchain eBLs cannot reach mass adoption given the current status unless a critical mass is reached among either carriers (about 15% in case 1 or 16% in case 2) or shippers (about 39% in case 1 or 58% in case 2); (ii) it is more efficient to promote blockchain adoption by focusing on carriers than shippers because carriers require a lower critical mass than shippers (15% < 39% in case 1 or 16%<58% in case 2); (iii) players are more inclined to use blockchain eBLs for low-value products in the current market situation; (iv) when blockchain adoption is the evolutionarily stable strategy, the convergence speed is faster if carriers instead of shippers pay the blockchain eBL transaction fee.

5) To develop an estimation framework with concrete methods to evaluate the GHG impact of digitalising shipping documents with blockchain and compare it with centralised systems in their GHG impact.

This objective has been fulfilled in Chapter 7 based on a process analysis approach. An estimation framework with concrete methods is proposed according to the conceptual guidelines of GHG protocol for project accounting. Taking Singapore and China as examples, the research estimates the unit emissions of different shipping events in a paper system and a digital system. Then the potential emission reductions from digitalisation with blockchain and centralised systems are compared. The major results are (i) digitalisation can reduce over 99% of paper document-related emissions in Singapore; (ii) car transport to transfer documents is the largest emission source in paper systems constituting over 90% of emissions per shipping event; (iii) blockchain and centralised systems have similar effects on emission reductions; so do integrated and separated platforms.

8.2 Main research contributions

Through achieving the research objectives, this research makes contributions to academia and practitioners. The contributions of each study in the research are summarised below.

The contributions of the study in Chapter 4 are four-fold. Firstly, it develops a novel conceptual framework to systematically conceptualise blockchain adoptions in the maritime industry. It helps researchers and practitioners to converge their understanding of blockchain adoption in the industry and form a common basis and guide for future research. Moreover, this framework can be extended as a general tool for analysing the applications of a specific technology in a specific industry. Secondly, this paper is the first to consolidate the state-of-the-art of blockchain applications in the maritime industry. It assists stakeholders to better understand why and how blockchain can be applied in different maritime sectors and hence stimulates use case development in the industry. Thirdly, the implications and recommendations provided in the paper shed light to individual organisations on how to ride on the wave of blockchain smartly and to government agencies on how to better promote and govern blockchain innovation. Lastly, this study identifies ample future research opportunities and represents a research agenda for the field of blockchain adoption in the maritime industry.

The study in Chapter 5 deepens the literature on blockchain adoption by answering an important practical question about whether and when to adopt the technology. It is the first in the literature to analyse the optimal adoption time of blockchain technology in an industry. In terms of methodological significance, a novel algorithm is developed to obtain the numerical solutions of companies' optimal adoption time. For practitioners, this study sheds light on how to decide the optimal adoption time of blockchain with the requests from a big customer, which is a current market trend. It also provides useful insights to blockchain promoters or policymakers on how to facilitate and accelerate blockchain adoption.

The study in Chapter 6 makes the following contributions. Academically, it is the first attempt to analyse the evolution of blockchain adoption from the perspective of adoption rate. The case of blockchain eBLs is applied in the study as a promising emerging application in the maritime industry. An evolutionary game model is proposed to conduct the evolutionary analysis considering economic factors, network effects and the impact of incumbent systems. The proposed model can serve as a baseline for future research on evolution of blockchain adoption in different cases. Practically, it provides implications for stakeholders to establish more efficient policies to promote blockchain-based maritime systems and accelerate adoption.

The study in Chapter 7 contributes to academia and practitioners in the following ways. It advances the literature by developing an estimation framework with concrete methods to quantitatively measure the GHG impact of digitalising shipping documents across maritime supply chains. The proposed framework could also be applied to work on document-related emissions in other industries. Additionally, it introduces a novel concept of unit emission of shipping event, which could serve as an indicator of a country's performance in the environmental efficiency of shipping documentation and is useful for country-wise comparison. For maritime practitioners, it sheds light on how to digitalise the processes of shipping documents across stakeholders such as the key areas to focus on and whether blockchain is environmentally better than centralised systems. Besides, the cases of Singapore and China provide useful references for other countries in deciding digitalisation development for shipping documents.

In short, this thesis advances blockchain research in the maritime industry from conceptual, analytical and practical perspectives. From a conceptual perspective, it develops a novel conceptual framework to converge the understanding of blockchain adoption in the maritime industry. From an analytical perspective, specific mathematical models are developed based on non-cooperative game theory and evolutionary game theory to analyse adoption problems of blockchain, particularly in the maritime industry. From a practical perspective, the research solves practical questions of blockchain adoption such as whether and when to adopt, how the adoption rate will evolve over time, what is the critical mass to encourage mass adoption and what is the environmental impact. The main findings provide useful insights for stakeholders on decision making regarding blockchain adoption and facilitation.

8.3 Limitations and future research

Despite its significance, this research has some limitations. This section discusses the limitations of each study in the research and proposes future research directions.

The study in Chapter 4 has captured the current major blockchain applications and emerging adoption trends in the maritime industry. However, with the continuing development of blockchain and the growing understanding of the technology in the industry, more use cases and other potential benefits and challenges of blockchain could arise and may not be included in the paper. Therefore, this study serves as a baseline for future deployment of blockchain in the maritime industry and the conceptual framework developed in the study creates value by guiding future research.

The study in Chapter 5 is a new contribution to understand how companies make blockchain adoption decisions. It leaves space for extensions in future studies. For example, in reality, the customer's demand may fluctuate. Future research may extend the model by including demand uncertainty. Another important research direction is to analyse how a big customer makes substitution decisions to maximise its payoff based on vendors' blockchain strategies.

Two main limitations exist in the study in Chapter 6. Firstly, it does not consider the impact of legal barriers on blockchain adoption. Besides, there are additional stakeholders involved in a BL such as banks which may affect the dynamics of blockchain adoption but are not analysed in the model. Future research could consider exploring the evolutionary path of blockchain adoption by including the potential legal factors and more stakeholders.

The study in Chapter 7 is limited in the way that shipping documentation procedures may be slightly different in different provinces or states in a country, which are not considered in the case of China. Future research could consider obtaining data at the provincial or state level. Besides, international transport between countries is not included in the study as we focus on national emissions. However, it is considered an important factor of global emissions relating to shipping documents in view of the long distance and large emission factor of transport involved like airfreight. Future research could consider the impact of international transport relating to shipping documents, which requires more detailed shipment data on international trade.

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APPENDIX A: PROOFS OF OPTIMAL ADOPTION TIME AS A LEADER AND AS A FOLLOWER IN THE BASE MODEL AND THE EXTENDED MODELS

1. Proof of Lemma 1

Being a leader, the condition $T_i \leq T_c$ holds.

$$U_i^{l'}(T_i, T_{-i}) = \mathrm{e}^{-\lambda T_i}\lambda C_i^0 + \frac{\mathrm{e}^{-\lambda T_i}}{1-e^{-\lambda}}\lambda C_i^a - \mathrm{e}^{-\gamma T_i}\epsilon_i(q_i^0).$$

$$U_i^{l''}(T_i, T_{-i}) = -\mathrm{e}^{-\lambda T_i}\lambda^2 C_i^0 - \frac{\mathrm{e}^{-\lambda T_i}}{1-e^{-\lambda}}\lambda^2 C_i^a + \mathrm{e}^{-\gamma T_i}\gamma\epsilon_i(q_i^0).$$

By the first order condition, $U_i^{l'}\left(\widehat{T_\iota}, \widehat{T_{-\iota}}\right) = 0$, then

$$\widehat{T_\iota} = \frac{1}{\lambda-\gamma}\ln\frac{\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}}C_i^a}{\epsilon_i\left(q_i^0\right)}.$$

a) If $\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}}C_i^a > \epsilon_i(q_i^0)$ (i.e., $r_i^l < 1$), $U_i^{l''} < 0$ given that $\lambda > \gamma$ and $\gamma T_c < \lambda T_c < 1$.

   $$U_i^{l''} < -\lambda\epsilon_i(q_i^0)e^{-\lambda T_i} + \gamma\epsilon_i(q_i^0)e^{-\gamma T_i} = \epsilon_i(q_i^0)\left(\gamma e^{-\gamma T_i} - \lambda e^{-\lambda T_i}\right) < 0.$$

   $f(x) = x\mathrm{e}^{-xT_i}$ is a monotonically increasing function for $xT_i < 1$. Given $T_i \leq T_c$ and $\gamma T_c < \lambda T_c < 1$, then $\gamma T_i < \lambda T_i < 1$. Given $\gamma < \lambda$, then $f(\gamma) < f(\lambda)$, i.e., $\gamma e^{-\gamma T_i} < \lambda e^{-\lambda T_i}$. Since $\epsilon_i(q_i^0)$ is always positive, $\epsilon_i(q_i^0)\left(\gamma e^{-\gamma T_i} - \lambda e^{-\lambda T_i}\right) < 0$, i.e., $U_i^{l''} < 0$.

   If $\widehat{T_\iota} \leq T_c, U_i^l$ has a maximum value at $T_i = \widehat{T_\iota}$ for $T_i \in [0, T_c]$.

   $$T_i^l = \widehat{T_\iota} = \frac{1}{\lambda-\gamma}\ln\frac{\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}}C_i^a}{\epsilon_i\left(q_i^0\right)}.$$

   However, if $\widehat{T_\iota} > T_c$, U_i^l is a monotonically increasing function when $T_i \in [0, T_c]$, U_i^l has a maximum value at T_c. Hence

   $T_i^l = T_c.$

b) If $\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}}C_i^a \leq \epsilon_i(q_i^0)$ (i.e. $r_i^l \geq 1$) , $\widehat{T_\iota} \leq 0$. Then $U_i^{l'} \leq \mathrm{e}^{-\lambda T_i}\epsilon_i(q_i^0) - \mathrm{e}^{-\gamma T_i}\epsilon_i(q_i^0) = \left(\mathrm{e}^{-\lambda T_i} - \mathrm{e}^{-\gamma T_i}\right)\epsilon_i(q_i^0)$. Since $\gamma < \lambda, e^{-\gamma T_i} > e^{-\lambda T_i}$. We can have $\mathrm{e}^{-\lambda T_i} - \mathrm{e}^{-\gamma T_i} < 0$. Thus $\left(\mathrm{e}^{-\lambda T_i} - \mathrm{e}^{-\gamma T_i}\right)\epsilon_i(q_i^0) < 0$.

   As such, $U_i^{l'} < 0$. U_i^l is a monotonically decreasing function with respect to T_i for $T_i \in [0, T_c]$, so it has a maximum value at $T_i = 0$. Hence $T_i^l = 0$.

Therefore, the optimal adoption time of ship operator i as a leader (T_i^l) is:

$$T_i^l = \begin{cases} \min(\frac{1}{\lambda-\gamma}\ln\frac{\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}}C_i^a}{\epsilon_i(q_i^0)}, T_c), & \text{if } r_i^l < 1 \\ 0 \qquad\qquad\qquad\qquad , & \text{if } r_i^l \geq 1 \end{cases},$$

where $r_i^l = \frac{\epsilon_i(q_i^0)}{C_i'(0)} = \frac{\epsilon_i(q_i^0)}{\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}}C_i^a}$.

2. Proof of Lemma 2

Being a follower, the condition $T_i > T_c$ holds.

$$U_i^{f'}(T_i, T_{-i}) = \mathrm{e}^{-\lambda T_i}\lambda C_i^0 + \frac{\mathrm{e}^{-\lambda T_i}}{1-e^{-\lambda}}\lambda C_i^a - \mathrm{e}^{-\gamma T_i}\epsilon_i(q_i^0 - \beta q_i^0).$$

$$U_i^{f''}(T_i, T_{-i}) = -\mathrm{e}^{-\lambda T_i}\lambda^2 C_i^0 - \frac{\mathrm{e}^{-\lambda T_i}}{1-e^{-\lambda}}\lambda^2 C_i^a + \mathrm{e}^{-\gamma T_i}\gamma\epsilon_i(q_i^0 - \beta q_i^0).$$

By the first order condition, $U_i^{f'}(\widehat{T_f}, \widehat{T_{-f}}) = 0$, then

$$\widehat{T_f} = \frac{1}{\lambda-\gamma}\ln\frac{\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}}C_i^a}{\epsilon_i(q_i^0 - \beta q_i^0)}.$$

a) If $\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}}C_i^a > \epsilon_i(q_i^0 - \beta q_i^0)$ $(i.e.\ r_i^f < 1)$, $U_i^{f''} < 0$ given that $\lambda > \gamma$ and $\gamma T_c < \lambda T_c < 1$.

   $U_i^{f''} < \epsilon_i(q_i^0 - \beta q_i^0)(\gamma e^{-\gamma T_i} - \lambda e^{-\lambda T_i})$. As approved in the proof of Lemma 1, $\gamma e^{-\gamma T_i} < \lambda e^{-\lambda T_i}$. Hence $\epsilon_i(q_i^0 - \beta q_i^0)(\gamma e^{-\gamma T_i} - \lambda e^{-\lambda T_i}) < 0$, i.e., $U_i^{f''} < 0$.

   So if $\widehat{T_f} > T_c$, U_i^f has a maximum value at $T_i = \widehat{T_f}$ for $T_i \in (T_c, \infty)$. Hence

   $$T_i^f = \widehat{T_f} = \frac{1}{\lambda-\gamma} ln\frac{\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}}C_i^a}{\epsilon_i(q_i^0 - \beta q_i^0)}.$$

   However, if $\widehat{T_f} \leq T_c$, U_i^f is a monotonically decreasing function when $T_i \in (T_c, \infty)$, U_i^f has a maximum value when T_i is approaching T_c^+. Hence

   $T_i^f = T_c + \Delta$, where Δ is a small real number to ensure $T_i^f > T_c$.

b) If $\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}}C_i^a \leq \epsilon_i(q_i^0 - \beta q_i^0)$ (i.e. $r_i^f \geq 1$), $\widehat{T_f} \leq 0$ and $U_i^{f'} < 0$ (similar to the proof of Lemma 1-b). U_i^f is a monotonically decreasing function with respect to T_i for $T_i \in (T_c, \infty)$. Therefore, given the condition of being a follower ($T_i > T_c$), the ship operator has a maximum value at $T_i = T_c + \Delta$. Hence,

   $$T_i^f = T_c + \Delta.$$

Therefore, the optimal adoption time of ship operator i as a follower (T_i^f) is:

$$T_i^f = \begin{cases} \max\left(\frac{1}{\lambda-\gamma}\ln\frac{\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}}C_i^a}{\epsilon_i\left(q_i^0 - \beta q_i^0\right)}, T_c + \Delta\right), & \text{if } r_i^f < 1 \\ T_c + \Delta \qquad , & \text{if } r_i^f \geq 1 \end{cases},$$

where $r_i^f = \frac{\epsilon_i\left(q_i^0-\beta q_i^0\right)}{C_i'(0)} = \frac{\epsilon_i\left(q_i^0-\beta q_i^0\right)}{\lambda C_i^0+\frac{\lambda}{1-e^{-\lambda}}C_i^a}$ and Δ is a small positive real number to ensure $T_i^f > T_c$.

3. Proof of Lemma 3

In a mixed pricing structure, the first and second derivatives of a leader's payoff function are as below

$$U_i^{l'}(T_i, T_{-i}) = \mathrm{e}^{-\lambda T_i}\lambda C_i^0 + \frac{\mathrm{e}^{-\lambda T_i}}{1-e^{-\lambda}}\lambda C_i^a + \mathrm{e}^{-\lambda T_i}q_i^0 C_i^b - \mathrm{e}^{-\gamma T_i}\epsilon_i(q_i^0).$$

$$U_i^{l''}(T_i, T_{-i}) = -\mathrm{e}^{-\lambda T_i}\lambda^2 C_i^0 - \frac{\mathrm{e}^{-\lambda T_i}}{1-e^{-\lambda}}\lambda^2 C_i^a - \mathrm{e}^{-\lambda T_i}\lambda q_i^0 C_i^b + \mathrm{e}^{-\gamma T_i}\gamma\epsilon_i(q_i^0).$$

Similar to the proof of Lemma 1, the optimal adoption time of ship operator i in the extended model as a leader (T_i^l) can be derived as below:

$$T_i^l = \begin{cases} \min\left(\frac{1}{\lambda-\gamma}\ln\frac{\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}}C_i^a + q_i^0 C_i^b}{\epsilon_i\left(q_i^0\right)}, T_c\right), & if\ r_i^l < 1 \\ 0 \qquad , & if\ r_i^l \geq 1 \end{cases},$$

where $r_i^l = \frac{\epsilon_i\left(q_i^0\right)}{C_i'(0)} = \frac{\epsilon_i\left(q_i^0\right)}{\lambda C_i^0+\frac{\lambda}{1-e^{-\lambda}}c_a+c_b q_i^0}$.

4. Proof of Lemma 4

In a mixed pricing structure, the first and second derivatives of a leader's payoff function are as below

$$U_i^{f'}(T_i, T_{-i}) = \mathrm{e}^{-\lambda T_i}\lambda C_i^0 + \frac{\mathrm{e}^{-\lambda T_i}}{1-e^{-\lambda}}\lambda C_i^a + \mathrm{e}^{-\lambda T_i}(q_i^0 - \beta q_i^0)C_i^b - \mathrm{e}^{-\gamma T_i}\epsilon_i(q_i^0 - \beta q_i^0).$$

$$U_i^{f''}(T_i, T_{-i}) = -\mathrm{e}^{-\lambda T_i}\lambda^2 C_i^0 - \frac{\mathrm{e}^{-\lambda T_i}}{1-e^{-\lambda}}\lambda^2 C_i^a - \mathrm{e}^{-\lambda T_i}\lambda(q_i^0 - \beta q_i^0)C_i^b + \mathrm{e}^{-\gamma T_i}\gamma\epsilon_i(q_i^0 - \beta q_i^0).$$

Similar to the proof of Lemma 2, the optimal adoption time of ship operator i in the extended model as a follower (T_i^f) can be derived as below:

$$T_i^f = \begin{cases} \max\left(\frac{1}{\lambda-\gamma}\ln\frac{\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}}C_i^a + C_i^b(q_i^0-\beta q_i^0)}{\epsilon_i\left(q_i^0-\beta q_i^0\right)}, T_c+\Delta\right), & if\ r_i^f < 1 \\ T_c+\Delta \quad , & if\ r_i^f \geq 1 \end{cases},$$

where $r_i^f = \frac{\epsilon_i\left(q_i^0-\beta q_i^0\right)}{C_i'(0)} = \frac{\epsilon_i\left(q_i^0-\beta q_i^0\right)}{\lambda C_i^0+\frac{\lambda}{1-e^{-\lambda}}c_a+c_b\left(q_i^0-\beta q_i^0\right)}$ and Δ is a small positive real number to ensure that $T_i^f > T_c$.

5. Proof of Lemma 5.

Being a leader, $T_i \in [0,T_c]$ holds.

First of all, $U_i^l(T_i,T_{-i})$ is continuous at T_s, because $\lim_{T_i\to T_s} U_i^l(T_i,T_{-i})$=$U_i^l(T_s,T_{-i})$.

1) If $T_s < T_c$ (Condition 1)

a) For $T_i \in [0,T_s]$, the first and second derivatives of leader's payoff function are as below:

$$U_i^{l'} = \frac{\mathrm{e}^{-\lambda T_i}\lambda C_i^a}{1-\mathrm{e}^{-\lambda}} + \mathrm{e}^{-\lambda T_i}\lambda C_i^0 + \mathrm{e}^{-\lambda T_i}C_i^b(1+\delta)q_i^0 - \mathrm{e}^{-\gamma T_i}\left(\epsilon_i((1+\delta)q_i^0) + \tau_i((1+\delta)q_i^0)\right)$$

$$U_i^{l''} = -\frac{\lambda^2\mathrm{e}^{-\lambda T_i}C_i^a}{1-\mathrm{e}^{-\lambda}} - \lambda^2\mathrm{e}^{-\lambda T_i}C_i^0 - \lambda\mathrm{e}^{-\lambda T_i}C_i^b(1+\delta)q_i^0 + \gamma\mathrm{e}^{-\gamma T_i}\left(\epsilon_i((1+\delta)q_i^0) + \tau_i((1+\delta)q_i^0)\right)$$

By the first order condition, let T_i^{l1} denote the solution of $U_i^{l'}(T_i,T_{-i}) = 0$ under this condition. Then

$$T_i = T_i^{l1} = \frac{1}{\lambda-\gamma}\ln\frac{1}{r_i^{l1}}\text{, where } r_i^{l1} = \frac{\epsilon_i\left((1+\delta)q_i^0\right) + \tau_i\left((1+\delta)q_i^0\right)}{\lambda C_i^0 + \frac{\lambda C_i^a}{1-\mathrm{e}^{-\lambda}} + (1+\delta)q_i^0C_i^b}.$$

i) If $r_i^{l1} < 1$ (i.e., $\lambda C_i^0 + \frac{\mathrm{e}^{-\lambda T_i}C_i^a}{1-\mathrm{e}^{-\lambda}} + (1+\delta)q_i^0C_i^b > \epsilon_i\left((1+\delta)q_i^0\right) + \tau_i\left((1+\delta)q_i^0\right)$), $T_i^{l1} > 0$. At the same time $U_i^{l''} \leq 0$, because

$$\begin{aligned} U_i^{l''} &< -\lambda e^{-\lambda T_i}\left[\epsilon_i\left((1+\delta)q_i^0\right)+\tau_i\left((1+\delta)q_i^0\right)\right]+\gamma e^{-\gamma T_i}\left[\epsilon_i\left((1+\delta)q_i^0\right)+\tau_i\left((1+\delta)q_i^0\right)\right] \\ &= \left(\gamma e^{-\gamma T_i}-\lambda e^{-\lambda T_i}\right)\left[\epsilon_i\left((1+\delta)q_i^0\right)+\tau_i\left((1+\delta)q_i^0\right)\right]. \end{aligned}$$

As proved in the proof of Lemma 1, $\gamma e^{-\gamma T_i} < \lambda e^{-\lambda T_i}$. Given $\epsilon_i\left((1+\delta)q_i^0\right)$ and $\tau_i\left((1+\delta)q_i^0\right)$ are both positive in the model setting, $\left(\gamma e^{-\gamma T_i}-\lambda e^{-\lambda T_i}\right)\left[\epsilon_i\left((1+\delta)q_i^0\right)+\tau_i\left((1+\delta)q_i^0\right)\right]<0.$ Hence, $U_i^{l''}<0.$ Therefore, U_i^l has a maximum value at T_i^{l1}.

Thus, a maximum value of U_i^l for $T_i\in[0,T_s]$ is expected when

$$T_i=\begin{cases} T_i^{l1}, \text{ if } 0<T_i^{l1}<T_s \\ T_s, \text{ if } T_i^{l1}\ge T_s \end{cases}.$$

ii) If $r_i^{l1}\ge 1$ (i.e., $\lambda C_i^0+\dfrac{e^{-\lambda T_i}C_i^a}{1-e^{-\lambda}}+(1+\delta)q_i^0C_i^b\le\epsilon_i\left((1+\delta)q_i^0\right)+\tau_i\left((1+\delta)q_i^0\right)$), $T_i^{l1}\le 0$. And $U_i^{l'}<0$, because

$$\begin{aligned} U_i^{l'} &\le e^{-\lambda T_i}\left[\epsilon_i\left((1+\delta)q_i^0\right)+\tau_i\left((1+\delta)q_i^0\right)\right]-e^{-\gamma T_i}\left[\epsilon_i\left((1+\delta)q_i^0\right)+\tau_i\left((1+\delta)q_i^0\right)\right] \\ &= \left(e^{-\lambda T_i}-e^{-\gamma T_i}\right)\left[\epsilon_i\left((1+\delta)q_i^0\right)+\tau_i\left((1+\delta)q_i^0\right)\right]<0. \end{aligned}.$$

Thus, under this condition U_i^l is a monotonically decreasing function with respect to T_i for $T_i\in[0,T_s]$ and it has a maximum value at $T_i=0$ for $T_i\in[0,T_s]$, if $r_i^{l1}\ge 1$(i.e., $T_i^{l1}\le 0$).

Therefore, U_i^l has a maximum value for $T_i\in[0,T_s]$ when

$$T_i=\begin{cases} 0, \text{ if } T_i^{l1}\le 0 \\ T_i^{l1}, \text{ if } 0<T_i^{l1}<T_s \\ T_s, \text{ if } T_i^{l1}\ge T_s \end{cases}.$$

b) For $T_i\in[T_s,T_c]$,the first and second derivatives of leader's payoff function are as below:

$$\begin{aligned} U_i^{l'} &= \frac{e^{-\lambda T_i}\lambda C_i^a}{1-e^{-\lambda}}+e^{-\lambda T_i}\lambda C_i^0+e^{-\lambda T_i}C_i^bq_i^0-e^{-\gamma T_i}\epsilon_i(q_i^0) \\ U_i^{l''} &= -\frac{\lambda^2e^{-\lambda T_i}C_i^a}{1-e^{-\lambda}}-\lambda^2e^{-\lambda T_i}C_i^0-\lambda e^{-\lambda T_i}C_i^bq_i^0+\gamma e^{-\gamma T_i}\epsilon_i(q_i^0) \end{aligned}$$

By the first order condition, let T_i^{l2} denote the solution of $U_i^{l'}(T_i, T_{-i}) = 0$ under this condition. Then

$$T_i = T_i^{l2} = \frac{1}{\lambda - \gamma} \ln \frac{1}{r_i^{l2}} \text{. where } r_i^{l2} = \frac{\epsilon_i(q_i^0)}{\lambda C_i^0 + \frac{\lambda C_i^a}{1 - e^{-\lambda}} + C_i^b q_i^0} .$$

Similar to the proof of Lemma 5-1)-a), we have the following:

i) $r_i^{l2} < 1$ (i.e., $\lambda C_i^0 + \frac{\mathrm{e}^{-\lambda T_i} C_i^a}{1 - \mathrm{e}^{-\lambda}} + C_i^b q_i^0 > \epsilon_i(q_i^0)$), $U_i^{l''} < 0$. Therefore, U_i^l has a maximum value at T_i^{l2}. Hence, a maximum value of U_i^l for $T_i \in [T_s, T_c]$ is expected when

$$T_i = \begin{cases} T_i^{l2}, \text{ if } T_s < T_i^{l2} < T_c \\ T_s, \text{ if } T_i^{l2} \le T_s \\ T_c, \text{ if } T_i^{l2} \ge T_c \end{cases} .$$

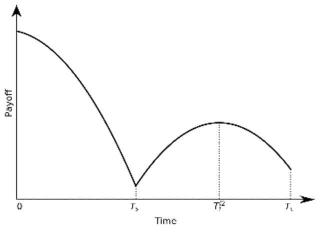
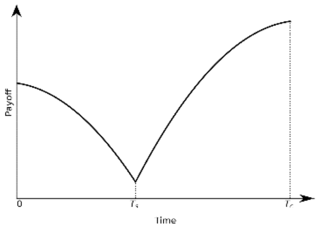
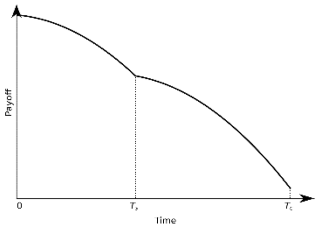
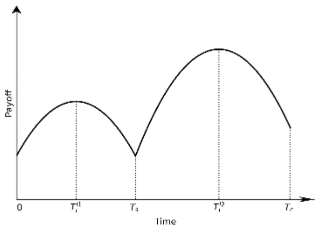
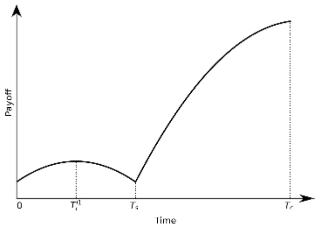
ii) If $r_i^{l2} \ge 1$ (i.e., $\lambda C_i^0 + \frac{\mathrm{e}^{-\lambda T_i} C_i^a}{1 - \mathrm{e}^{-\lambda}} + C_i^b q_i^0 \le \epsilon_i(q_i^0)$), $T_i^{l2} \le 0$ and $U_i^{l'} < 0$. Thus, under this condition U_i^l is a monotonically decreasing function with respect to T_i for $T_i \in [T_s, T_c]$. It has a maximum value at $T_i = T_s$ for $T_i \in [T_s, T_c]$ if $r_i^{l2} \ge 1$ (i.e., $T_i^{l2} \le 0$).

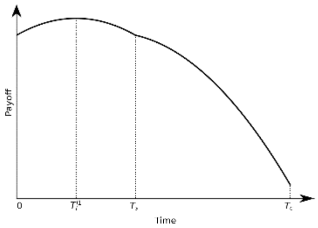
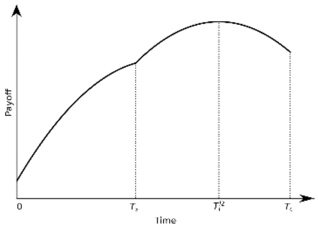
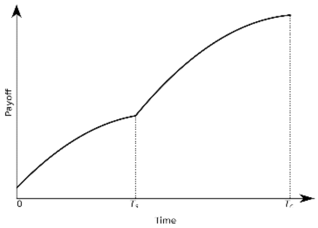
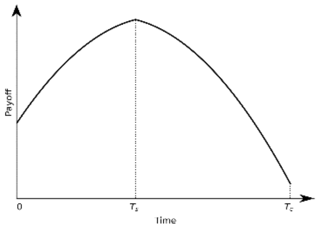
Therefore, for $T_i \in [T_s, T_c]$, U_i^l has a maximum value when

$$T_i = \begin{cases} T_i^{l2}, \text{ if } T_s < T_i^{l2} < T_c \\ T_s, \text{ if } T_i^{l2} \le T_s \\ T_c, \text{ if } T_i^{l2} \ge T_c \end{cases} .$$

In condition 1 ($T_s < T_c$), the payoff functions of leaders, and corresponding conditions and optimal adoption time can be summarised in Table A.1.

Table A.1. Optimal adoption time and graphs of payoff functions for a leader when $T_s < T_c$.

Conditions	Illustrative graphs of a leader's payoff function	Optimal adoption time as a leader
When $r_i^{l1} \geq 1$ (i.e., $T_i^{l1} \leq 0$):		
$T_s < T_i^{l2} < T_c$		$\underset{T_i \in \{0, T_i^{l2}\}}{\arg\max} U_i^l(T_i, T_{-i})$
$T_i^{l2} \geq T_c$		$\underset{T_i \in \{0, T_c\}}{\arg\max} U_i^l(T_i, T_{-i})$
$T_i^{l2} \leq T_s$		0
When $r_i^{l1} < 1$ (i.e., $T_i^{l1} > 0$):		
$T_i^{l1} < T_s$ and $T_s < T_i^{l2} < T_c$		$\underset{T_i \in \{T_i^{l1}, T_i^{l2}\}}{\arg\max} U_i^l(T_i, T_{-i})$
$T_i^{l1} < T_s$ and $T_i^{l2} \geq T_c$		$\underset{T_i \in \{T_i^{l1}, T_c\}}{\arg\max} U_i^l(T_i, T_{-i})$

$T_i^{l1} < T_s$ and $T_i^{l2} \le T_s$		T_i^{l1}
$T_i^{l1} \ge T_s$ and $T_s < T_i^{l2} < T_c$		T_i^{l2}
$T_i^{l1} \ge T_s$ and $T_i^{l2} \ge T_c$		T_c
$T_i^{l1} \ge T_s$ and $T_i^{l2} \le T_s$		T_s

2) If $T_s \ge T_c$ (Condition 2)

Under this condition, the first and second derivatives of a leader's payoff function are as below:

$$U_i^{l'} = \frac{\mathrm{e}^{-\lambda T_i}\lambda C_i^a}{1-\mathrm{e}^{-\lambda}} + \mathrm{e}^{-\lambda T_i}\lambda C_i^0 + \mathrm{e}^{-\lambda T_i} C_i^b (1+\delta) q_i^0 - \mathrm{e}^{-\gamma T_i}\left(\epsilon_i((1+\delta)q_i^0) + \tau_i((1+\delta)q_i^0)\right)$$

$$U_i^{l''} = -\frac{\lambda^2 \mathrm{e}^{-\lambda T_i} C_i^a}{1-\mathrm{e}^{-\lambda}} - \lambda^2 \mathrm{e}^{-\lambda T_i} C_i^0 - \lambda \mathrm{e}^{-\lambda T_i} C_i^b (1+\delta) q_i^0 + \gamma \mathrm{e}^{-\gamma T_i}\left(\epsilon_i((1+\delta)q_i^0) + \tau_i((1+\delta)q_i^0)\right)$$

By the first order condition, the solution of $U_i^{l'}(T_i, T_{-i}) = 0$ under this condition is

$$T_i = T_i^{l1} = \frac{1}{\lambda - \gamma} \ln \frac{1}{r_i^{l1}}, \text{ where } r_i^{l1} = \frac{\epsilon_i\left(\left(1+\delta\right)q_i^0\right) + \tau_i\left(\left(1+\delta\right)q_i^0\right)}{\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}} C_i^a + \left(1+\delta\right)q_i^0 C_i^b}.$$

a) As proved above, if $\lambda C_i^0 + \frac{\mathrm{e}^{-\lambda T_i} C_i^a}{1-\mathrm{e}^{-\lambda}} + (1+\delta)q_i^0 C_i^b > \epsilon_i\left((1+\delta)q_i^0\right) + \tau_i\left((1+\delta)q_i^0\right)$ (i.e., $r_i^l < 1$), $T_i^{l1} > 0$. And $U_i^{l''} < 0$. Therefore, U_i^l has a maximum value at T_i^{l1}. As such, a maximum value of U_i^l for $T_i \in [0, T_c]$ is expected when $T_i = \begin{cases} T_i^{l1}, \text{ if } 0 < T_i^{l1} < T_c \\ T_c, \text{ if } T_i^{l1} \geq T_c \end{cases}$, i.e., $T_i = \min(T_i^{l1}, T_c)$ for $T_i \in [0, T_c]$.

b) As proved above, if $\lambda C_i^0 + \frac{\mathrm{e}^{-\lambda T_i} C_i^a}{1-\mathrm{e}^{-\lambda}} + (1+\delta)q_i^0 C_i^b \leq \epsilon_i\left((1+\delta)q_i^0\right) + \tau_i\left((1+\delta)q_i^0\right)$ (i.e. $r_i^{l1} \geq 1$), $U_i^{l'} < 0$, U_i^l is a monotonically decreasing function with respect to T_i. so U_i^l has a maximum value at $T_i = 0$ for $T_i \in [0, T_c]$.

Therefore, in condition 2, the optimal adoption time of leaders can be summarised as $T_i^l = \begin{cases} 0, \text{ if } r_i^{l1} \geq 1 \\ \min(T_i^{l1}, T_c), \text{ if } r_i^{l1} < 1 \end{cases}$.

In short, the optimal adoption time of ship operators as a leader T_i^l is:

(a) If $T_s \geq T_c$,

$$T_i^l = \begin{cases} 0, \text{ if } r_i^{l1} \geq 1 \\ \min(T_i^{l1}, T_c), \text{ if } r_i^{l1} < 1 \end{cases}$$

(b) If $T_s < T_c$,

$$T_i^l = \begin{cases} \left.\begin{cases} \underset{T_i \in \{0, T_i^{l2}\}}{\arg\max} U_i^l(T_i, T_{-i}), \text{ for } T_s < T_i^{l2} < T_c \\ \underset{T_i \in \{0, T_c\}}{\arg\max} U_i^l(T_i, T_{-i}), \text{ for } T_i^{l2} \geq T_c \\ 0, \text{ for } T_i^{l2} \leq T_s \end{cases}\right\}, \text{ if } r_i^{l1} \geq 1, \\ \left.\begin{cases} \underset{T_i \in \{T_i^{l1}, T_i^{l2}\}}{\arg\max} U_i^l(T_i, T_{-i}), \text{ for } T_i^{l1} < T_s \text{ and } T_s < T_i^{l2} < T_c \\ \underset{T_i \in \{T_i^{l1}, T_c\}}{\arg\max} U_i^l(T_i, T_{-i}), \text{ for } T_i^{l1} < T_s \text{ and } T_i^{l2} \geq T_c \\ T_i^{l1}, \text{ for } T_i^{l1} < T_s \text{ and } T_i^{l2} \leq T_s \\ T_i^{l2}, \text{ for } T_i^{l1} \geq T_s \text{ and } T_s < T_i^{l2} < T_c \\ T_c, \text{ for } T_i^{l1} \geq T_s \text{ and } T_i^{l2} \geq T_c \\ T_s, \text{ for } T_i^{l1} \geq T_s \text{ and } T_i^{l2} \leq T_s \end{cases}\right\}, \text{ if } r_i^{l1} < 1, \end{cases}$$

where $T_i^{l1} = \dfrac{1}{\lambda - \gamma} \ln \dfrac{1}{r_i^{l1}}$, $r_i^{l1} = \dfrac{\epsilon_i \left(\left(1+\delta\right) q_i^0 \right) + \tau_i \left(\left(1+\delta\right) q_i^0 \right)}{\lambda C_i^0 + \dfrac{\lambda}{1-e^{-\lambda}} C_i^a + \left(1+\delta\right) q_i^0 C_i^b}$,

$T_i^{l2} = \dfrac{1}{\lambda - \gamma} \ln \dfrac{1}{r_i^{l2}}$ and $r_i^{l2} = \dfrac{\epsilon_i \left(q_i^0\right)}{\lambda C_i^0 + \dfrac{\lambda}{1-e^{-\lambda}} C_i^a + q_i^0 C_i^b}$.

6. Proof of Lemma 6.

Being a follower, the condition $T_i \in (T_c, \infty)$ holds.

First of all, $U_i^f(T_i, T_{-i})$ is continuous at T_s, because $\lim_{T_i \to T_s} U_i^f(T_i, T_{-i}) = U_i^f(T_s, T_{-i})$.

1) If $T_s \geq T_c$ (Condition 1)

   a) If $T_i \in (T_c, T_s)$, the first and second derivative of leader's payoff function is as below:

$$\begin{aligned} U_i^{f\,'} &= \frac{\mathrm{e}^{-\lambda T_i} \lambda C_i^a}{1-\mathrm{e}^{-\lambda}} + \mathrm{e}^{-\lambda T_i} \lambda C_i^0 + \mathrm{e}^{-\lambda T_i} C_i^b (1-\beta)(1+\delta) q_i^0 \\ &\quad - \mathrm{e}^{-\gamma T_i} \left(\epsilon_i ((1-\beta)(1+\delta) q_i^0) + \tau_i ((1-\beta)(1+\delta) q_i^0) \right) \end{aligned}$$

$$\begin{aligned} U_i^{f\,''} &= -\frac{\lambda^2 \mathrm{e}^{-\lambda T_i} C_i^a}{1-\mathrm{e}^{-\lambda}} - \lambda^2 \mathrm{e}^{-\lambda T_i} C_i^0 - \lambda \mathrm{e}^{-\lambda T_i} C_i^b (1-\beta)(1+\delta) q_i^0 \\ &\quad + \gamma \mathrm{e}^{-\gamma T_i} \left(\epsilon_i ((1-\beta)(1+\delta) q_i^0) + \tau_i ((1-\beta)(1+\delta) q_i^0) \right) \end{aligned}$$

By the first order condition, let T_i^{f1} denote the solution of $U_i^{f'}(T_i, T_{-i}) = 0$ under this condition. Then

$$T_i = T_i^{f1} = \frac{1}{\lambda - \gamma} \ln \frac{1}{r_i^{f1}},$$

where $r_i^{f1} = \dfrac{\epsilon_i\left((1-\beta)(1+\delta)q_i^0\right) + \tau_i\left((1-\beta)(1+\delta)q_i^0\right)}{\lambda C_i^0 + \dfrac{\lambda}{1-e^{-\lambda}} C_i^a + (1-\beta)(1+\delta)q_i^0 C_i^b}$.

i) If

$$\lambda C_i^0 + \frac{\lambda C_i^a}{1-\mathrm{e}^{-\lambda}} + C_i^b(1-\beta)(1+\delta)q_i^0 > \epsilon_i\left((1-\beta)(1+\delta)q_i^0\right) + \tau_i\left((1-\beta)(1+\delta)q_i^0\right)$$

(i.e., $r_i^{f1} < 1$), $T_i^{f1} > 0$. And $U_i^{f''} \le 0$ because

$$\begin{aligned} U_i^{f''} &< -\lambda e^{-\lambda T_i}\left[\epsilon_i\left((1-\beta)(1+\delta)q_i^0\right) + \tau_i\left((1-\beta)(1+\delta)q_i^0\right)\right] \\ &\quad +\gamma e^{-\gamma T_i}\left[\epsilon_i\left((1-\beta)(1+\delta)q_i^0\right) + \tau_i\left((1-\beta)(1+\delta)q_i^0\right)\right] \\ &= \left(\gamma e^{-\gamma T_i} - \lambda e^{-\lambda T_i}\right)\left[\epsilon_i\left((1-\beta)(1+\delta)q_i^0\right) + \tau_i\left((1-\beta)(1+\delta)q_i^0\right)\right]. \end{aligned}$$

As proved in the proof of Lemma 1, $\gamma e^{-\gamma T_i} < \lambda e^{-\lambda T_i}$. Given $\epsilon_i\left((1-\beta)(1+\delta)q_i^0\right)$ and $\tau_i\left((1-\beta)(1+\delta)q_i^0\right)$ are both positive in the model setting, $\left(\gamma e^{-\gamma T_i} - \lambda e^{-\lambda T_i}\right)\left[\epsilon_i\left((1-\beta)(1+\delta)q_i^0\right) + \tau_i\left((1-\beta)(1+\delta)q_i^0\right)\right] < 0$. Hence, $U_i^{f''} < 0$.

Therefore, U_i^f has a maximum value when $T_i = \begin{cases} T_i^{f1}, \text{ if } T_c < T_i^{f1} < T_s \\ T_s, \text{ if } T_i^{f1} \ge T_s \\ T_c + \Delta, \text{ if } 0 < T_i^{f1} \le T_c \end{cases}$ for $T_i \in (T_c, T_s)$.

ii) If

$$\lambda C_i^0 + \frac{\lambda C_i^a}{1-\mathrm{e}^{-\lambda}} + C_i^b(1-\beta)(1+\delta)q_i^0 \le \epsilon_i\left((1-\beta)(1+\delta)q_i^0\right) + \tau_i\left((1-\beta)(1+\delta)q_i^0\right)$$

(i.e., $r_i^{f1} \ge 1$), $T_i^{f1} \le 0$. And $U_i^{f'} < 0$, because

$$
\begin{aligned}
U_i^{f'} &\le e^{-\lambda T_i}\left[\epsilon_i\left((1-\beta)(1+\delta)q_i^0\right)+\tau_i\left((1-\beta)(1+\delta)q_i^0\right)\right] \\
&\quad -e^{-\gamma T_i}\left[\epsilon_i\left((1-\beta)(1+\delta)q_i^0\right)+\tau_i\left((1-\beta)(1+\delta)q_i^0\right)\right] \\
&= \left(e^{-\lambda T_i}-e^{-\gamma T_i}\right)\left[\epsilon_i\left((1-\beta)(1+\delta)q_i^0\right)+\tau_i\left((1-\beta)(1+\delta)q_i^0\right)\right]<0.
\end{aligned}
$$

U_i^f is a monotonically decreasing function with respect to T_i, so it has a maximum value at $T_i = T_c + \Delta$, if $T_i^{f1} \le 0$ (i.e., $r_i^{f1} \ge 1$) for $T_i \in (T_c, T_s)$.

b) if $T_i \in [T_s, \infty)$, the first and second derivatives of leader's payoff function are as below:

$$
U_i^{f'} = \frac{\mathrm{e}^{-\lambda T_i}\lambda C_i^a}{1-\mathrm{e}^{-\lambda}} + \mathrm{e}^{-\lambda T_i}\lambda C_i^0 + \mathrm{e}^{-\lambda T_i}C_i^b(1-\beta)q_i^0 - \mathrm{e}^{-\gamma T_i}\epsilon_i((1-\beta)q_i^0)
$$

$$
U_i^{f''} = -\frac{\lambda^2\mathrm{e}^{-\lambda T_i}C_i^a}{1-\mathrm{e}^{-\lambda}} - \lambda^2\mathrm{e}^{-\lambda T_i}C_i^0 - \lambda\mathrm{e}^{-\lambda T_i}C_i^b(1-\beta)q_i^0 + \gamma\mathrm{e}^{-\gamma T_i}\epsilon_i((1-\beta)q_i^0)
$$

By the first order condition, let T_i^{l2} denote the solution of $U_i^{l'}(T_i, T_{-i}) = 0$ under this condition. Then

$$
T_i = T_i^{f2} = \frac{1}{\lambda-\gamma}\ln\frac{\lambda C_i^0 + \dfrac{\lambda C_i^a}{1-\mathrm{e}^{-\lambda}} + C_i^b(1-\beta)q_i^0}{\epsilon_i\left((1-\beta)q_i^0\right)},
$$

where $r_i^{f2} = \dfrac{\epsilon_i\left((1-\beta)q_i^0\right)}{\lambda C_i^0 + \dfrac{\lambda C_i^a}{1-\mathrm{e}^{-\lambda}} + C_i^b(1-\beta)q_i^0}$.

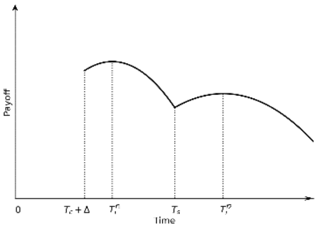
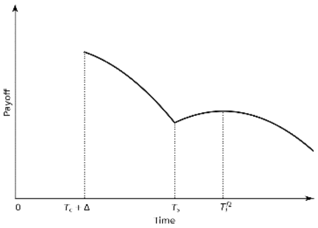
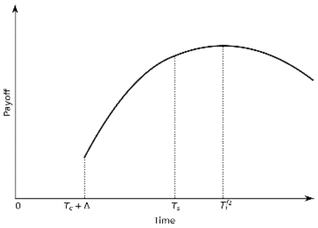
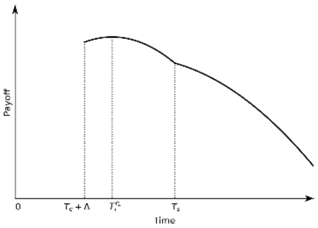
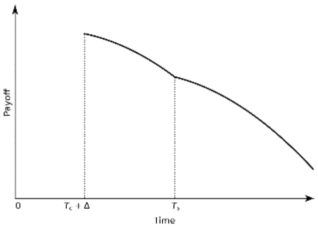
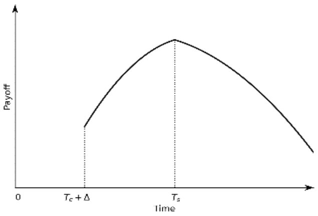
Based on the proof of Lemma 4:

i) If $\lambda C_i^0 + \dfrac{\mathrm{e}^{-\lambda T_i}C_i^a}{1-\mathrm{e}^{-\lambda}} + C_i^b(1-\beta)q_i^0 > \epsilon_i((1-\beta)q_i^0)$ (i.e. $r_i^{f2} < 1$), U_i^f has a maximum value at $T_i = \begin{cases} T_s, & \text{if } 0 < T_i^{f2} \le T_s \\ T_i^{f2}, & \text{if } T_i^{f2} > T_s \end{cases}$ for $T_i \in [T_s, \infty)$.

ii) If $\lambda C_i^0 + \dfrac{\mathrm{e}^{-\lambda T_i}C_i^a}{1-\mathrm{e}^{-\lambda}} + C_i^b(1-\beta)q_i^0 \le \epsilon_i((1-\beta)q_i^0)$ (i.e., $r_i^{f2} \ge 1$), $T_i^{f2} \le 0$. And U_i^f is a monotonically decreasing function with respect to T_i. Hence U_i^f has a maximum value at $T_i = T_s$ for $T_i \in [T_s, \infty)$ if $r_i^{f2} \ge 1$ (i.e., $T_i^{f2} \le 0$).

In condition 1 ($T_s \geq T_c$), the payoff functions of followers, and corresponding conditions and optimal adoption time can be summarised in Table A.2.

Table A.2 Optimal adoption time and graphs of payoff functions for a follower when $T_s \geq T_c$.

Conditions	Illustrative graphs of a leader's payoff function	Optimal adoption time as a follower
$T_c < T_i^{f1} < T_s$ and $T_i^{f2} > T_s$		$\underset{T_i \in \{T_i^{f1}, T_i^{f2}\}}{\arg\max} U_i^f(T_i, T_{-i})$
$T_i^{f1} \leq T_c$ and $T_i^{f2} > T_s$		$\underset{T_i \in \{T_c + \Delta, T_i^{f2}\}}{\arg\max} U_i^f(T_i, T_{-i})$
$T_i^{f1} \geq T_s$ and $T_i^{f2} > T_s$		T_i^{f2}
$T_c < T_i^{f1} < T_s$ and $T_i^{f2} \leq T_s$		T_i^{f1}
$T_i^{f1} \leq T_c$ and $T_i^{f2} \leq T_s$		$T_c + \Delta$
$T_i^{f1} \geq T_s$ and $T_i^{f2} \leq T_s$		T_s

2) If $T_s < T_c$ (Condition 2)

Under this condition, the first and second derivatives of a leader's payoff function are as below:

$$U_i^{f'} = \frac{\mathrm{e}^{-\lambda T_i}\lambda C_i^a}{1-\mathrm{e}^{-\lambda}} + \mathrm{e}^{-\lambda T_i}\lambda C_i^0 + \mathrm{e}^{-\lambda T_i} C_i^b (1-\beta) q_i^0 - \mathrm{e}^{-\gamma T_i}\epsilon_i \left((1-\beta)q_i^0\right)$$

$$U_i^{f''} = -\frac{\lambda^2 \mathrm{e}^{-\lambda T_i} C_i^a}{1-\mathrm{e}^{-\lambda}} - \lambda^2 \mathrm{e}^{-\lambda T_i} C_i^0 - \lambda \mathrm{e}^{-\lambda T_i} C_i^b (1-\beta) q_i^0 + \gamma \mathrm{e}^{-\gamma T_i}\epsilon_i \left((1-\beta)q_i^0\right)$$

By the first order condition, the solution of $U_i^{f'}(T_i, T_{-i}) = 0$ under this condition is

$$T_i = T_i^{f2} = \frac{1}{\lambda-\gamma}\ln\frac{1}{r_i^{f2}}, \text{ where } r_i^{f2} = \frac{\epsilon_i\left((1-\beta)q_i^0\right)}{\lambda C_i^0 + \dfrac{\lambda C_i^a}{1-\mathrm{e}^{-\lambda}} + C_i^b(1-\beta)q_i^0}.$$

As proved in condition 1 (i.e., $T_s \ge T_c$),

i) If $\lambda C_i^0 + \dfrac{\mathrm{e}^{-\lambda T_i} C_i^a}{1-\mathrm{e}^{-\lambda}} + C_i^b(1-\beta)q_i^0 > \epsilon_i((1-\beta)q_i^0)$ (i.e. $r_i^{f2} < 1$), U_i^f has a maximum value at $T_i = \begin{cases} T_c + \Delta, \text{ if } 0 < T_i^{f2} \le T_c \\ T_i^{f2}, \text{ if } T_i^{f2} > T_c \end{cases}$ for $T_i \in (T_c, \infty)$.

ii) If $\lambda C_i^0 + \dfrac{\mathrm{e}^{-\lambda T_i} C_i^a}{1-\mathrm{e}^{-\lambda}} + C_i^b(1-\beta)q_i^0 \le \epsilon_i((1-\beta)q_i^0)$ (i.e., $r_i^{f2} \ge 1$), $T_i^{f2} \le 0$. And U_i^f is a monotonically decreasing function with respect to T_i. Hence U_i^f has a maximum value at $T_i = T_c + \Delta$ for $T_i \in (T_c, \infty)$ if $r_i^{f2} \ge 1$ (i.e., $T_i^{f2} \le 0$).

Therefore, in condition 2, the optimal adoption time of followers T_i^f can be summarised as

$$T_i^f = \begin{cases} T_i^{f2}, \text{ if } T_i^{f2} > T_c \\ T_c + \Delta, \text{ if } T_i^{f2} \le T_c \end{cases}.$$

In short, the optimal adoption time of ship operators as a leader T_i^f is:

(a) If $T_s < T_c$,

$$T_i^{f} = \begin{cases} T_i^{f2}, \text{ if } T_i^{f2} > T_c \\ T_c + \Delta, \text{ if } T_i^{f2} \le T_c \end{cases}$$

(b) If $T_s \ge T_c$,

$$T_i^{f} = \begin{cases} \underset{T_i \in \{T_i^{f1}, T_i^{f2}\}}{\arg\max}\, U_i^{f}(T_i, T_{-i}), \text{ for } T_c < T_i^{f1} < T_s \text{ and } T_i^{f2} > T_s, \\ \underset{T_i \in \{T_c + \Delta, T_i^{f2}\}}{\arg\max}\, U_i^{f}(T_i, T_{-i}), \text{ for } T_i^{f1} \le T_c \text{ and } T_i^{f2} > T_s, \\ T_i^{f2}, \text{ for } T_i^{f1} \ge T_s \text{ and } T_i^{f2} > T_s, \\ T_i^{f1}, \text{ for } T_c < T_i^{f1} < T_s \text{ and } T_i^{f2} \le T_s, \\ T_c + \Delta, \text{ for } T_i^{f1} \le T_c \text{ and } T_i^{f2} \le T_s, \\ T_s, \text{ for } T_i^{f1} \ge T_s \text{ and } T_i^{f2} \le T_s. \end{cases}$$

where $T_i^{f1} = \frac{1}{\lambda - \gamma} \ln \frac{1}{r_i^{f1}}$, $r_i^{f1} = \dfrac{\epsilon_i\left(\left(1-\beta\right)\left(1+\delta\right)q_i^0\right) + \tau_i\left(\left(1-\beta\right)\left(1+\delta\right)q_i^0\right)}{\lambda C_i^0 + \frac{\lambda}{1-e^{-\lambda}} C_i^a + \left(1-\beta\right)\left(1+\delta\right)q_i^0 C_i^b}$,

$$T_i^{f2} = \frac{1}{\lambda - \gamma} \ln \frac{1}{r_i^{f2}}, \; r_i^{f2} = \frac{\epsilon_i\left((1-\beta)q_i^0\right)}{\lambda C_i^0 + \frac{\lambda C_i^a}{1-\mathrm{e}^{-\lambda}} + (1-\beta)q_i^0 C_i^b}.$$

APPENDIX B: PROOF OF FIXED POINTS

There are 16 scenarios when solving fixed points:

1) $p_x^B=0,\ p_x^E=0,\ p_y^B=0,\ \text{and}\ p_y^E=0$

The solution is $((0,0),(0,0))$.

2) $(1-p_x^B)(\pi_x^B-\pi_x^P)-p_x^E(\pi_x^E-\pi_x^P)=0,\ p_x^E=0,\ p_y^B=0,\ \text{and}\ p_y^E=0$

Since $p_y^B=0,\ \pi_x^B=\pi_x^P$. $(1-p_x^B)(\pi_x^B-\pi_x^P)-p_x^E(\pi_x^E-\pi_x^P)=0$ is always true for any p_x^B within [0,1]. Therefore, the solution is $((w_{x1},0),(0,0))$ for $\forall w_{x1}\in[0,1]$.

3) $p_x^B=0,\ (1-p_x^E)(\pi_x^E-\pi_x^P)-p_x^B(\pi_x^B-\pi_x^P)=0,\ p_y^B=0,\ \text{and}\ p_y^E=0$

Given $p_x^B=0$ and $\pi_x^E=\pi_x^P$ (since $p_y^E=0$), $(1-p_x^E)(\pi_x^E-\pi_x^P)-p_x^B(\pi_x^B-\pi_x^P)=0$ is always true for any p_x^E within [0,1]. Therefore, Therefore, the solution is $((0,w_{x1}),(0,0))$ for $\forall w_{x1}\in[0,1]$.

4) $p_x^B=0,\ p_x^E=0,(1-p_y^B)(\pi_y^B-\pi_y^P)-p_y^E(\pi_y^E-\pi_y^P)=0,\ \text{and}\ p_y^E=0$

Given $p_y^E=0$ and $\pi_y^B=\pi_y^P$ (since $p_x^B=0$), $(1-p_y^B)(\pi_y^B-\pi_y^P)-p_y^E(\pi_y^E-\pi_y^P)=0$ is always true for any p_y^B within [0,1]. Therefore, Therefore, the solution is $((0,0),(w_{y1},0))$ for $\forall w_{y1}\in[0,1]$.

5) $p_x^B=0,\ p_x^E=0,\ p_y^B=0,\ \text{and}\ (1-p_y^E)(\pi_y^E-\pi_y^P)-p_y^B(\pi_y^B-\pi_y^P)=0$

Given $p_y^B=0$ and $\pi_y^E=\pi_y^P$ (since $p_x^E=0$), $(1-p_y^E)(\pi_y^E-\pi_y^P)-p_y^B(\pi_y^B-\pi_y^P)=0$ is always true for any p_y^E within [0,1]. Therefore, the solution is $((0,0),(0,w_{y1}))$ for $\forall w_{y1}\in[0,1]$.

6) $p_x^B=0,\ (1-p_x^E)(\pi_x^E-\pi_x^P)-p_x^B(\pi_x^B-\pi_x^P)=0,(1-p_y^B)(\pi_y^B-\pi_y^P)-p_y^E(\pi_y^E-\pi_y^P)=0,\ \text{and}\ p_y^E=0$

Given $p_x^B=0$ and $p_y^E=0$, $\pi_y^B=\pi_y^P$ and $\pi_x^E=\pi_x^P$. $(1-p_x^E)(\pi_x^E-\pi_x^P)-p_x^B(\pi_x^B-\pi_x^P)=0$ and $(1-p_y^B)(\pi_y^B-\pi_y^P)-p_y^E(\pi_y^E-\pi_y^P)=0$ are always true for any p_y^B and p_x^E within [0,1]. Therefore, the solution is $((0,w_{x1}),(w_{y1},0))$ for $\forall w_{x1},w_{y1}\in[0,1]$.

7) $p_x^B=0,\ (1-p_x^E)(\pi_x^E-\pi_x^P)-p_x^B(\pi_x^B-\pi_x^P)=0,\ p_y^B=0,\ \text{and}\ (1-p_y^E)(\pi_y^E-\pi_y^P)-p_y^B(\pi_y^B-\pi_y^P)=0$

Given $p_x^B=0$ and $p_y^B=0$, $(1-p_x^E)(\pi_x^E-\pi_x^P)=0$ and $(1-p_y^E)(\pi_y^E-\pi_y^P)=0$. Four situations have to be discussed:

a) If $\pi_x^E\neq\pi_x^P$ and $\pi_y^E\neq\pi_y^P$, $p_x^E=p_y^E=1$. Hence the solution in this situation is $((0,1),(0,1))$.

b) If $\pi_x^E=\pi_x^P$ and $\pi_y^E\neq\pi_y^P$, $p_y^E=1$ and p_x^E can be any value within [0,1]. Hence the solution in this situation is $((0,w_{x1}),(0,1))$ for $\forall w_{x1}\in[0,1]$.

c) If $\pi_x^E\neq\pi_x^P$ and $\pi_y^E=\pi_y^P$, $p_x^E=1$ and p_y^E can be any value within [0,1]. Hence the solution in this situation is $((0,1),(0,w_{y1}))$ for $\forall w_{y1}\in[0,1]$.

d) If $\pi_x^E=\pi_x^P$ and $\pi_y^E=\pi_y^P$, p_x^E and p_y^E can be any value within [0,1]. Hence the solution in this situation is $((0,w_{x1}),(0,w_{y1}))$ for $\forall w_{x1},w_{y1}\in[0,1]$.

Since $((0,1),(0,1))$ is a solution under all the four situations a), b), c) and d), it is a fixed point without any constraints.

8) $p_x^B = 0,\ p_x^E = 0, (1-p_y^B)(\pi_y^B - \pi_y^P) - p_y^E(\pi_y^E - \pi_y^P) = 0,$ and $(1-p_y^E)(\pi_y^E - \pi_y^P) - p_y^B(\pi_y^B - \pi_y^P) = 0$

Given $p_x^B = 0$ and $p_x^E = 0$, $\pi_y^B = \pi_y^E = \pi_y^P$. $(1-p_y^B)(\pi_y^B - \pi_y^P) - p_y^E(\pi_y^E - \pi_y^P) = 0$ and $(1-p_y^E)(\pi_y^E - \pi_y^P) - p_y^B(\pi_y^B - \pi_y^P) = 0$ are always true for any p_y^B and p_y^E within [0,1]. Therefore, the solution is $((0,0),(w_{y1},w_{y2}))$ for $\forall w_{y1}, w_{y2} \in [0,1]$, as long as $w_{y1} + w_{y2} \le 1$.

9) $p_x^B = 0,\ (1-p_x^E)(\pi_x^E - \pi_x^P) - p_x^B(\pi_x^B - \pi_x^P) = 0,\ (1-p_y^B)(\pi_y^B - \pi_y^P) - p_y^E(\pi_y^E - \pi_y^P) = 0,$ and $(1-p_y^E)(\pi_y^E - \pi_y^P) - p_y^B(\pi_y^B - \pi_y^P) = 0$

Given $p_x^B = 0$, $\pi_y^B = \pi_y^P$ and $(1-p_x^E)(\pi_x^E - \pi_x^P) = 0$. If $\pi_x^E = \pi_x^P$, p_x^E can be any value within [0,1]. If $\pi_x^E \ne \pi_x^P$, $p_x^E = 1$. Since $\pi_y^B = \pi_y^P$, $-p_y^E(\pi_y^E - \pi_y^P) = 0$ and $(1-p_y^E)(\pi_y^E - \pi_y^P) = 0$. If $\pi_y^E = \pi_y^P$, p_y^B and p_y^E can be any value within [0,1]. If $\pi_y^E \ne \pi_y^P$, there is no solution of p_y^E in this case. Therefore, the solutions in this scenario are as follows:

a) $((0,1),(w_{y1},w_{y2}))$ for $\forall w_{y1} \in [0,1]$ as long as $w_{y1} + w_{y2} \le 1$, if $\pi_x^E \ne \pi_x^P$ and $\pi_y^E = \pi_y^P$

b) $((0,w_{x1}),(w_{y1},w_{y2}))$ for $\forall w_{x1}, w_{y1} \in [0,1]$ as long as $w_{y1} + w_{y2} \le 1$, if $\pi_x^E = \pi_x^P$ and $\pi_y^E = \pi_y^P$

10) $(1-p_x^B)(\pi_x^B - \pi_x^P) - p_x^E(\pi_x^E - \pi_x^P) = 0,\ (1-p_x^E)(\pi_x^E - \pi_x^P) - p_x^B(\pi_x^B - \pi_x^P) = 0, p_y^B = 0,$ and $p_y^E = 0$

Given $p_y^B = 0$ and $p_y^E = 0$, $\pi_x^B = \pi_x^E = \pi_x^P$. $(1-p_x^B)(\pi_x^B - \pi_x^P) - p_x^E(\pi_x^E - \pi_x^P) = 0$ and $(1-p_x^E)(\pi_x^E - \pi_x^P) - p_x^B(\pi_x^B - \pi_x^P) = 0$ are always true for any p_x^B and p_x^E within [0,1]. Therefore, the solution is $((w_{x1},w_{x2}),(0,0))$ for $\forall w_{x1}, w_{x2} \in [0,1]$, as long as $w_{x1} + w_{x2} \le 1$.

11) $(1-p_x^B)(\pi_x^B - \pi_x^P) - p_x^E(\pi_x^E - \pi_x^P) = 0,\ p_x^E = 0, (1-p_y^B)(\pi_y^B - \pi_y^P) - p_y^E(\pi_y^E - \pi_y^P) = 0,$ and $p_y^E = 0$

Given $p_x^E = 0$ and $p_y^E = 0$, $\pi_x^E = \pi_x^P$ and $\pi_y^E = \pi_y^P$. Then $(1-p_x^B)(\pi_x^B - \pi_x^P) = 0$ and $(1-p_y^B)(\pi_y^B - \pi_y^P) = 0$. There are four situations to be discussed:

a) If $\pi_x^B \ne \pi_x^P$ and $\pi_y^B \ne \pi_y^P$, $p_x^B = 1$ and $p_y^B = 1$. Hence the solution in this situation is $((1,0),(1,0))$,

b) If $\pi_x^B = \pi_x^P$ and $\pi_y^B \ne \pi_y^P$, $p_y^B = 1$ and p_x^B can be any value within [0,1]. Hence the solution in this situation is $((w_{x1},0),(1,0))$ for $\forall w_{x1} \in [0,1]$,

c) If $\pi_x^B \ne \pi_x^P$ and $\pi_y^B = \pi_y^P$, $p_x^B = 1$ and p_y^B can be any value within [0,1]. Hence the solution in this situation is $((1,0),(w_{y1},0))$ for $\forall w_{y1} \in [0,1]$.

d) If $\pi_x^B = \pi_x^P$ and $\pi_y^B = \pi_y^P$, p_x^B and p_y^B can be any value within [0,1]. Hence the solution in this situation is $((w_{x1},0),(w_{y1},0))$ for $\forall w_{x1}, w_{y1} \in [0,1]$.

Since $((1,0),(1,0))$ is a solution under all the four situations a), b), c) and d), it is a fixed point without any constraints.

12) $(1-p_x^B)(\pi_x^B - \pi_x^P) - p_x^E(\pi_x^E - \pi_x^P) = 0,\ p_x^E = 0, p_y^B = 0,$ and $(1-p_y^E)(\pi_y^E - \pi_y^P) - p_y^B(\pi_y^B - \pi_y^P) = 0$

Given $p_y^B = 0$ and $p_x^E = 0$, $\pi_y^E = \pi_y^P$ and $\pi_x^B = \pi_x^P$. $(1-p_x^B)(\pi_x^B - \pi_x^P) - p_x^E(\pi_x^E - \pi_x^P) = 0$ and $(1-p_y^E)(\pi_y^E - \pi_y^P) - p_y^B(\pi_y^B - \pi_y^P) = 0$ are always true for $\forall p_x^B, p_y^E \in [0,1]$. Therefore, the solution is $((w_{x1},0),(0,w_{y1}))$ for $\forall w_{x1}, w_{y1} \in [0,1]$.

13) $(1-p_x^B)(\pi_x^B - \pi_x^P) - p_x^E(\pi_x^E - \pi_x^P) = 0,\ (1-p_x^E)(\pi_x^E - \pi_x^P) - p_x^B(\pi_x^B - \pi_x^P) = 0,$
$(1-p_y^B)(\pi_y^B - \pi_y^P) - p_y^E(\pi_y^E - \pi_y^P) = 0,$ and $p_y^E = 0$

Given $p_y^E = 0$, $\pi_x^E = \pi_x^P$. Then $(1-p_x^B)(\pi_x^B - \pi_x^P) = 0,\ -p_x^B(\pi_x^B - \pi_x^P) = 0,$ and $(1-p_y^B)(\pi_y^B - \pi_y^P) = 0.$ Three situations need to be discussed:

a) If $\pi_x^B \neq \pi_x^P$ and $\pi_y^B \neq \pi_y^P$, there is no solution to p_x^B,

b) If $\pi_x^B = \pi_x^P$ and $\pi_y^B \neq \pi_y^P$, $p_y^B = 1$, p_x^B and p_x^E can be any value within [0,1]. Hence the solution in this situation is $((w_{x1},w_{x2}),(1,0))$ for $\forall w_{x1}, w_{x2} \in [0,1]$,

c) If $\pi_x^B = \pi_x^P$ and $\pi_y^B = \pi_y^P$, p_y^B, p_x^B and p_x^E can be any value within [0,1]. Hence the solution in this situation is $((w_{x1},w_{x2}),(w_{y1},0))$ for $\forall w_{x1}, w_{x2}, w_{y1} \in [0,1]$ as long as $w_{x1} + w_{x2} \leq 1$.

14) $(1-p_x^B)(\pi_x^B - \pi_x^P) - p_x^E(\pi_x^E - \pi_x^P) = 0,\ (1-p_x^E)(\pi_x^E - \pi_x^P) - p_x^B(\pi_x^B - \pi_x^P) = 0,\ p_y^B = 0,$ and
$(1-p_y^E)(\pi_y^E - \pi_y^P) - p_y^B(\pi_y^B - \pi_y^P) = 0$

Given $p_y^B = 0$, $\pi_x^B = \pi_x^P$. Then $-p_x^E(\pi_x^E - \pi_x^P) = 0,\ (1-p_x^E)(\pi_x^E - \pi_x^P) = 0,$ and $(1-p_y^E)(\pi_y^E - \pi_y^P) = 0.$ Three situations need to be discussed:

a) If $\pi_x^E \neq \pi_x^P$, there is no solution to p_x^E,

b) If $\pi_x^E = \pi_x^P$ and $\pi_y^E \neq \pi_y^P$, $p_y^E = 1$, p_x^B and p_x^E can be any value within [0,1]. Hence the solution in this situation is $((w_{x1},w_{x2}),(0,1))$ for $\forall w_{x1}, w_{x2} \in [0,1]$,

c) If $\pi_x^E = \pi_x^P$ and $\pi_y^E = \pi_y^P$, p_y^E, p_x^B and p_x^E can be any value within [0,1]. Hence the solution in this situation is $((w_{x1},w_{x2}),(0,w_{y1}))$ for $\forall w_{x1}, w_{x2}, w_{y1} \in [0,1]$ as long as $w_{x1} + w_{x2} \leq 1$,

15) $(1-p_x^B)(\pi_x^B - \pi_x^P) - p_x^E(\pi_x^E - \pi_x^P) = 0,\ p_x^E = 0, (1-p_y^B)(\pi_y^B - \pi_y^P) - p_y^E(\pi_y^E - \pi_y^P) = 0,$ and
$(1-p_y^E)(\pi_y^E - \pi_y^P) - p_y^B(\pi_y^B - \pi_y^P) = 0$
Given $p_x^E = 0$, $\pi_y^E = \pi_x^P$. Then $(1-p_x^B)(\pi_x^B - \pi_x^P) = 0,\ (1-p_y^B)(\pi_y^B - \pi_y^P) = 0$ and $-p_y^B(\pi_y^B - \pi_y^P) = 0$ Three situations need to be discussed:

a) If $\pi_y^B \neq \pi_y^P$, there is no solution to p_y^B,

b) If $\pi_y^B = \pi_y^P$ and $\pi_x^B \neq \pi_x^P$, $p_x^B = 1$, p_y^B and p_y^E can be any value within [0,1]. Hence the solution in this situation is $((1,0),(w_{y1},w_{y2}))$ for $\forall w_{y1}, w_{y2} \in [0,1]$,

c) If $\pi_y^B = \pi_y^P$ and $\pi_x^B = \pi_x^P$, p_x^B, p_y^B and p_y^E can be any value within [0,1]. Hence the solution in this situation is $((w_{x1},0),(w_{y1},w_{y2}))$ for $\forall w_{x1}, w_{y1}, w_{y2} \in [0,1]$ as long as $w_{y1} + w_{y2} \leq 1$.

16) $(1-p_x^B)(\pi_x^B - \pi_x^P) - p_x^E(\pi_x^E - \pi_x^P) = 0,\ (1-p_x^E)(\pi_x^E - \pi_x^P) - p_x^B(\pi_x^B - \pi_x^P) = 0,$
$(1-p_y^B)(\pi_y^B - \pi_y^P) - p_y^E(\pi_y^E - \pi_y^P) = 0,$ and $(1-p_y^E)(\pi_y^E - \pi_y^P) - p_y^B(\pi_y^B - \pi_y^P) = 0$

By subtracting the first two equations on both sides, $\pi_x^B = \pi_x^E$ and $p_x^B + p_x^E = 1$. By subtracting the last two equations on both sides, $\pi_y^B = \pi_y^E$ and $p_y^B + p_y^E = 1$. Since $\pi_x^B = \pi_x^E$ and $\pi_y^B = \pi_y^E$ are two cubic functions of p_x^B and p_y^B, there exist only one real solution p_x^B and p_y^B to make $\pi_x^B = \pi_x^E$ and $\pi_y^B = \pi_y^E$, denoted as w_{x1}^* and w_{y1}^* respectively. Therefore the solution is $((w_{x1}^*, 1-w_{x1}^*), (w_{y1}^*, 1-w_{y1}^*))$, where $p_x^B = w_{x1}^*$ and $p_y^B = w_{y1}^*$ are the only solution to the functions $\pi_x^B = \pi_x^E$ and $\pi_y^B = \pi_y^E$.

APPENDIX C: METHODS TO CALCULATE PRIMARY AND SECONDARY EFFECTS

Based on the calculation methods in section 7.2.4 and parameter values set in section 7.3, the primary and secondary effects of a digitalisation project can be obtained. In the following equations, the subscripts aft and bef represent the situations after and before the digitalisation project, respectively.

$$PE1 = \sum_k \left(E_k^p \times N_k\right)_{aft} - \sum_k \left(E_k^p \times N_k\right)_{bef}, \qquad (A.1)$$

$$PE2 = \sum_k (E_k^t \times N_k)_{aft} - \sum_k (E_k^t \times N_k)_{bef}, \qquad (A.2)$$

$$PE3 = \sum_k \left(E_k^d \times N_k\right)_{aft} - \sum_k \left(E_k^d \times N_k\right)_{bef}, \qquad (A.3)$$

$$SE1 = \sum_k (E_k^w \times N_k)_{aft} - \sum_k (E_k^w \times N_k)_{bef}, \qquad (A.4)$$

$$\begin{aligned} SE2 = &\sum_k (r_k \times N_k \times EF^{dp} \times \mu \times D^{VT})_{aft} \\ &- \sum_k (r_k \times N_k \times EF^{dp} \times \mu \times D^{VT})_{bef}, \end{aligned} \qquad (A.5)$$

$$SE3 = \sum_k \left(E_k^{dp} \times N_k\right)_{aft} - \sum_k \left(E_k^{dp} \times N_k\right)_{bef}, \qquad (A.6)$$

where all symbols are defined in Section 7.3, except for E_k^{dp} which will be defined in the following part. It is also worth to mention that for SE2, van transport (VT) is assumed for transporting documents to warehouses based on normal practice.

E_k^{dp} represents the emissions from disposed paper waste in a single shipping event k. It can be obtained by

$$E_k^{dp} = EF^{dp} \times \tau_k \times \mu, \qquad (A.7)$$

where EF^{dp} is the emission factor of handling paper wastage (in kg CO2e/ton); τ_k denotes the annual number of paper wastage in sheets in a single event k, which can be estimated by γ_k which is the total sheets of documents that need to be stored per year; μ is the unit weight per paper sheet (in g/sheet). EF^{dp} is set as 0.05 kg CO2e/ton based on the combustion method (the main method to handle paper wastage in Singapore and China) (EPA, 2018).

APPENDIX D: DOCUMENTS RELATING TO CUSTOMS AND TRANSPORTATION GENERATED – SINGAPORE

Process	Document	No. of copies	Import	Export	Transshipment	Printing
Customs clearance	Application form	1	√	√	√	√
	Commercial invoice	1	√	√	√	√
	Books of accounts	1	√	√	√	√
	Bills of lading or air waybill	1	√	√	√	√
	Packing list	1	√	√	√	√
	Certificate of origin	1	√	√	√	√
	Certificate of analysis	1	√	√	√	√
	Certificate of insurance	1	√	√	√	√
	Import permit	1	√	-	-	√
	Export permit	1	-	√	-	√
	Transshipment permit	1	-	-	√	√
Customs endorsement*	Bills of lading or air waybill	1	√	√	√	√
	Packing list	1	√	√	√	√
	Import permit	1	√	-	-	-
	Export permit	1	-	√	-	-
	Transhipment permit	1	-	-	√	-
	Invoice	1	√	√	√	√
Transportation	Min 3 passenger trips are generated for paper movements: Shipper/FF agent → Customs → Shipper/FF agent					

Note: FF - Freight forwarder.

[*] For containerised cargoes imported by sea: it is not required to present the customs permit and supporting documents to the checkpoint officers at the entry points.

Source: Compiled by author based on government regulations and interviews with shipping agents.

APPENDIX E: DOCUMENTS RELATING TO GATE OPERATIONS AND TRANSPORTATION GENERATED – SINGAPORE

Process	Document	No. of copies	Import	Export	Transshipment	Printing
Gate operations	Booking application	1	√	√	√	√
	Cargo manifest	1	√	√	√	√
	Transhipment local instruction*	1	√	√	√	√
	Pre-gate application	1	√	√	√	√
	Truck instruction document*	1	√	√	√	√
	Equipment interchange receipt*	1	√	√	√	√
	Delivery order	1	√	-	√	√
	Delivery note	1	√	-	-	√
	Unloading advice	1	-	√	-	√
	Shipping note	1	-	√	-	√
	Transshipment shipping note	1	-	-	√	√
Transportation	Min 3 passenger trips are generated for paper movements. Shipper or FF obtains delivery order from shipping company by surrendering original BL: Shipper/FF agent → Shipping company → Shipper/FF agent Haulier obtains documents from Shipper/FF Agent for gate operations: Haulier → Shipper/FF agent					

Note: FF - Freight forwarder. BL - Bills of lading.

* For containerised cargoes only.

Source: Compiled by author based on government regulations, terminal requirements and interviews with shipping agents.

APPENDIX F: DOCUMENTS RELATING TO PORT CLEARANCE FOR VESSEL ARRIVAL AND DEPARTURE AND TRANSPORTATION GENERATED – SINGAPORE

Process	Document	No. of copies	Arrival	Departure	Printing
Vessel clearance	General declaration	2	√	√	√
	Crew list	2	-	√	√
	Last port clearance certificate	1	√	-	-
	Vessel certificates*	1	√	√	-
	Port clearance certificate	1	-	√	√
Immigration clearance	Arrival advice - Before vessel arrival	1	√	-	√
	Arrival crew list - Before vessel arrival	1	√	-	√
	Arrival crew list - After vessel arrival	4	√	-	√
	Departure advice - Before vessel departure	1	-	√	√
	Departure crew list - Before departure	2	-	√	√
Health and quarantine clearance	Maritime health declaration	1	√	√	√
Transportation	Min 6 trips are generated for paper movements relating to vessel arrival and departure (Due to short port stay, agents usually process formalities for vessel arrival and departure together at one time): Shipping company's agent → Vessel → (MPA → ICA → NEA) # → Vessel → Shipping company's agent				

Note: MPA – Maritime and Port Authority, ICA – Immigration & Checkpoints Authority, NEA – The National Environment Agency.

* Vessel certificates required in Singapore's paper system were in original form and hence did not generate printing. These certificates usually were: Certificate of Registry, Load Line Certificate, Cargo Ship Safety Construction Certificate, Cargo Ship Safety Equipment Certificate, Cargo Ship Safety Radio Certificate, Certificate of Insurance in respect of Civil Liability for Oil Pollution Damage (CLC), International Oil Pollution Prevention (IOPP) Certificate, with approved Shipboard Oil Pollution Emergency Plan (SOPEP), International Tonnage Certificate (ITC69), International Safety Management (ISM) Code, Document of Compliance (DOC), Safety Management Certificate (SMC), International Ship Security Certificate, International Air Pollution Prevention Certificate, International Sewage Pollution Prevention Certificate.

\# The transportation sequence in the bracket is for illustration only and can be different in different cases.

Source: Compiled by author based on government regulations and interviews with shipping agents.

APPENDIX G: DOCUMENTS RELATING TO CARGO CLEARANCE AND TRANSPORTATION GENERATED IN THE PAPER SYSTEM - CHINA

Processes	Document	No. of copies	Import	Export	Transshipment	Printing
Customs clearance	Authorisation letter	1	√	√	√	√
	General declaration for import	1	√	-	√	√
	General declaration for export	1	-	√	√	√
	Certificate for Foreign-Exchange Verification	1	√	√	-	√
	Import licence	1	√	-	-	√
	Export licence	1	-	√	-	√
	Transshipment licence	1	-	-	√	√
	Invoice	1	√	√	-	√
	BLs or sea waybills	1	√	√	√	√
	Packing list	1	√	√	-	√
	Commercial Contract	1	√	√	-	√
	Certificate of origin	1	√	√	-	√
	Packaging Certificate	1	√	√	-	√
	Certificate of quality	1	√	√	-	√
	Insurance certificate	1	√	√	-	√
	Customs Clearance of Entry Commodities	1	√	-	-	√
	Customs Clearance of Export Commodities	1	-	√	-	√
	Import permit	1	√	-	-	√
	Export permit	1	-	√	-	√
	Cargo manifest for import	2	-	-	√	√
	Cargo manifest for export	2	-	-	√	√
	Tally report for import	1	-	-	√	√
	Tally report for export	1	-	-	√	√
	Foreign transshipment cargo approval letter	2	-	-	√	√
	Transshipment cargo release order	2	-	-	√	√
Inspection and Quarantine clearance	Authorisation letter	1	√	√	-	√
	Application form	1	√	√	-	√
	Commercial Contract	1	√	√	-	√
	Invoice	1	√	√	-	√
	BLs or sea waybills	1	√	√	-	√
	Packing list	1	√	√	-	√
	Certificate of quality	1	√	√	-	√
	Certificate of weight	1	√	√	-	√
	Certificate of quantity	1	√	√	-	√
Transportation	Min 3 passenger trips are generated for paper movements: Shipper/FF agent → Customs → CIQ → Shipper/FF agent					

Note: BLs - Bills of lading; CIQ - China Entry-Exit Inspection and Quarantine Bureau; FF - Freight forwarder.

Source: Compiled by author based on government regulations and interviews with shipping agents.

APPENDIX H: DOCUMENTS RELATING TO GATE OPERATIONS AND TRANSPORTATION GENERATED IN THE PAPER SYSTEM - CHINA

Process	Document	No. of copies	Import	Export	Transshipment	Printing
Gate operations	Pre-gate appointment letter for pickup	1	√	-	√	√
	Pre-gate appointment letter for drop-off	1	-	√	√	√
	Cargo manifest for import	1	√	-	√	√
	Cargo manifest for export	1	-	√	√	√
	Delivery order	1	√	-	-	√
	Cargo release order	1	√	-	-	√
	EIR for import	3	√	-	√	√
	EIR for export	3	-	√	√	√
	Cargo drop-off order	1	-	√	-	√
	Transshipment cargo release order	1	-	-	√	-
Transportation	Min 3 passenger trips are generated in the paper system. Shipper or FF obtains delivery order from shipping company by surrendering original BLs: Shipper/FF agent → Shipping company → Shipper/FF agent Haulier obtains documents from Shipper/FF Agent for gate operations: Haulier → Shipper/FF agent					

Note: EIR - Equipment interchange receipt. FF - Freight forwarder.

Source: Compiled by author based on government regulations, terminal requirements and interviews with shipping agents.

APPENDIX I: DOCUMENTS RELATING TO VESSEL CLEARANCE FOR ARRIVAL AND DEPARTURE AND TRANSPORTATION GENERATED – CHINA

Processes	Document	No. of copies	Arrival	Departure	Printing
Immigration clearance	Application letter of vessel departure	1	-	√	√
	General declaration - arrival	1	√	-	√
	General declaration - departure	1	-	√	√
	Crew list - arrival	2	√	-	√
	Crew list – departure	2	-	√	√
	Seafarer's book	20	√	-	-
	Crew's effects declaration	1	√	-	√
	Onland application for crew	1	√	-	√
	Quarantine certificate	1	√	-	-
	Approval of onland application	20	√	-	√
	Approval letter	1	√	-	√
	Endorsement list of vessel departure	1	-	√	√
Health and quarantine clearance	Maritime health declaration	1	√	-	√
	General declaration - arrival	1	√	-	√
	Ship's stores declaration	1	√	-	√
	Free Pratique	3	√	-	√
	Quarantine application for departure	1	-	√	√
	General declaration - departure	1	-	√	√
	Ship's stores declaration	1	-	√	√
	Cargo declaration	1	-	√	√
	Cargo manifest	1	-	√	√
	Endorsement list of vessel departure	1	-	√	-
	Ship sanitation (exemption) certificate	3	-	√	√
Customs clearance	General declaration - arrival	1	√	-	√
	General declaration - departure	1	-	√	√
	Cargo manifest – arrival	2	√	-	√
	Cargo manifest - departure	2	-	√	√
	Cargo declaration - arrival	1	√	-	√
	Cargo declaration - departure	1	-	√	√
	Crew list - arrival	1	√	-	√
	Crew list - departure	1	-	√	√
	Crew's effects declaration	1	√	-	√
	Ship's stores declaration	1	√	-	√
	Port of calls	1	√	-	√

	Endorsement list of vessel departure	1	-	√	-
Port clearance	Application letter of vessel departure	1	√	-	√
	Last port clearance certification	1	√	-	-
	Ship’s particular	1	√	√	√
	General declaration - arrival	1	√	-	√
	Cargo declaration - arrival	1	√	-	√
	Crew list - arrival	1	√	-	√
	Port of calls	1	√	-	√
	Vessel certificates*	1	√	-	√
	General declaration - departure	1	-	√	√
	Cargo declaration - departure	1	-	√	√
	Crew list - departure	1	-	√	√
	Endorsement list of vessel departure	1	-	√	-
	Port clearance certificate	1	-	√	√
Transportation	Min 13 additional passenger trips are generated for vessel arrival and departure in the paper system. <u>Vessel arrival:</u> Shipper/FF agent → Vessel → (CII → Customs → Maritime authority)# → Vessel → Shipper/FF agent <u>Vessel departure:</u> Shipper/FF agent → Vessel → (CII → CIQ → Customs → Maritime authority)# → Shipper/FF agent				

Note: CII - China Immigration Inspection Station; CIQ - China Inspection and Quarantine Bureau.

* Vessel certificates usually include: Certificate of Registry, Tonnage Certificate, Minimum safe manning document, Cargo Ship Safety Construction Certificate, Cargo Ship Safety Equipment Certificate, Cargo Ship Safety Radio Certificate, Certificate of Insurance in respect of Civil Liability for Oil Pollution Damage (CLC), International Oil Pollution Prevention (IOPP) Certificate, IOPP - Form B, International Safety Management (ISM) Code, Document of Compliance (DOC), Safety Management Certificate (SMC), International Ship Security Certificate (ISSC), International Air Pollution Prevention Certificate (IAPP), International Anti-fouling Certificate. Some are required in original form like the first two certificates, so printing is not needed. Some others are required in a copy, so printing is needed.

[#] The transportation sequence in the bracket is for illustration only and can be different based on their locations in a port city. CIQ is not included for vessel arrival as the CIQ will go onboard directly to do physical inspection within 24 hours of vessel’s arrival at a port. This trip cannot be avoided with digitalisation as physical inspection is required.

Source: Compiled by author based on government regulations and interviews with shipping agents.