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How technology can advance port operations and address supply chain disruptions

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HOW TECHNOLOGY CAN ADVANCE PORT OPERATIONS AND ADDRESS SUPPLY CHAIN DISRUPTIONS

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ABSTRACT

Supply chain disruptions continue to be a significant challenge as the world economy recovers from the pandemic-related shutdowns that have strained global supply chains. Shocks challenge the adaptability and resilience of maritime ports. The reaction of automated container terminals to supply chain disruptions has renewed interest, given the dramatic scenes of ships anchored for weeks. In this dissertation, I provide a vision of how technology can enhance a port's ability to anticipate and handle shocks by improving coordination, cooperation, and information exchange across port stakeholders. The vision will be helpful for academics and practitioners to perform research that advances theory and practice on the use of advanced technologies to improve port operations. I use complex adaptive systems theory to develop a qualitative cross-case study of the ports of Los Angeles, Vancouver, and Rotterdam. I examine the effect that automation and other technologies have had on the efficiency of these ports, both in daily operations and during the disruption caused by the COVID-19 pandemic. Using critical tenets of complexity and with a rigorous application of the case study method, I develop theoretical propositions and practical insights to ground the vision of the port of the future based on current practices. The findings from the cross-case study suggest that automated terminals were more efficient during the pandemic than non-automated terminals. I propose that transitioning to higher levels of automation, supported by emerging technologies like blockchain and the internet of things, will make ports more resilient to supply chain disruptions when those systems are coordinated through Port Community Systems.

Keywords: supply chain, coordination, cooperation, information exchange

CHAPTER 1. INTRODUCTION

Overview

It has been almost 30 years since the Port of Rotterdam opened the world's first automated container terminal (ACT). Since then, over 30 ACTs have ensued in other locations, with the pace intensifying over the last 10 years. Ostensibly, automation is introduced to decrease the cost per container as it moves from ship to rail or truck. Approximately 97% of the world's container terminals are not automated. Often the advantages of automation are not attained as automated terminals struggle to achieve anticipated productivity levels and cost benefits. A common thread appears to be that several different technological innovations have been implemented without appropriate supply chain integration (Huynh et al., 2019). A container terminal automation project that is configured and employed appropriately, can transform terminals into reliable and flexible logistics hubs that achieve predictable flows of containers in and out of the terminal (Chu et al., 2018). Maritime ports need to prepare for an era of automation, leveraging the opportunities to improve supply chain operation.

Supply chain disruptions continue to be a significant challenge in 2022 as the world economy recovers from the pandemic-related shutdowns in China that have strained global supply chains. Supply bottlenecks have been exacerbated by changes in trading regimes and patterns following Brexit. Recent developments related to geopolitics (e.g., invasion of Ukraine by Russia) and imposed sanctions by the world community have created additional challenges, including worldwide inflation. Those at the end of the supply chain have been forced to reevaluate their dependence on single suppliers and just-in-time supply. Ports are often at the epicenter of the bottlenecks and are under intense pressure to resolve the global supply slowdown. Additionally, ports need to be better prepared to face the next shock. European ports are already facing the supply chain disruption from the Ukraine-Russia war. In this dissertation, I embrace the notion that technological progress, including ACTs and other emerging technologies, can offer solutions for ports to become more resilient to these shocks.

Problem Addressed

In the global supply chain, the network of collaborators across ports needs to create operational management processes built for efficiency. Many ports have looked to Port Community Systems (PCSs) as electronic platforms that connect transportation stakeholders such as marine terminal managers and railroad analysts. A PCS is an inter-organizational information system (IOS) that enables the intelligent and secure exchange of information between private and public organizations, with the primary aim of improving a port's efficiency and competitiveness. Container terminal automation has the potential to create a new paradigm on how PCSs can be leveraged to enhance port operations. Often, terminals that undergo automation do not consider the inter-organizational effects the automation may have on other stakeholders. For PCSs to achieve their functional and intended purpose as a coordinating mechanism across stakeholders, they must incorporate the changes in the ecosystem including terminal automation. In this dissertation, I investigate the aggregate impact of container terminal automation, PCSs, and other technologies on the movement of containers in a port operation. The additional technologies being considered are internet of things (IoT), blockchain, and artificial intelligence (AI), among others.

Research Question(s)

The research questions examined in this dissertation are:

- How are ports using technology to enhance coordination and react to shocks?
- How should they do so in the future?

- What were the drivers of complexity and inefficiency of port operations during the pandemic?
- How can port stakeholders leverage technology to improve efficiency and manage operational shocks?

Significance of the Proposed Research

In this dissertation, I examine the impact of technology on efficient coordination between marine transport chains as they undergo automation efforts. Poorly implemented automation and digitalization efforts may result in less efficient terminal operations. I will contribute to the literature on the use of technology to improve efficiency in maritime ports through enhanced coordination and cooperation.

In a port setting, marine terminals undergoing automation have different needs and requirements compared to non-automated terminals. Automated terminals need skilled labor to operate and maintain automated equipment, and they need to adapt the terminal's layout to ensure safe operations are conducted using autonomous equipment. PCSs also need to adapt to a new technological ecosystem in order to provide inter-organizational benefits that enhance supply chain efficiency. In addition, other technologies that support automation like blockchain, AI, and IoT must be considered to fully leverage the potential of technology in port operations, both for daily operations and for operations during times of shock such as the COVID-19 pandemic.

This study contributes to existing IOS literature. First, I examine how to successfully utilize PCSs in an automation environment, contributing to the literature on the antecedents of successful IOS integration with emerging technologies. Second, this research will also contribute to the understanding of the transformational effect that automation and other emerging technologies like blockchain and AI can have on the inter-organizational operation in a port setting, which can have implications for other industries.

CHAPTER 2. OVERVIEW OF THE RESEARCH AREA AND APPROACH

Foundational Literature Review

The literature on IOSs and complementary technologies to improve coordination and cooperation is broad in scope across industries and only a portion of it incorporates the granularity and specific context of port operations. However, many of the conclusions are relevant. For example, Zaini et al. (2019) concluded that a key pillar of supply chain management is to integrate information systems across partnering organizations, which underscores why it is essential to adapt IOSs in supply chains as technology advances. Elbert et al. (2017) looked at IOSs in maritime transport chains by evaluating how information was exchanged and modeling key business processes. Their analysis of basic aspects of digitalization, such as the use of IOSs, shows that 75% of organizations that are involved in hinterland transport have an IOS, compared to less than 25% for maritime transport organizations. Oliveira and Lumineau (2019) looked at the negative dimensions of inter-organizational relationships to ascertain the damaging impact. They found that a sustainable collaboration can be achieved by correctly governing company relationships in an inter-organizational context. In an interpretive case study, Rodon and Pastor (2007) applied grounded theory to IOSs, looking at managers' roles before and after IOS implementation. They found that stakeholders need to agree on the system's operational use and balance the degree of integration of the IOS. These lessons from the IOS literature can be applied to the maritime port context.

Within the port technology literature, Heilig et al. (2017) examined digital technologies and their influence on modern seaports. In marine terminals at the establishment of containerization, digitalization allowed a notable degree of automation and simplified port procedures. Moros-Daza et al. (2020) performed a literature review on PCSs spanning two decades. The paper is comprehensive in capturing the state-of-the-art in the PCS literature. The authors exposed several topics that have been neglected. They found that there has been a lack of coverage of PCS design to take advantage of new technologies and on conceiving ports as information centers. Also, more emphasis is needed on services (e.g., intermodality and business modeling) to improve performance, including fewer transactions per period.

PCS literature covers the inhibitors of successful PCS operations, some of which are addressed in this dissertation. Moros-Daza et al. (2020) recommend more research looking at innovation barriers such as organized labor's opposition to automation. They also investigate barriers such as resistance to collaborative implementation of PCSs in emerging economies. Carlan et al.'s (2016) work on barriers to successful PCS operations is one of the most cited: "The PCS operator supports the development and implementation of a new form of port stakeholder collaboration that facilitates their communication operations, gaining new benefits and increasing their competitiveness as a community." (p. 29). Nevertheless, the authors found a current trend towards collaboration and innovation in the maritime supply chain leveraging new technologies.

PCS studies often lack a quantitative analysis of port data (Carlan et al., 2016). Aydogdu and Aksoy (2015) observed that there have been several studies related to PCSs, but most of them employ a qualitative and descriptive methodology. To remedy the situation, Aydogdu and Aksoy (2015) illustrated the quantitative impact of PCSs. They compared a conventional port logistics business with a conceptual port model having a hypothetical PCS in place. Researchers are often limited in their access to proprietary industry data. Often, publicly available data is not granular enough for the study of marine terminal performance. For example, the Ports of Los Angeles and Long Beach (POLA/LB) both publish container volumes by month and year for import and export, aggregated for all marine terminals, but the granularity of this data is limited because it is not broken down by individual marine terminals. Comparisons of automated terminals with non-automated terminals is not feasible with this data. However, comparisons with the other U.S. and international ports are possible.

Much of the literature neglects connection to rail transportation into and out of the ports (Aydogdu & Aksoy, 2015). Rail is often relied upon for pollution mitigation efforts in busy urban ports. In my review, I found references to PCS systems that link railroads with the other organizations in a port (Carlan et al., 2016; Chandra & van Hillegersberg, 2018). However, I have not encountered research addressing why PCSs have not been fully adopted in many ports, including the POLA/LB. Further research is needed to understand why that is the case.

The IOS literature examines trust in inter-organizational relationships (Oliveira & Lumineau, 2019). However, it does not address railroad anti-trust legislation related to the involvement of railroads as PCS stakeholders. More generally, full integration of land transportation with port operations warrants further investigation. Given the scarcity of research on coordination and cooperation between ground transportation and maritime terminals, an inductive, theory-building effort is appropriate by looking at specific cases to see how ports interact to move containers efficiently.

This literature review lays the foundation for the importance of my research problem and research questions because my goal in this dissertation is to fill some of the gaps identified. I have outlined relevant research trends in the study of PCSs and IOSs since they anchor my area of research. However, I realized in the process of this study that the complexity of a port operation is in the context of a very complex system of stakeholders. It is also important to examine other factors to understand the role that technology can play. Therefore, in this study, I also consider environmental factors such as the COVID-19 pandemic and its impact on port operations, labor issues, and container movements, among others.

Research Agenda and Justification

This dissertation addresses how PCSs, automation, and other technologies enhance coordination and information exchange in maritime transport chains to increase efficiency. In particular, the study contributes to theory and practice on the use of technology for more efficient movement of containers between ships and land transportation. The first paper is a literature review with a view on the changing role of technology in port supply chains. As automation efforts proliferate, changes need to be made to integrate the automation into existing PCS protocols, and to leverage other emerging technologies. The paper builds on the existing PCS and IOS literature, with an integrative view that includes other technological innovations based on automation, artificial intelligence, and blockchain. The product is a vision of the port of the future and the emerging role that technology will play.

I adopt a cross-case study approach for the second paper, investigating the POLA/LB, the Port of Vancouver (Canada), and the Port of Rotterdam. An in-depth analysis is performed on the POLA/LB, while Port of Rotterdam and Port of Vancouver are used for a cross-case analysis to extract theoretical propositions. In the POLA/LB port complex, a railroad-centric PCS manages container movement through the lens of railcars and trains. The POLA/LB has 15 marine terminals and two railroads, and the PCS, called the Business Exchange (BEX), is used by all stakeholders. In contrast, PCSs at other ports are typically managed by the respective port authority while railroads remain one of many stakeholders, so a comparison to other cases is in order. At the Port of Rotterdam, a PCS called Portbase is in use, and there are more automated terminals relative to the POLA/LB. The Port of Vancouver is similar to the POLA/LB in that it is a North American West Coast operation, but it also is different in other ways in which it operates. From the cross-case analysis I develop descriptive propositions on the complexity of port operations and prescriptive propositions that seek to build theory on the use of technology for port operations to address this complexity. I hope to influence decision-making for port managers and regional and national authorities to encourage proactive advancements that lead to technology-enabled efficiency gains.

The cross-case design with three ports was a particularly rich setting for analysis because I compared operations across terminals within each port and across ports including Port of Rotterdam and Port of Vancouver. The two levels of analysis, cross-port and cross-terminal within a port, allowed for the development of valuable insights for practice and theoretical propositions for future research.

A two-paper approach was chosen because it made logical sense in the context of the research questions and current literature. The first paper is a building block to the case study in the second paper. In the first paper, I examine the state-of-the-art and the integrated effect of PCSs, automation, and other emerging technologies in a generalized port setting. I develop a view on the ways in which technology can enhance the adaptability of port operations to extraneous shocks by facilitating coordination and cooperation between supply chain stakeholders with both contemporary and forward-looking perspectives.

An efficient port operation results in the least amount of time with the least number of resources. Efficiency signifies the peak performance level that uses the least input to achieve the highest output, minimizing the use of resources while reaching the desired output. Technology can lead to both efficiency and effectiveness, and efficiency can lead to effectiveness if it helps meet the end goal. The literature review with a view addresses the issue of port effectiveness, considering the impact of technology.

The second paper is a case study that examines the ways in which technology plays a role in port operations to make theoretical propositions about how technology can contribute to higher efficiency. The paper benefits from the visionary insights gained from the contemporary view developed in the first paper. An analysis of the POLA/LB, Port of Vancouver, and Port of Rotterdam was conducted to evaluate the effects of technology on efficiency in port operations, both in daily operations and in periods of disruption, prior to and during the COVID-19 pandemic. The insights gained in the first paper guided the preliminary direction of data collection and analysis for the second paper, although as expected in the case study methodology, as data was collected, new insights and directions emerged.

Increasingly, maritime terminals are looking to technology and automation to increase productivity and decrease labor costs. To reduce costs and increase efficiency, ports look for sources of innovation. Drucker (2002) explained that most innovation results from an enterprise's search for innovation opportunities. These drivers of opportunity are unexpected occurrences, incongruities, process needs, industry and market changes, demographic changes, changes in perception, and new knowledge. I was inspired by this list of drivers for innovation to identify barriers that may cause terminals to stumble in their innovation efforts, even if powered by promising emerging technologies. Specifically, I was drawn to seek recommendations related to the use of technology to improve port efficiency. I hope this dissertation will provide practitioners and academics with a useful vision for the future of technology-enabled ports.

CHAPTER 3. THE PORT OF THE FUTURE: HOW EMERGING TECHNOLOGIES CAN ENHANCE PORT OPERATIONS

Introduction

The COVID-19 pandemic exposed multilayered vulnerabilities of globally linked supply chains and caused significant disruption due to the interconnectedness and complexity of supply chains. Both finished goods and raw materials have languished in supply chain chokepoints as some ports became overwhelmed. The disruptions have caused businesses to shutter and plants to lay off employees. Carballo Piñeiro et al. (2021) forewarned that "the repercussions of the pandemic sent warnings to all the relevant actors in preparing plans and increasing their resilience for future risks and disruptions as well as to ensure that shipping, ports, and terminals function well along the global supply chain." (p. 132). The reasons behind bottlenecks and congestion include mandatory lockdowns, lack of labor, and transportation capacity.

The pandemic left many people at home without traditional diversions such as eating out. Many used their extra time, unused income, and stimulus checks to shop online, creating a spike in demand and a big surge for goods. Existing supply chain models have been deficient in addressing the resulting supply chain backups and the consequent adverse impacts. As supply chains address current inadequacies in the prolonged recovery phase, they will need to counter the looming crisis but also build sustained resilience going forward. Resilience is defined as the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events (National Research Council, 2012). Based on this definition, a port with high resilience would be able to quickly adapt to operational shocks and disruptions while maintaining continuous business operations.

Supply chain managers will need to develop strategies to manage the adverse impacts of significant shocks and disturbances, like those caused by the pandemic. Eventually, once the crisis averts, the lessons learned can provide a unique opportunity to reevaluate existing supply chain models and structures to proactively safeguard against future disruptions and crises.

The purpose of this paper is to provide a literature review with a view on the use of technology to enhance a port's ability to anticipate and handle shocks by improving coordination, cooperation, and information exchange across the different parties in the supply chain. To do so, I build on existing literature on port community systems (PCSs), among other technologies. A PCS is an inter-organizational system (IOS) that enables the intelligent and secure exchange of information between private and public organizations in a port operation, with the primary aim of improving the port's efficiency and competitiveness. A PCS is the primary technology used to coordinate port operations among stakeholders. It consists of a platform for port stakeholders to cooperate, and if well managed, to build supply chains that are resilient to shocks like the pandemic. I also examine other technologies that can improve future port operations and make ports more resilient to shocks, including automation, artificial intelligence (AI), the internet of things (IoT), and blockchain.

I examine two research questions:

- How are ports using technology to enhance coordination and react to shocks?
- How should they do so in the future?

To answer the first question, I present literature on existing knowledge of the use of technology in port operations. Then, to answer the second question, I develop a vision for academics to theorize and perform research on the port of the future and for practitioners to leverage technology to improve port operations.

Coordination and Cooperation in Maritime Ports

The Need for Coordination and Cooperation

Multimodal transportation systems employ various transportation modes, such as truck, rail, air, and ocean-river navigation. Intermodal transportation refers to the transportation of people or freight from their origin to their destination by a sequence of at least two transportation modes (Ambrosino et al., 2021). This paper focuses on the movement of shipping containers through intermodal transportation.

With numerous supply chain stakeholders involved in the movement of containers, both coordination and cooperation are essential. Applying the context of strategic alliances, Kretschmer and Vanneste (2017) used a game theory lens to redefine coordination and cooperation. Coordination occurs when actions are aligned between parties, while cooperation can exist when incentives are aligned between parties. According to these definitions, it follows that the more aligned the incentives are through cooperation, the more effective coordination is. I adopt these definitions to develop a vision of the port of the future, contending that coordination and cooperation are critical for ports to improve performance.

A port example helps to illustrate the distinction between coordination and cooperation. A train departing with containers from two adjacent competing terminals would need to have the logistics coordinated such that both terminals load their respective containers into the train based on a specified departure time. If each terminal is owned by a different ocean carrier, there will be a reluctance to cooperate and share space on the same departing train. However, both of their shipments would depart sooner by aligning incentives through cooperation, in order to decrease the container dwell (i.e., waiting time) for both terminals. Through coordination and cooperation, PCSs and emerging technologies can potentially help solve the problem, which is a fundamental underlying premise of this analysis.

Reacting to Change

Maritime ports need to react quickly to changes and shocks by staying agile and efficient. Terminals need to respond to vessel delays, strikes, container shortages, railcar supply issues, train departure delays, truck shortages, driver issues, and extraneous shocks like pandemics. The terminals can react to these changes in several ways across time horizons. In the short term, when trade and transportation demands are high, terminals can increase the size of the labor force. If the railroad does not have enough railcars to satisfy terminal demand, terminals can also shift the mix of land transportation modes for containers. When demand is low, terminals can decide not to call in labor shifts. In an extreme downturn, one or more terminals can be idled. In the medium and long term, maritime port participants can invest in technology and implement technology-enabled enhancements to their operations (Carlan et al., 2017; Haraldson, 2015; Heilig et al., 2017; Irannezhad, 2020; Jensen et al., 2019).

Inter-organizational Systems

The potential role of PCSs in maritime ports is informed by the IOS literature since PCS is one instance of the more general IOS concept. An IOS is a shared information system that connects organizations electronically. Electronic data interchange is one of the most common technologies to exchange information rapidly across organizational boundaries. An IOS can create more efficient communication and interconnection between participating organizations in its optimal state. It also improves services delivered to customers. Organizations that share an IOS do so to communicate and collaborate to address their interdependencies, which will benefit all participants in a way that a single organization could not accomplish independently (Killmeyer et al., 2014).

Oliveira and Lumineau (2019) found that if inter-organizational relationships are not structured correctly, bad practices may emerge. When considering IOS participation, organizations face several challenges, including resistance to change or organizational inertia, lack of trust, organizational culture misalignment, organizational compatibility, system complexity, and opportunistic behavior. For an IOS to be successful, a mutual understanding of expectations is required (Killmeyer et al., 2014).

IOSs perform a crucial role in the e-commerce environment because they provide significant business benefits to supply chain partners (Garfield et al., 2004). IOS advantages are likely to be realized when these systems are carefully launched by following appropriate adoption processes. Garfield et al. (2004) found that champions are crucial to an IOS implementation's success as organization leaders who actively and passionately promote their vision to use technology to communicate and cooperate.

Klein and Rai (2009) studied strategic information flows between buyers and suppliers within logistics supply chain relationships. They found evidence that relationship-specific IT investments allow partners to receive characteristic information leveraged in their interfirm relationship to help co-create relational value. Despite the capital-intensive IT assets needed to deploy IOSs and the high devaluation of these assets, there has been robust growth in interfirm relationships using IOSs.

Zaini et al. (2019) evaluated the connection between inter-organizational compatibility and supply chain capability. They weighed the mediating role of the IOS integration on the relationship between supply chain capability and inter-organizational compatibility and found that unrelated groups complicate IOS integration (Zaini et al., 2019). Therefore, it is essential to consider strategic, cultural, and technical inter-organizational compatibility across organizations when evaluating IOS integration. This is particularly relevant to ports because the expanding role of globalization and mounting environmental uncertainties has amplified managerial inter-organizational challenges in effectively delivering goods and services. Zaini et al. (2019) conclude that incorporating information systems throughout partnering organizations has become the cornerstone of supply chain management.

This synopsis of IOS research underscores the role IOSs play in the supply chain to enable coordination and cooperation between participating organizations. All participants benefit by collaborating to address their interdependencies. A successful IOS implementation can be achieved by ensuring a mutual understanding of expectations. Champions are instrumental in avoiding implementation pitfalls. IOSs can help foster interfirm relationships. Not all supply chain partners are compatible, which will decrease the coordination potential through IOSs. Consideration needs to be given to vertical and horizontal relationships, which is evident in a port environment.

Port Community Systems

Container technology has evolved significantly from the days of slinging crates off ships and loading with forklifts into trucks or boxcars. Today, it is imperative to move the freight fast because companies like Amazon, UPS, and FedEx demand short delivery time periods. Technology such as automated cranes controlled by Terminal Operating Systems (TOSs) has streamlined container flow through the terminal. TOSs are a vital part of a maritime supply chain because they control the movement and storage of various cargo types in and around a container terminal, track containers, and control the automated cranes.

The coordination between land transportation and container terminals is often accomplished using an IOS shared data platform known as a PCS. A PCS enables the intelligent and secure exchange of information between private and public organizations (Chandra & van Hillegersberg, 2018). The primary aim of PCSs is to improve a port's efficiency and competitiveness. One of the most critical functions of a PCS is information sharing. Through information sharing, each participant provides services to other actors while receiving information and services from the other participants, improving their ability to cooperate. Information exchanged via PCSs includes vessel arrival schedules that are shared with the port, terminals, and ground transportation companies. PCSs can also share TOS data among terminals, including container movements (Chandra & van Hillegersberg, 2018).

The COVID-19 pandemic showed that PCSs could play an important role for ports to react to an operational shock effectively. A 'new normal' is evolving for worldwide ports as they emerge from the devastating effects of the COVID-19 pandemic. Ports and shippers have issued an urgent call to action to accelerate the pace of digitalization and adoption of secure data exchange. The pandemic painfully revealed the lack of functioning and consistent worldwide systems for electronic data exchange. Only 49 of the 174 member states of the International Maritime Organization (IMO) possessed functioning PCSs as of June 2020, calling for wide-ranging adoption of secure electronic data exchange (World Bank, 2020). Carlan et al. (2017) looked at the rate of acceptance and adoption of PCSs and found that the speed at which digital innovation is reshaping the port sector is lower than in other industries. They suggest that a possible reason is the competition between terminals and the consequent reluctance to cooperate.

Nevertheless, some ports have enjoyed successful PCS implementations. The Port of Rotterdam utilizes a PCS called Portbase. It supports shipping companies, agents, terminals, and other service providers to exchange information about their port calls. Portbase produces vital information about a port call by combining public data, data provided directly from participating companies.

PCSs can create value through the exchange and co-production of services if they can be configured as service-based value networks (Nota, 2018). Aydogdu and Aksoy (2015) compared Turkish ports with a PCS and those without a PCS. They used the Arena simulation program, a discrete event simulation and automation software. They found that PCSs impart indirect economic benefits such as reduced cost of information access, extra government user fees, accurate taxation, smuggling and bribery mitigation, increased competitiveness, increased information quality, increased operations performance, and paperwork reduction.

Cargo Community Systems (CCSs) are similar to PCSs and are used in an airport environment. A CCS is an IOS that connects supply chain actors in air freight communities, integrating their administrative systems and supporting inter-organizational supply chain activities. Air cargo is often used for valuable, dangerous, or time-sensitive goods. Despite that, most of the transport time in air cargo is waiting time, which is caused by the inefficient communication between actors (Elbert et al., 2017).

Chandra and van Hillegersberg (2019) examined the development of Amsterdam Schiphol Airport's CCS, Cargonaut. This Cargonaut case study revealed that establishing inter-organizational governance is a fluid process that requires updates as the situation evolves. The Amsterdam Schiphol air freight community endured two lifecycles of governance which demonstrated that instituting Cargonaut’s CCS was only the first step in achieving competitive advantage. Subsequently, the implementation needed to be updated with a set of governance mechanisms and structure adapted to the relevant situation. Cargonaut's CEO eloquently summarized this study's managerial implication: "You can buy the technology, but it will be of no use. Because first, you have to have a good collaboration model, and then you can apply the technology. If you do not have the collaboration model, and you don't have the ability to act and decide as a community, technology is worthless" (Chandra & van Hillegersberg, 2019, p. 8).

PCS implementations may have similar shortcomings and may benefit from lessons learned in the aviation community. The CCS lessons on coordination and cooperation have value in the port environment and form the basis for my view of the port of the future. One key lesson is that governance is important for PCSs to stay relevant and to retain the ability to accomplish the original design functions. Therefore, it is not just about the technology, but also about cooperating to develop processes that lead to coordinated actions for a mutual benefit.

Port Community Systems, Cooperation, and Trust

Marine terminals often compete against each other, yet cooperation would benefit all parties involved. Logistic resources are often shared, and unilateral decisions can undermine the efficiency of a maritime port. Di Vaio and Varriale (2020) researched inter-organizational relationships and their effect on port competitiveness and found that PCSs decreased coordination and control costs to manage information and data about port operations, improving timing schedules, shipment time, and reducing paperwork. Further, they found that sharing knowledge and data can lead to higher transparency, lower uncertainty for port operators and managers, and higher trust between stakeholders. Their analysis shows that PCSs can be a vital mechanism to increase trust in inter-organizational relationships in the sea-land supply chain.

PCSs are used to coordinate the arrival and departure of intermodal trains. For example, an arriving multi-block train is broken up or switched into several terminals in a port with several marine terminals. Likewise, a departing multi-block train is consolidated from two or more terminals before departure. This combination train is needed for train size. Railroad operating costs are lower for longer trains, mainly because the train crews necessary are less per railcar.

Coordination between the railroad and container terminals is needed to arrive and depart these multi-block trains efficiently. A departing train with blocks from two terminals needs the loaded railcars ready for departure from each of the terminals simultaneously for the train to depart on time. Similarly, an arriving multi-block train would require that both terminals have adequate capacity to receive their respective block on arrival. If one terminal does not have room, that block would have to be temporarily stored, or the train needs to be held away from both terminals until they are ready to receive the blocks. The overall transit cost would increase since rail storage adjacent to the port is limited and the train would need to be handled multiple times. Similar situations occur in the coordination between terminals and other forms of land transportation, and PCSs can play an important role in making these interdependent stakeholders individually more efficient.

In summary, PCSs provide similar benefits of IOSs but in a port environment. The role of PCSs in information sharing can enable a port to react to a system shock and increase resilience to those shocks. Research shows that sharing knowledge and data in seaports has resulted in greater transparency and trust amongst stakeholders. The resulting increase in cooperation has helped individual port members achieve superior results compared to working alone.

Other Technologies

Automation. Automation of container terminals provides many advantages, including increased operating efficiency, environmental compliance, reduced labor costs, maximized use of all available acreage, improved competitive position for the terminal, and consistent and reliable performance. Container terminal automation consists of automating the container movements in the yard, dock-yard interchanges, and crane-ship operations. Automation efforts become especially significant as vessels and cargo exchanges increase in size. However, only 3% of approximately 1,300 container terminals worldwide have been automated. Nearly 40 partly or fully automated ports are now in operation worldwide. It is estimated that at least $10 billion has been invested in these automation efforts. Over the next five years, an additional $10 billion to $15 billion is anticipated for port automation (Chu et al., 2018).

Terminals need to consider when it makes sense to automate fully or partially. It may be best for high-volume terminals with an inability to expand acreage. For high-volume terminals with constrained footprints in developing gateways, either full or semi-automation may make sense and even become a requirement to remain competitive (Mongelluzzo, 2019). Full automation is best suited to high-volume gateways in North America and Europe that generate local and discretionary transshipment cargo. Most ports have limited room to expand. Instead, they attempt to eke out extra capacity, throughput, and efficiency through automation. According to Moody’s (2019), automated terminals support efficient land use and the ability to expand vertically without degrading productivity. The primary benefit of automation is it delivers steady, reliable performance, which is exceptionally significant as vessels and cargo exchanges increase in size.

It appears that there is an optimal size for terminals wishing to automate. If the total acreage is too small, the terminal must cease all other activities while the automated equipment operates. Rail access is impeded as a result. Half of the terminal can have the automated equipment moving in larger terminals while the other half has the manual cranes running. A better operational blend is achieved while keeping the containers moving out of the terminal more efficiently.

An agile terminal would change the proportion of automated versus non-automated depending on variables such as shipping cost, truck and railcar availability, and fuel cost. Worley (2016) discusses four routines that high-performing companies can use to enhance organizational agility: strategizing routine, perceiving routine, testing routine, and implementing routine. Agile management processes are broken down into fast management processes and flexible management processes. Fast management processes are achieved by sharing relevant information and transparency between stakeholders. Automation can assist a terminal in adapting to change and shock by enabling flexible processes. For example, the effects of the shortage of available longshoremen during the COVID-19 pandemic were mitigated at automated terminals since they required a smaller labor force. Uncertainty of available labor was minimized, allowing for better strategic planning. When the terminal knew it would not have the labor for a night shift labor, it could schedule a fully automated shift instead.

Advances in automation are addressing the problems inherent to container stacking. For decades, a global standard practice has entailed manually stacking containers directly on top of each other. Shipping containers are piled up to seven high at most major ports while waiting for movement in or out of the terminal. These container stacks take up an inordinate amount of terminal acreage. Accessing and picking up specific containers can be time-consuming. In Dubai's Jebel Ali port, BOXBAY is being tested as a fully automated container stacking and sorting system. BOXBAY has direct access to every container, eradicating unpaid and unproductive reshuffling. The result is significant gains in handling speed, safety, and energy efficiency (Labrut, 2021).

Another benefit of port automation is that an additional off-peak shift can be added to a container terminal’s daily operating schedule. This automated shift can be used to conduct container re-stacking to optimize the order of the boxes for the next day's rail and truck loading operations. An automated container stacking system like BOXBAY is ideally suited to operate autonomously during this off-peak shift, resulting in better blocking, more unit trains, and quicker truckaway departures. The overall cost of transporting a container to its destination would decrease due to lower labor costs and faster trains.

Blockchain. Another technology of interest is blockchain. Beyond the cryptocurrency space, blockchain technology has drawn attention of established firms that have become associated with trials and proofs of concept or have significant commercial projects already in production. Many blockchain projects result from multi-lateral collaboration between diverse sets of actors, including industry competitors and supply chain partners. A blockchain project might start as an alignment between organizations. Once established, the blockchain network can grow to include other inter-organizational partners such as industry rivals, suppliers, service providers, and authorities (Jensen et al., 2019).

Trust across competitors can lead to mutual benefits in supply chains. A prisoner's dilemma scenario can arise where competitors prefer a sub-optimal outcome due to a lack of trust (Flood, 1958). Differences in cooperative behavior appear to be driven primarily by the corresponding differences in the trade-off between initiating cooperation versus defection when there is uncertainty about the strategy followed by one's opponent (Embrey et al., 2018). For example, as cooperation becomes more valuable, either because the payoff to cooperation increases or the continuation probability increases, subjects are more likely to use strategies to support at least some cooperation (Flood, 1958).

In the port environment, terminals may feel it is better to work alone and not cooperate with other competing terminals in the same port. In landlord ports, the port authority retains land ownership by leasing terminals and other infrastructure to private operating companies. Often there is a reluctance to share business data with port authorities in landlord ports, resulting in the failure of PCSs in those ports. The barriers to PCS implementation include distrust, lack of transparency, and lack of efficiency (Carlan et al., 2017).

Blockchain may be one solution to enhancing trust between parties in a port environment. Blockchain is an open-source and distributed platform that allows a more efficient, transparent, and trustworthy data flow and transactions between companies. Ports are now looking to blockchain technology to maintain the security and immutability of the shared data so that multiple parties can trust the accuracy and reliability of the data. Therefore, blockchain technology can potentially surmount PCS implementation barriers and facilitate horizontal and vertical integration. Blockchain affords a level of transparency that enables supply chain managers to acquire the information consumers are requiring and therefore impact their companies' competitive advantages (Francisco & Swanson. 2018).

Blockchain technology may alleviate some of the concerns arising from a prisoner's dilemma scenario by providing greater visibility of service partner activities. Dal Bó and Fréchette (2019) found that the strategies used to support cooperation change with the game's parameters. A blockchain-enabled PCS can increase trust and cooperation through better transparency. Participation risk is significantly reduced, yet optimal integration of all stakeholders can only be achieved through information and data connectivity. There must be a willingness to share information by the PCS stakeholders and agreement with the level or amount of data to be shared. They also need to feel confident that the information will be protected and not be used for the wrong purposes. PCS stakeholders need to be convinced of the more significant benefit of sharing data than in acting alone.

The development and implementation of novel technology such as blockchain does not ensure that it will be accepted and widely utilized. It is necessary to comprehend the underlying motivators and barriers that will affect companies' decisions to adopt blockchain technologies for supply chain traceability and transparency (Francisco & Swanson, 2018). Blockchain currently must overcome obstacles to ensure greater acceptance. Further blockchain enhancements are required to attain the required data transparency in the supply chain and to restrain unlimited access to sensitive data (Hellani et al., 2021).

Internet of Things. Technology has advanced significantly since the early days of PCSs. The first PCSs made primary port data available such as ship schedules and custom information. Today the amount of available data increases exponentially, facilitated by sensors embedded in containers and goods, also known as the Internet of Things (IoT). IoT provides a mechanism to ensure that critical data is obtained and passed along in real-time to all connected supply chain partners. IoT technology and blockchain are among the most-used techniques to achieve more supply chain transparency (Hellani et al., 2021).

Container tracking utilizes GPS and shorter-range wireless container tracking systems. The application of these container tracking technologies is not universal since the need for tracking depends on the purpose. For example, railroads do not track containers with either technology. They are more interested in the movement of the railcar the container is on. Railroads combine several technological methods including RFID technology, AEI tag readers, and virtual geographic zones to keep track of cars. Once a container is loaded on a railcar, it is billed to that railcar via EDI. The container is essentially associated with the railcar it is riding on and is located based on this association. Problems arise when a container is loaded onto a railcar with the incorrect container number. Since railroads do not use GPSs for containers, the wrong container may arrive at a destination. IoT can enable faster and more accurate information exchange and communication to address these, and other issues related to locating containers and goods by tracing containers using GPS data and keeping related historical records.

In marine terminals at the establishment of containerization, digitization has allowed a notable degree of automation and simplification of port procedures (Heilig et al., 2017). For example, Haraldson (2015) found that the RFID-equipped container contributes to the sustainability of sea transport and significantly enhances international intermodal container traffic transparency and security. The authors observed an efficiency improvement in the area of ship operations, as well as an optimization of the maritime traffic through the exchange of data between ship–ship and ship–land actors through the use of information and communications technology such as RFID and AIS.

Some ports have become oriented towards users' and customers' changing needs through digitalization. Sea Traffic Management (STM) is a concept for maritime services based on standards and open interfaces. STM is built on information sharing and cooperating to optimize the maritime transport chain while improving safety and sustainability (Watson et al., 2017). Shipping agents and other marine logistics actors rely on collaboration and information sharing to organize and execute their business (Haraldson, 2015). This calls for safe and effective means to share information among these actors to facilitate environmentally sustainable sea transports and operational efficiency for all involved actors. For example, Port Call Optimization is an independent, neutral coalition of maritime organizations dedicated to reducing and optimizing vessel berth time at ports. The Port Optimization Task Force created a structure to support individual vessel port calls by facilitating electronic information sharing. The goal was to significantly decrease traditional person-to-person communications among ship operators and agents, pilots, port facilities, and government agencies. This is accomplished by standardizing ship-shore data exchange with data gathered through IoT. Successful use of Port Call Optimization will reduce ship emissions enroute and in-port. It will lower costs for shipping lines, shippers, terminals, and ports. It will also improve crew rest hour planning.

Artificial Intelligence and Analytics. AI and IoT are being combined to realize an even more significant advantage. After being analyzed, AI data can spot logistics chain patterns. Prediction times for vessel and container arrival to the terminals are calculated with great accuracy and thus optimize planning for future equipment needs. AI is the ability of a computer program or a machine to think and learn. With AI, computers make decisions on their own without being encoded with commands. Machines learn from experience, adjust to new inputs and perform human-like tasks.

AI is used in ports in autonomous container trucks, automated guided vehicles, and straddle carriers. Similarly, autonomous trucks, robots, and drones are used for intralogistics and last-mile delivery. This helps reduce the impact of any fall outs of shift plans caused, for instance, by the sickness of a large number of workers. A logistics workforce crunch has resulted from pandemic infections and worker disincentives. The lack of truck drivers has made the situation more acute. Autonomous vehicles are increasingly seen as a cost-effective way to power repeatable middle-mile routes. Walmart has started using fully driverless trucking in its online grocery business to build capacity, lower inefficiencies, and reduce labor costs.

Modeling of resilience in maritime supply chain intermodal networks is still in its infancy and has much room for improvement when compared to railways and roads intermodal networks (Wendler-Bosco et al., 2020). Shortage of data standards and data silos are inherent problems in ports pursuing automation. The quality of data and the data analytics are insufficient due to an inadequate structured, transparent data pool making it challenging to monitor and diagnose the operations and performance of equipment quickly (Chu et al., 2018).

To show the potential benefits of analytics, Zerbino (2019) applied business analytics to the information flow in port freight transportation processes. These operations are data-intensive because of the high number of data attributes that characterize the cargos. Business analytics is regarded as enabling better process efficiency. Zerbino (2019) found that lowering the time length of information and document sharing can affect the overall port efficiency to a certain extent. The author also found that current digitization trends and wider data availability in port contexts strengthen the analytics capabilities, such as process mining, which can be exploited for in-depth and partly automatable analyses of process data. Besides, the exploitation of analytics in multi-stakeholder contexts might allow us to identify process inefficiencies or other issues caused by the behavior of a specific kind of stakeholder. Interestingly, Zerbino (2019) also noted that fixing such inefficiencies might require involving multiple parties, such as the marine terminals. Increasing digitalization and advancements in information capture, diagnostics capabilities, and predictive abilities will enable a more significant role for data analytics to positively affect container port strategy and performance (Yap et al., 2021).

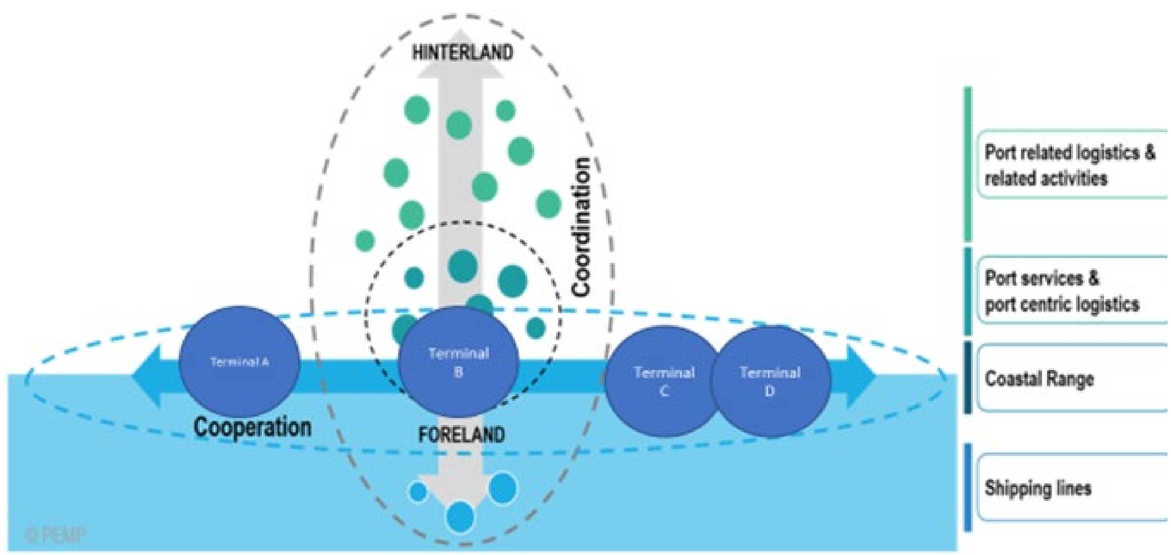
Analysis of Current Use of Technology in Maritime Ports

In this section, I develop a framework for a view of the port of the future. To arrive at the framework, I examine the primary benefits of each port technology and classify them based on their potential value to improve coordination and cooperation. Port technologies need to be evaluated not only for the immediate benefits provided, but also for the positive effect of information sharing to achieve a broader advantage to the supply chain.

Figure 1 shows a representation of coordination vs cooperation in a port environment. It delineates two geographic areas: the foreland and hinterland. The *foreland* represents the ports and overseas markets linked by a port's shipping services. The foreland is a maritime space that enables a port to maintain commercial relationships with its overseas customers. The *hinterland* is the inland region lying behind a port and is the area it serves, both for imports and exports. The port links the hinterland and the foreland as part of a logistics chain, creating a high level of interdependency. Cooperation occurs horizontally between competing marine terminals, while coordination exists vertically between hinterland and foreland.

Figure 1

Port Coordination and Cooperation



Note. Adapted from Port Economics, Management and Policy

Inter-organizational relationships can be described by their bilateral linkages (Ebers, 2001). The participating members can be organized horizontally and vertically. Vertically organized members operate before or after each other in the supply chain. For example, a maritime shipping company and a terminal operator can agree to coordinate their services. The coordination process is common in supply chains, even if there is little impetus for cooperation. Vertical cooperation, in this sense, is not required since coordination is implicit in the vertical relationship. Therefore, in my framework, coordination as joint action is prevalent for vertical relationships.

In a port operation, the participating marine terminals are horizontally arranged at the same point in the supply chain. Horizontally related members are often in direct competition and tend to distrust one another because they play the same value-added role. There are times when horizontal cooperation is unwarranted and even illegal because antitrust statutes limit railroads from anti-competitive behavior. Therefore, the driving force for successful horizontal relationships lies in their ability to cooperate. Once cooperation through aligned incentives is accomplished, mutual benefits can be achieved through coordinated actions. Horizontal coordination can only take place after horizontally related members agree to cooperate. For example, an equipment pool can be established to improve usage of all available assets.

I evaluated each port technology in its current use to determine where it provides benefits related to cooperation and coordination. Having been tested as a proof of concept in limited ports, I evaluated blockchain and AI based on their features and benefits. Table 1 theorizes how each technology contributes to coordination and cooperation in vertical and horizontal relationships based on current practices. The value of investing in port technology can be optimized by having a positive impact on both coordination and cooperation. Significant planning needs to occur between horizontal and vertical supply chain partners to achieve these inter-organizational benefits.

Table 1

Port Technology Rating for Coordination and Cooperation

	Vertical		Horizontal	
	Coordination	Cooperation	Coordination	Cooperation
PCS	High	Medium	High	Low
Automation	High	High	Low	Low
Blockchain	High	High	High	High
IoT	High	High	Medium	Low
AI	High	High	High	High

A PCS is the primary technology used to coordinate port operations among stakeholders and therefore receives high utility for vertical and horizontal coordination. The most significant shortcoming of a PCS is its lack of implementation worldwide. Also, the current information exchange systems based on EDI and PCS are not adequate to address complications in cooperative communication (Sarabia-Jacome et al., 2019). The lack of trust among port stakeholders is often the culprit, as is a lack of perceived value or usefulness of PCSs. Therefore, because of these issues and in line with inter-organizational challenges for coordination and cooperation, it is often a struggle for maritime ports to maximize the potential of PCSs. Due to a lack of perceived trust, I rate PCSs as providing medium value for vertical cooperation.

Horizontally aligned stakeholders often compete for market share and therefore do not have complete trust and are reluctant to coordinate. For example, railroad and trucking compete for market share in receiving containers from marine terminals for land-based transportation as each seeks to maximize the transportation distance for a container. A PCS receives low value for horizontal coordination due to a lack of trust between competing horizontal stakeholders. Each is subject to the prisoner's dilemma in evaluating their own needs versus the broader supply chain.

The current role of automation primarily benefits each automated terminal and its vertical supply chain partners: ocean carriers and land transportation. A terminal spending billions of dollars and enduring years of transition has little interest in sharing the automation benefits with its horizontal competitors. Ostensibly, the only benefit to other competing terminals is that they are able to use the idle labor that is no longer needed by the competitor's automated terminal. Automation, therefore, realizes low value for horizontal coordination and cooperation. Conversely, automation achieves high value in vertical coordination and cooperation. This is evident at entry gates for container terminals and rail terminals. Many have automated the entry and exit processes. One of the benefits is quicker turn times for the containers to make it to land transportation.

Blockchain technology provides the advantages of maintaining the security and immutability of shared data. Blockchain technology can facilitate horizontal and vertical coordination and cooperation. Unfortunately, blockchain implementation in shared port data systems such as PCSs is in its infancy. Blockchain-enabled PCSs are only in the test phase in select global ports. Being tested as a proof of concept in limited ports, I evaluated blockchain based on its features and benefits and assigned high value for all four categories. Major ocean carrier alliance members to enter the 2020 TradeLens Agreement. Ocean carriers are investing in innovative technologies, such as blockchain, to digitalize transport documents, trace shipments, and optimize information flows. Fedi et al. (2022) suggest that this type of cooperation signifies a crucial stage of carrier integration, which could launch a new generation of substantially integrated strategic alliances where carriers create and operate common IT systems to coordinate their international networks significantly more than in the past.

IoT data acquisition has been facilitated in maritime ports by sensors embedded in containers and goods. IoT provides a method for ensuring all critical data is not only obtained but is also passed along in real-time to all vertically connected supply chain partners with limited dissemination of proprietary data to horizontal actors. Therefore, I rated IoT high in vertical coordination and cooperation. On the other hand, I rated it medium for horizontal coordination due to limits on sharing data. For example, a container terminal does not have access to the proprietary container data of a competitor, and it is not likely that the competitor will share it unless there is mutual benefit. Any cooperation between terminals to share rail or truck assets would likely need the proprietary competitor container data provided through IoT. Terminals need to have the ability to coordinate before cooperation can be considered as an option. Coordination would be enabled if an IoT data sharing agreement were to exist. Likewise, cooperation would then be supported but would still have the competitive hurdles existing between terminals. Therefore, I rated IoT low for horizontal cooperation because the alignment of incentives needs to occur before IoT-generated data can be effectively used for coordination.

The current use of AI in autonomous container trucks, automated guided vehicles, and straddle carriers have significantly benefited the terminals that own them. Current usage limits its usefulness to other vertical and horizontal stakeholders. The linking of big data with AI is also in its infancy. Being tested as a proof of concept in limited ports, based on AI features and benefits I rated it high for all four categories.

The View: Port of the Future

In this section, I lay out my view of future port operations where existing technologies are adapted for enhanced collaboration and cooperation at ports, leading to resilience to shocks and disruptions.

How Technology Will Drive the Port of the Future

Port Community Systems. PCSs are used to coordinate all supply chain players to synchronize plans and avoid a supply-demand misalignment and enhance cooperation. I rated PCSs with high value for vertical and horizontal coordination. There is room for improvement since PCSs achieved a medium and low grade for vertical and horizontal cooperation respectively. A PCS is a mature technology that has been in use for over 20 years. It has improved incrementally as technology has changed. The trend has been for a PCS to act as a trusted digital shipping hub. Port organizations will continue to invest in new technologies such as AI, IoT, and blockchain. As I elaborate on in this section, future gains in horizontal and vertical cooperation will be achieved by integrating these technologies with PCSs.

Blockchain. Transparency is a basis for trust between organizations. Transparency will be enhanced by creating communication and data-sharing channels with supply chain partners where they do not already exist. Data visibility through blockchain technology will instill trust in supply chain stakeholders to have confidence in container movement decisions made by the advanced blockchain-enabled PCSs. Having been tested as a proof of concept in a handful of ports, I rate blockchain technology high for cooperation and coordination across horizontal and vertical relationships. Wider adoption of PCSs will be facilitated by blockchain-based features that will allow port stakeholders to share data to improve inter-organizational processes. Blockchain technology provides the advantages of maintaining the security and immutability of shared data, which will help overcome the PCS implementation barriers that include inaccurate and unreliable data and lack of transparency, trust, and visibility of port activity.

Several international ports have committed to delivering a pilot blockchain-based platform, including the Port of Antwerp, Port of Rotterdam, Port of Valencia, Associated British

Ports (ABP), Port of Abu Dhabi, Port of Montreal, and Port of Busan in South Korea (Irannezhad, 2020). PORTIC, the port community system of the Barcelona Port Community, has announced that it is now integrating data with TradeLens, the blockchain-enabled digital logistics platform jointly developed by A.P. Moller-Maersk and IBM. This integration enables more transparency in the exchange of information in real-time to allow greater detail about maritime operations (TradeLens, 2021).

Artificial Intelligence and Analytics. AI will transform all modes of port logistics. It can reduce human error, speed up operations, and lower emissions. Having been tested as a proof of concept in a handful of ports, I rate AI high for cooperation and coordination across horizontal and vertical relationships. AI is one part of a comprehensive process to digitize and modernize port operations. Optimization of port operations can be realized by designing a decision-making support system that uses a predictive model. As a subset of machine learning, deep learning algorithms are used to analyze data far more efficiently than humans ever could. AI has the potential to pull port stakeholders together in ways that PCSs could not accomplish in the past. PCSs augmented by relevant AI-mined insights will enhance collaboration between stakeholders.

AI-based analytics can lead to predictions in a port environment such as container availability to enhance data planning. Logistics chain patterns gleaned from AI and IoT will be analyzed and optimal container routing will be implemented. It will also predict future equipment needs to harmonize planned container stacking. Interconnected container terminals will mutually benefit from AI prediction analytics. Terminals in the same port are often exposed to the same factors, causing equipment shortages. PCSs that incorporate these tools will realize an advantage from mutually beneficial opportunities in sharing data, increasing horizontal coordination and cooperation. However, the data must have a standard interface to successfully convey the data and benefit from the projections, constraints, and insights. The Achilles heel for automation is data. AI-enabled automation will benefit from establishing data standards. Critically important is determining what data aspects will be most relevant to automation, robotics, autonomous vehicles, and ultimately what data should be shared between organizations.

To better collaborate between vertical supply chain stakeholders, marine terminals will adapt existing technologies such as business analytics to decide which containers to stack and move for land transportation departure. Business analytics enables better process efficiency by lowering the time length of information and document sharing (Choi & Lambert 2017, Choi et al., 2017). The information for the algorithm will come from linked logistics information from vertical supply chain partners using existing technology GPS location devices and IoT. A marine terminal may not care about the location of a container in a competitor's terminal using IoT data. However, they may be interested in IoT aggregated container data from all competing terminals in the same port. PCSs will provide horizontal coordination benefits. The container will still get to Dallas but travel on a quicker unit train (all Dallas-bound railcars). In the port of the past, it may have traveled with a small block of Dallas railcars on a multi-block train stopping in multiple states and taking much longer.

Port Automation. I rated automation high in potential for vertical coordination and cooperation. Optimized automated terminals with excess capacity can reallocate idle capacity to benefit supply chain capacity and reduce bottlenecks. If one terminal is at maximum capacity or is struggling with labor shortages, container traffic can be shifted to another terminal. Sharing agreements must be in place before disruptions and shocks occur so that precious time is not wasted negotiating.

An automated container stacking system like BOXBAY may help solve the blocking problems that hamstring rail, river, and truck transportation. For example, railroads that move intermodal trains can use a stacking system to improve vertical and horizontal cooperation. While railroads attempt to maximize the number of unit trains, the reality is that most intermodal trains are multi-block. This is because most terminals receive vessels with containers for multiple destinations. With a system like BOXBAY, container terminals are incentivized to cooperate and coordinate with each other to match destinations on the same train or other form of land transportation for quicker departure. Terminals can more readily sort containers with a stacking system, whereas currently many do not have the willingness (desire to cooperate) or capacity (ability to coordinate) to do so. Railroads and terminals both benefit and thus vertical cooperation and coordination increase.

Internet of Things. During the COVID-19 pandemic, many container vessels sat at anchor outside ports while awaiting a berth to unload. It did not make sense to have the vessels transit at rapid speed just to anchor for up to four weeks. Just-in-time (JIT) arrivals will enable more accurate prediction times for vessel arrival when a berth will be available to occupy immediately. The technology for JIT currently exists, including IoT and automatic identification system (AIS) data. AIS is an automatic tracking system that uses transceivers on ships and is used by vessel traffic services (VTS). Several of the largest container shipping companies formed a non-profit called the Digital Container Shipping Association (DCSA). DCSA promotes global collaboration by publishing standards that will allow carriers, ports, and terminals to automatically exchange event data uniformly (DCSA, 2021).

With JIT, a vessel will transit at a speed that will allow it to go straight alongside the berth on arrival. Avoiding anchoring will be an immediate benefit. The JIT Port Call program is a multi-year initiative designed to enable a digital, JIT port call process that will facilitate vessel speed optimization. Significant reductions in fuel consumption, CO2, and NOX will result. Another benefit of JIT arrival is that container arrival to the terminals can be calculated for accuracy and optimize planning for future equipment needs such as empty railcars and chassis.

Combining technologies such as GPS tracking, IoT, and business analytics will fine tune the marine terminal to the hinterland vertical supply chain. Incoming trains can be given arrival slotting to meet ship departure times. A quicker departure of the vessel with its export containers will ensue. Lengthy container storage in endless stacks will be reduced. The trucking industry will share this technology resulting in shorter truck lines and quick turn times on the trucks, containers, and chassis. Bluetooth-enabled PCS technology will alert drivers on ship movement and gate arrival times. Business analytics will be used to determine driver availability and container allocation to optimize container throughput via trucking.

The movement of the container after it leaves the port will also be affected by future technological advancements. A look at a container's typical overland rail journey is in order. The loaded container departs the container terminal and is moved by rail to its destination at the intermodal rail yard. The container is unloaded and trucked to a distribution center for unloading. The empty container then takes one of two paths. Often, it will remain empty and reverse the journey back to the origin port to meet a vessel. If it is to be reloaded for export, it may travel to a rural farm cooperative to be loaded with an agricultural product such as soybeans. This may add several weeks to the container journey back to the vessel. This circuitous routing can be better planned and coordinated through several technologies such as GPS tracking, IoT, PCS, and business analytics. Often a container arrives at the container terminal too late for ship movement. The container misses its planned vessel and needs to be assigned to another vessel.

Standardizing container tracking utilizing GPS and related technologies would be the first step. The second step is integrating and coordinating the loaded or empty container movement as it transits through the supply chain.

IoT enables the interconnection of any seaport equipment to the internet. The Port of Rotterdam Authority and IBM have entered a multi-year digitization initiative to rejuvenate the port's operational environment using the cloud and IoT technologies to support the port and those who use it. The plan is for the port to accommodate connected ships in the future. IBM's cloud based IoT technologies will analyze the data and provide information for the port to make decisions that reduce vessel wait times and determine optimal times for ships to dock, load, and unload and enable more ships into the available space (McCurry, 2019).

The Port of the Future Resilient to Shocks

The COVID-19 pandemic initially resulted in a drop in shipping volumes (Port of Long Beach, 2022; Port of Los Angeles, 2022). Subsequently, a surge in demand for goods resulted from increased buying from online shopping (Kent & Haralambides, 2022). As terminals look to invest in assets and sufficient physical capacity to handle sudden surges in demand, they must realize that spending on infrastructure will be an incomplete solution. Port infrastructure is costly and takes time to build. A supply chain disruption such as a pandemic significantly impacts ports due to the high level of interdependency. The previous analysis examined the relationship in ports where the hinterland and the foreland are linked as part of a logistics chain. Based on the framework presented, I propose that technology will enhance cooperation horizontally between competing marine terminals and coordination vertically between hinterland and foreland, in line with Ebers, (2001) and Zaini et al., (2019).

As demand decreased during the pandemic, container terminals, railroads, and trucking companies reduced their workforce and laid up equipment because they did not want idle assets and capacity. Unfortunately, when demand returned, the port industry was slow to ramp up hiring and return assets to service. Ports need to better anticipate spikes in demand to avoid bottlenecks and supply disruptions to increase resilience (Kent & Haralambides, 2022).

Port ecosystems with a digitized supply chains should be better able to rapidly react to shock because digital platforms reduce uncertainty regarding the management of port operations and enhance trust between port stakeholders due to easier and unlimited data accessibility and tracking (Di Vaio & Varriale 2020). As markets reopen, initial sales data can be quickly gathered. Logistics planning decisions can use data analytics to evaluate raw material purchasing and other production indication metric data to represent impending consumer demand by modeling recovery scenarios (Choi & Lambert 2017, Choi et al., 2017).

The PCS of the future will assist ports in reacting to supply chain disruptions. As a start, the Port of Rotterdam implemented a PCS by merging the Port Infolink and PortNET after identifying the issues that hinder the efficient flow of goods through the seaport (Tijan et al., 2021). PCSs will become the maestro of the port supply chain by directing the accumulation of buffer stock, principally for complex parts that necessitate collaboration with multiple suppliers. For example, many factories shuttered as the world shut down because of the COVID-19 pandemic. As a result, the supplies needed for chip manufacturing became unavailable for months. Critical supply moves would be identified, tracked, and prioritized through PCSs to ensure buffer stocks are maintained.

The increase in demand for consumer electronics caused shifts that rippled up the supply chain and dramatically affected the automotive industry and a car shortage for consumers. Vital inventory such as automotive microchips should be stored at major distribution centers, away from high-risk areas. One stakeholder with high resilience is not likely to prevent overall port bottlenecks. In the United States, the supply chain was not resilient. The POLA/LB became emblematic due to the dozens of container vessels at anchor waiting to unload. While there are potentially many causes for the supply chain backup, it is unlikely that one container terminal caused the problem. Instead, it appears to be a systems problem caused by multiple parties and inter-organizational issues are in play that can be resolved through increased coordination and cooperation.

One hurdle to overcome is the shortage of technologically skilled personnel, which is becoming a problem for automated terminals and terminals planning to automate in the future (Chu et al., 2018). Conceivably, the most significant obstacle to this more automated and efficient future is talent. Logistics companies must be aware that any investment in automation must have a commensurate investment in technical training for the operators and maintenance staff.

A second workforce problem is organized labor’s opposition to automation. The International Longshoremen’s Association (ILA) is the largest union of maritime workers in North America. In September 2021, the ILA warned shipping lines and developers of fully automated container vessels that ILA members will not work ships without crews aboard. In 2012, a strike by longshoremen from the International Longshore and Warehouse Union (ILWU) over labor contract issues crippled the POLA/LB, with associated supply chain disruptions rippling through the economy. The ILWU maintains solidarity with the ILA in resisting automation efforts in the POLA/LB as a fourth terminal prepares to automate. The union opposes the project because it will eliminate some dockworker jobs.

In summary, the port of the future will leverage existing technologies to enhance collaboration and cooperation, leading to resilience to shocks and disruptions. I used a framework that considers vertical and horizontal relationships in the port ecosystem to identify where the opportunities are for technology to enhance coordination and cooperation. There is significant opportunity for ports to improve their supply chain operations and to deal with shocks and disruptions, and technology is bound to play an important role as I tried to lay out in my view of the port of the future.

Conclusions

A port is the most vital point in the maritime logistics chain because of its multimodal and multifaceted nature. Presently, EDI and PCSs, as principal enablers of digital seaports, have exhibited their limitations to interchange information on time, accurately, efficiently, and securely, triggering elevated operation costs, low resource management, and low performance (Minerva et al., 2020).

A technological revolution is taking place in some ports worldwide due to systems interconnectivity. This transformation is driven by AI-enabled autonomous processes and machine learning, IoT, and blockchain. These technologies, combined with PCSs, will improve coordination, cooperation, resilience against shocks, and efficiency. As ports automate, PCSs will evolve to facilitate information exchange and communication, both horizontally and vertically. The role of PCSs needs to be transformed to facilitate greater integration of automation data to make the supply chain more efficient.

PCSs are the core technology that links the data generated through automation, blockchain, IoT, and AI to enhance coordination, cooperation, trust, and resilience to shock. As each technology advances, its prominence will be dictated by integration with existing port operations. As ports look to future investments in technology, they will need to evaluate the payback of each technology considering the perceived value. However, each technology cannot be considered in a vacuum. Value can be maximized through the integration of technologies.

There will be an emphasis on reducing carbon emissions and labor costs. The port of the future will need to react to change or shocks such as a labor strike or the wild volume surges during the COVID-19 pandemic. A geographically separated supply network will tolerate shocks by being able to source from global or local suppliers to minimize risks accompanying localized disruptions.

The port of the future will be influenced by research and innovation, increased dependence on automation, and other technological advances. Ports will see improvements in data security, information sharing, and enhanced environmental compliance. Increasingly larger container ships will call on environmentally friendly, sustainably built port facilities and expect faster processing. Port infrastructure will need to adapt to the impacts of climate change, rising sea levels, and increased frequency of severe weather events such as Hurricane Katrina and natural disasters such as the 2004 Indian Ocean tsunami.

Future ports will use advanced blockchain-enable PCS to link stakeholders and provide solutions in ways not dreamed of today. Perhaps improved through blockchain technology, the PCS of the future could provide a single neutral entity to flow AI-enabled container loading data to all stakeholders on behalf of the alliances, improving the efficiency around building container trains on-dock. For example, future AI-enabled PCSs could provide mutually beneficial occasions to capitalize on shared railroad destination blocking. Such a PCS would deliver a universal interface for AI-enabled solutions, predictions, and constraints.

Terminals today move containers to benefit their own facility. In the port of the future, container moves will be more like chess pieces moved by a chess grandmaster looking several moves ahead. These moves would benefit upstream and downstream stakeholders in ways not possible today. Machine learning can assess the effectiveness of the routing and then predict further movements in a way that could have never been accomplished before machine learning. AI algorithms would use reams of transport data to predict future patterns. Shortages and oversupply of vessels, containers, railcars, trucks, and chassis can be monitored, anticipated, and controlled for to achieve balance in the supply chain. For the most part, this is not happening today. The evidence is compelling when dozens of vessels sit at anchor off U.S. ports.

While there is ample evidence that new technologies such as AI benefit individual container supply chain players, the real advantage will be realized by the integration of technologies. Through mutual cooperation, agreements, and legislation, advanced technologies can be integrated to achieve a sum more significant than the individual parts. The lesson from the aviation Cargonaut community insisted that a collaboration model needs to be in place prior to purchasing technology. Otherwise, the technology will not have the intended value because the community will not be involved in the implementation. The supply chain does not create demand; it responds to it and attempts to fulfill it. Unfortunately, supply chains can suffer from delays or unfilled orders through inefficiencies. Eventually, the consumer will look elsewhere. The port of the future will need to incorporate emerging technologies into its operation to compete effectively.

It remains to be seen whether it is a shock or pure economic considerations that incentivize the change to a broader inter-organizational view and approach. Nevertheless, I believe the shift is necessary and inevitable due to the shipping industry’s trend towards larger container ships. The E-Class container ship can carry over 20,000 twenty-foot equivalent units. Due to terminal capacity, many worldwide container terminals cannot accommodate such a large vessel. High volume terminals with an inability to expand acreage will continue to look to technologies such as automation to leverage existing footprints to increase terminal throughput and thus capacity.

A change in perspective from inward to outward needs to happen to ensure that ports will be able to have the resilience to combat future supply chain disruptions. Port stakeholders are somewhat unique in that they do not operate in a vacuum. Instead, they exist in close proximity and cooperate to maximize the use of precious port land. Vessels use the same tugs and pilots. Trucks use the same roads. The impact of a shock often affects all. Conceivably, a disruption to the supply system may be the catalyst for widening the perspective to look beyond one’s own organization to the broader benefit potential of cooperation to the port community. The ongoing lessons of the COVID-19 pandemic may have shifted long-held parameters and provided the impetus needed to force cooperation amongst port stakeholders to ensure survival.

CHAPTER 4. THE DRIVERS OF COMPLEXITY AND EFFICIENCY IN PORT OPERATIONS: A CROSS CASE STUDY PRE AND POST PANDEMIC

Introduction

Recent events in Southern California ports merit the attention of port managers and executives as a call to action. On an average day in 2020, there was at most one ship at anchor holding offshore awaiting its time slot to arrive pier side into the ports of Long Beach and Los Angeles (POLA/LB). In January of 2021, the number jumped to a daily average of 35 vessels at anchor, peaking at 40. By November 2021, the number approached 100 vessels at anchor. Before the pandemic, the POLA/LB highest record had been 17 ships waiting at anchor, according to data from the Marine Exchange. In POLA, the average wait for berth space was over seven days (Port of Los Angeles, 2022). Some vessels even spent almost as much time at anchor as it normally takes to traverse the Pacific Ocean, roughly two weeks. The backlogged ships were full of TVs, computers, and appliances the economy planned to consume during the COVID-19 pandemic. The backlog was not expected to be resolved in short order due to continued consumer demand. Ships were alongside their berth longer than average also.

Several reasons accounted for this backup (Kent & Haralambides, 2022). First, a shortage of longshoremen due to COVID-19 infections was reported. Online shopping during COVID-19 lockdowns caused a surge in global shipping. Delays at marine terminals contributed to the logjam at sea. Abnormally high inbound container volumes from trucks and rail, combined with logistical complications inside and outside the ports, caused landside delays. Protracted anchorage times compelled some ocean carriers to cancel multiple sailings. There was a lack of ships in East Asian ports to pick up the burgeoning piles of containers due to most of the vessels remaining at anchor off West Coast ports. The vessel shortage was not due to a lack of cargo demand, but rather a lack of available ships to handle those services. As the backlogs continued, the cost of shipping rose. Consumers felt the brunt in the form of higher prices. Higher prices to ship containers encouraged rerouting of vessels from other shipping lanes to POLA/LB, seeking higher profits.

The POLA/LB congestion has been the center of attention in the crisis, even though many worldwide ports suffered similar congestion problems. Pictures and videos of dozens of large container ships (and cruise ships) at anchor have made a fascinating story and are a visceral reminder of the side-effects of the COVID-19 pandemic. In this study, I use the case study method to analyze the drivers of complexity and inefficiency that has led to the crisis, with the goal of identifying potential remedies to the inefficiency observed in ports worldwide, particularly in POLA/LB.

Ports are highly interconnected, adaptive, and self-organizing complex systems. Ports exhibit emergent properties driven by the connective structure of the port system's elements and resulting from unknown or poorly understood dependencies between port stakeholders. Supply chain disruptions and other exogenous shocks multiply the complexity port operations. In this study, I use complex adaptive systems (CAS) theory as a theoretical lens to analyze three port operations before and after the pandemic, in order to generate theoretical propositions about the drivers of complexity and efficiency of port operations. I then propose prescriptive recommendations on how to improve port efficiency and address congestion from extraneous shocks like the ones experienced from the pandemic.

I also examine the ways in which technology has affected port operations to make propositions about how technology can contribute to higher efficiency of port operations, and to propose a roadmap to normalcy in ports worldwide after the pandemic-induced disruptions. The technologies being used and considered by ports include Port Community Systems (PCSs), automation, internet of things (IoT), blockchain, and artificial intelligence (AI), among others. Specifically, PCSs and automation are evaluated in this study. PCSs can aid in the coordination and cooperation across port stakeholders. According to the European Port Community Systems Association (EPCSA, 2011), a PCS is a "neutral and open electronic platform enabling intelligent and secure exchange of information between public and private stakeholders in order to improve the competitive position of the sea and air ports' communities. It optimizes, manages and automates port and logistics efficient processes through a single submission of data and connecting transport and logistics chains" (p. 1). Container terminal automation includes automating the movements in the yard, dock-yard interchanges, and crane-ship operations. I examine the extent to which PCSs can alleviate complexity and increase efficiency.

Most large global ports utilize a PCS to link all players in a port's logistic chain. In 2017, the POLA launched a single window platform, Port Optimizer, providing visibility on inbound cargo, container tracking, truck turn times, and volume prediction (Port of Los Angeles, 2022). In December 2021, the POLB announced a new digital initiative called the Supply Chain Information Highway. The platform will facilitate the streamlining of goods movement by allowing stakeholders to integrate their already-existing systems to share information digitally throughout the supply chain (Port of Long Beach, 2022). Currently, the POLA/LB does not have a unified PCS in use by all marine container terminals. However, one shared data platform having the attributes of a PCS called the Business Exchange (BEX) is used by all POLA/LB marine container terminals and the two railroads.

When labor is constrained due to unforeseen shortages, port automation requires fewer longshoremen. Automation is the one of largest capital expenditures being considered by container terminals in ports worldwide. At the POLA/LB, there are currently two automated terminals between the two ports. One additional terminal is in the process of being automated and the automation of another terminal is in the negotiations stage.

This study's broader intended purpose is to understand the drivers of complexity and efficiency of port operations and to contribute to theory and practice. My goal is not only to address the pandemic-induced operational crisis at ports, but also to offer insights for future operational shocks, whether they are global or local. The research questions are:

- What were the drivers of complexity and inefficiency of port operations during the pandemic?
- How can port stakeholders leverage technology to improve efficiency and manage operational shocks?

I compare and contrast port operations across three ports: the POLA/LB, the Port of Rotterdam, and the Port of Vancouver (Canada). As the research questions suggest, the level of analysis is at the port level. However, I also examine efficiency across terminals within each port where appropriate to extract the drivers of complexity and efficiency from the case analysis. Four areas of port operations were examined: container ship movement, longshoremen labor, container availability and imbalance, and inter-organizational coordination. The depth of the analysis in these four areas allowed me to develop deep understanding of the factors that drive complexity and efficiency at the ports, to build theory that can inform future research and practice on port operations.

Theory on Drivers of Complexity and Efficiency in Port Operations

In this section, I review research and theory on the drivers of efficiency in port operations. This literature review is structured based on three categories for independent variables and their influence on a dependent variable of efficiency in port operations. The three categories for independent variables are *processes*, *technology*, and *people and organizations*. Regarding processes, I adopt the theoretical lens of ports as complex adaptive systems. Regarding technology, I focus on terminal automation and PCSs due to their current level of use and consideration by ports around the world. Regarding people and organizations, I discuss the effect of competitiveness and trust on relationships and their influence on port efficiency.

Operational Processes and Theoretical Framework: Complex Adaptive Systems

By examining the logistical supply chain, it is important to consider the complexity of the context and how the ports adapt (or not) to this complexity. This issue of complexity in the operation is more relevant in the context of the disruption caused by the COVID-19 pandemic. For this purpose, I adopt the theoretical lens of supply chain processes at ports as CASs.

Supply networks have been categorized as CASs in the supply chain literature (Choi et al., 2001; Yaroson et al., 2021; Zhao et al., 2019). Supply chain participants interact in a non-linear way over time and the supply chain exhibits emerging system behaviors. Bearing in mind that there is no agreement on the definition of complexity theory, Preiser (2019) constructed six general organizing principles that characterize and help identify complex adaptive systems. Next, I elaborate on these six principles and apply them to the port context.

1. Complex phenomena are relationally composed. In a CAS, any component in the system impacts and is impacted by the actions of others. Multifaceted behavior and structures materialize because of the repeating and cumulative patterns of the relations that exist between the components of the system. Positive and negative feedback loops exist between them. In a port environment, you can consider the different port stakeholder entities as the components of the CAS, which include container terminals, land transportation, and labor. There is a significant interaction between these stakeholders, which can be described based on their inter-organizational relationships in the form of bilateral linkages (Ebers, 2001).

The stakeholders are organized and connected horizontally and vertically. Vertical organization is related to situations where two stakeholders operate in sequence in the supply chain. For example, a maritime shipping company and a terminal operator have a bilateral linkage, whereby the terminal hands over containers from sea to land to the terminals in the import process and vice-versa for the export process. Horizontally linked stakeholders play the same value-added role in the supply chain. For example, railroads and truck companies both transport containers overland once they are released by the terminal operators.

These vertical and horizontal relationships between stakeholders can create operational complexity. For example, a positive feedback loop results from an increase in the number of arriving vessels, which creates congestion in the port terminals, which in turn causes a proportional increase in the number of railcars, trucks, and river vessels required to meet the demand for land transportation. A negative feedback loop occurs when a container terminal prioritizes one land transportation provider over another for not operating on schedule.

To address this complexity, port stakeholders must coordinate and cooperate, but they do not always have the incentives to do so. For example, horizontally linked stakeholders tend to distrust one another because they play the same value-added role (Karam et al., 2021).

2. Adaptive ability to co-evolve and self-organize regarding contextual changes. CASs seek to self-organize and to coevolve in relation to contextual changes. Reacting to an ever changing and dynamic environment, complex systems should exhibit learning and innovative attributes.

Port systems and their stakeholders develop inter-organizational process to coordinate and cooperate to become more efficient. Over time, structured processes emerge based on what works and what does not work across daily contextual changes or extraneous shocks like an economic downturn. For example, PCSs have emerged as inter-organizational systems at ports out of a need for self-organization by the different stakeholders including freight forwarders, customs, port authorities, terminal operators, and land transportation companies (Bisogno et al., 2015; Carlan et al., 2016). Decisions are based on existing information, and each member makes them with no over-arching arbiter.

3. The dynamic relationships that describe complex systems and their interaction are nonlinear. In CASs, actions do not develop smoothly from one stage to the next in a sequential or logical way. Connections and conclusions often arise from unrelated concepts or ideas, resulting in non-uniformity or disproportionality. Nonlinearity is a result of repeating feedback loops, which suppress or magnify disturbances away from equilibrium. Such oscillations exist both internally and between the system and its environment. CASs are difficult to control due to uncertainty and unpredictability resulting from this nonlinearity. Vertically organized inter-organizational structures are assumed to exhibit linear relationships between practices and performance, yet the adaptive nature of strategies and processes are discounted.

In a port system, any state of equilibrium is often transitory. For instance, instability results from a lack of coordination between horizontally organized container terminals. A surplus of containers may develop from over-ordering by multiple terminals after a short-term shortage. Resulting congestion can quickly escalate as terminals run out of space to operate, creating a bottleneck that in turn affects the efficiency of the system. Congestion in the terminals results in congestion for maritime shippers that must wait longer to unload containers and for land transportation companies that take longer to hand over containers to the terminal operators.

4. Complex systems are dependent on the context. In CASs, changing the context will have an impact on the function of the system. The environment suppresses or enhances possible systemic functions. Collaborative enterprises are affected by a wide range of contextual factors or variables.

In the port system, contextual factors are often beyond the control of inter-organizational authorities who enable collaborative processes. For example, container imbalance emerges from trade imbalance, so a percentage of containers will constantly be empty in one direction depending on the severity of the trade imbalance.

There are scenarios whereby the context of a port operation is affected by both internal and external factors, but the internal ones depend on one entity or stakeholder. For example, a key process variable for efficiency at ports is the availability of pooled assets such as containers and chassis that move containers on wheels. A chassis pool is located near a terminal where chassis are stored to support the daily usage of intermodal chassis by motor carriers. Chassis are pooled together to support a more efficient way of obtaining chassis for trucking companies due to the ability to use the chassis from any of the chassis companies interchangeably (Chassiakos et al., 2018). A shortage of a pooled asset such as chassis may result from factors within the port, such as a gate fee per inbound or outbound container, which is set by the port authority. Pooled assets tend to cycle episodically, yet other external factors may be relevant such as high fuel prices that limit long distance chassis movement to replenish shortages.

5. Complex systems are radically open systems. In CASs, the system's activity in relation to its environment defines it as open. Specifically, in a radically open system, the boundary line between the system and its environment is not clearly defined because the environment is integral to the identity of the system. Intractable problems outside the ports such as road congestion are often synergistically interconnected to the efficiency of a port's operation. As such, they can only be solved through systemic interventions once system boundaries are acknowledged and processes are developed so that port stakeholders are assigned to influence the resolution of those problems outside the port.

There are situations where the openness of the port system leaves it vulnerable, with little to no ability to influence a problem outside the system. During the pandemic, port workers were designated essential workers by federal and state authorities because of their critical role in maintaining the nation's supply chain. In January 2022, the POLA/LB longshoremen accounted for about 80% of the 1,850 infections reported for all West Coast longshoremen (Hassan, 2022). The shortage of available labor occurred as 90 container ships were at anchor. The container imbalance problem is also an issue driven by the fact that containers flow in and out of the ports, so port operations are impacted by external forces that affect container flow.

6. Emergent phenomena materialize stemming from complex causality. In CASs, emergence occurs when entities are observed to have systemic properties that are different and nonreducible to the properties of the constituent elements. Emergence occurs in a port setting when the whole port system produces outcomes that differ categorically from those that the port actors can produce individually. An emergent property in a port is driven by the connective structure of the port system's elements. Complex causality arises from horizontal and vertical connections and is the result of circular and interrelational, non-linear, and dynamic interactions. Emergent consequences can result from unknown or poorly understood dependencies between port stakeholders.

With complex causation, complex effects cause each member to see their own part of the cause of something, but often none sees all the causes. For example, the threat of looming port container fees for excess dwell caused some POLA/LB terminals to leave incoming railcars loaded with export containers. The dwell clock would start as soon as the railcars were unloaded. The terminals had very limited room to stack the containers since the two ports were flooded with excess containers. Terminals were temporarily helped with this strategy, yet railroads were hurt due to not having their railcars back.

Complexity and Efficiency

Given that port operations are CASs, it is not surprising that extraneous shocks like the pandemic have really disturbed the global supply chain, with ports at the heart of the congestion problem. Port systems are not only open and vulnerable to economic, social, natural, and political shocks, but they are also complex operationally so handling these shocks requires careful set up and coordination. In the end, the goal should be to maintain a reasonable level of efficiency despite the inherent complexity of the operation and the increased complexity driven by extraneous shocks.

Efficiency signifies the peak performance level that uses the least inputs to achieve the highest output. Technology advancements can lead to both efficiency and effectiveness. An efficient operation produces results in the least amount of time with the least amount of resources. "It is fundamentally the confusion between effectiveness and efficiency that stands between doing the right things and doing things right" (Drucker, 1963, p. 1). It is pointless to perform a task efficiently when it should not have been performed in the first place. In supply chains, efficiency leads to effectiveness, but this case study focuses on efficiency.

Technology

The types of technologies currently available to marine terminals across ports include automated cranes and vehicles to move containers, truck technology, ingate and outgate automation, and PCSs. PCSs have centralized relevant data that is readily available to competing terminals. For instance, two terminals may have railcars on the same inbound train. With a PCS, both terminals have access to information on that train's arrival and can coordinate railcar delivery. With automation, each individual terminal can then move the containers faster, so the coordination leads to higher efficiency.

Even though the two terminals are fierce competitors, they have a joint interest in the arrival of the railcars and could agree to share the relevant information and speed movements through automation. Problems with implementing port technology and automation changes can be minimized by concentrating on project governance, experienced staffing, and proper external data flow (Chu et al., 2018).

Container terminals can be automated to transform from mostly manual operations to a much more machine-led process. Automated ship to shore cranes or quay cranes are used to load and unload containers from container vessels. Automated Guided Vehicles are used for horizontal movement on the terminal. Container stacks are managed by automated stacking cranes are rail-mounted gantry cranes. Terminal access is facilitated through automated gate systems where optical character recognition and radio frequency identification are used to accurately gather data about inbound and outbound containers (Notteboom et al., 2021).

Once they are optimized, automated container terminals (ACTs) are faster, safer, and more efficient than conventional terminals. Several advantages can be achieved can result in improved operational efficiency. These include increased terminal capacity, container traceability, and reduced container vessel berthing time (Yu et al., 2022). However, research on the effect of ACTs in reacting to supply chain disruptions is still nascent.

The obstacles to container terminal automation include very large investments and investments in development projects and equipment, such as larger ship-to-shore cranes and the need for increased space utilization. Deeper channels and longer berths are needed for larger vessels. Also, resistance from the workforce can be encountered at major ports, and operation and repair of automated equipment may be limited by a lack of skilled manpower (Chambers & Peterson, 2019)

Port operations and inter-organizational processes are affected by container terminal automation. For instance, railroads and trucks cannot operate simultaneously with automated equipment, especially autonomously operated equipment. This is amplified for smaller ACTs. Larger ACTs can geographically fence automated operations. In choosing to automate, smaller terminals are less able to realize automation advantages because the ships must partially unload and go back to anchor while the containers are transferred to land transportation. Small ACTs at times constrain vertical members of the port supply chain. For instance, a small ACT is limited in how many refrigerated containers it can take in per day. Excess refrigerated containers need to be held out by railroads. On the positive side, ACTs use less labor, so when labor is short, other terminals benefit because there is less competition for the labor pool.

PCSs and Efficiency. Technology-related literature on PCSs can be categorized based on research in the PCS context, industry context, and adoption. PCSs can assist with the coordination and communication required to react to daily operational issues and to mid-level shocks like a longshoremen strike or dramatic events like the pandemic. Chandra and van Hillegersberg (2018) suggest that PCSs have evolved to address traditional collaborations regarding operational and information system-related challenges. Companies anticipate receiving a competitive advantage from these collaborations, including network expansion, business process simplification, and cost reduction (Chandra & van Hillegersberg, 2018). Enhanced coordination and information exchange can lead to greater efficiency. Coordination between competing stakeholders involves trust. Di Vaio and Varriale (2020) contend that reaction time will decrease if trust exists between member organizations. This will also enhance the agility of the port to react to change. Carlan et al. (2016) describe how a PCS can improve efficiency:

- It aids decision making using information that is ambiguous and costly in an uncertain environment.
- It connects multiple users and speeds up the flow of communication.
- It prevents data inconsistency due to the significant amount of repeated data.
- It minimizes the waste of resources such as workforce, money, and time.
- It organizes a shared electronic data pool for the required data accessible by each stakeholder.

There is ample evidence and rationale in the literature on how PCSs can improve efficiency. Shipping agents and other marine logistics actors rely on collaboration and information sharing to organize and execute their business (Haraldson, 2015). This calls for safe and effective means to share information among these actors to facilitate environmentally sustainable sea transports and operational efficiency for all involved actors.

Di Vaio and Varriale (2020) compared two ports with a PCS in Italy. They found that port operations management using PCSs has simplified and automated processes, reducing single actions and interactions between port players. There was also a reduction of coordination and control costs to manage information and data about the port operations. This led to an improvement in timing schedules and a reduction of paper documents. An additional benefit reported is that higher transparency for all port stakeholders can be achieved in sharing knowledge and data. There was also a lower uncertainty regarding the management of port operations. Ease of access and unlimited accessibility and tracking also increased the level of trust between port stakeholders. This is an important finding because trust is a common concern with inter-organizational relationships when some users are competitors. The authors found that PCSs represent the primary coordination mechanism in inter-organizational relationships between the port users in the sea-land supply chain, taking the place of face-to-face meetings and phone calls.

These results are promising in terms of finding the drivers of efficiency in a high impact shock at a port, suggesting that if the operation needs to stay agile with an ability to react to change, there is a need for easily accessible, accurate data. Also, if trust exists between member organizations, reaction time will decrease, which will in turn enhance the port's efficiency. I focus on this trust factor and other people-related factors next.

People and Organizations

A proper understanding of how to govern the relationships between companies in an inter-organizational context is needed to achieve a sustainable collaboration (Oguz et al., 2018). But there is a dark side to inter-organizational relationships. If not structured correctly, harmful practices may emerge. Firms should devise policies, procedures, codes of conduct, and training programs to prevent the dark side's different manifestations (Oliveira & Lumineau, 2019). A sustainable collaboration can be achieved by correctly understanding how to govern companies' relationships in an inter-organizational context.

Stakeholders in a port system are often competitors. The element of trust emerges when competitors are forced to share information. Governance of PCSs can affect participant behavior, and there could be deterrents to collaborate, leading to prisoner's dilemma environments.

Villena et al. (2019) looked at the concept of trust as it applies to the buyer-supplier relationship with a focus on the buyer's perspective. The authors used survey data to examine buyer dependence and market instability as two types of uncertainties that cause positive and negative effects. They theorized that inter-organizational trust and efficiency exhibited an inverted-U-shaped association. After a certain point, the negative effects of trust offset its benefits and beyond that point performance is degraded. They also investigated the relationship between buyer dependence and rate of efficiency with market instability as a moderator. They found that there needs to be a level of information transparency when port stakeholders share information to sustain and cultivate trust.

The prisoner's dilemma is a classic example of a scenario in game theory that shows why two entirely rational individuals might not cooperate, even if it appears that it is in their best interest to do so (Flood, 1958). The prisoner's dilemma has applicability to the port logistics supply chain. Terminal managers and operators may feel it is better to work alone and not cooperate with other competing terminals in the same port. These siloed decisions result from terminals' failure to see the big picture of their port's standing in competing against other ports globally. By cooperating and collaborating, competing terminals can enable their port to attain a competitive advantage against threats like the shipping via the Panama Canal.

Study Design

This research is a theory building cross-case study of the POLA/LB, the Port of Vancouver, and the Port of Rotterdam before and after the pandemic to gain an understanding of the drivers of complexity and efficiency of port operations and to develop theoretical propositions that are both descriptive and prescriptive.

The case study approach offers an ideal method to compare and contrast operations across ports and across terminals within a port to tease out the drivers of complexity and efficiency in port operations. The case study method enables the collection of significant details that would not normally be easily acquired by other research designs (Yin, 2011). The data collected is of greater depth, so while the findings may not be statistically significant, they allow for the development of theoretical propositions that can be further tested through bigger samples in future research. Case studies delve beyond the superficial and provide a deeper and more relevant understanding of a complex research problem. Table 2 illustrates the contexts studied, both across ports and within the POLA/LB port, which was one of the most affected by the pandemic.

Table 2

Case Study Description

Level of Analysis	Port(s) Analyzed	Topic Analyzed
Within Case	POLA/LB terminals	Ship movement data for automated terminals vs. manual terminals.
Within Case	POLA/LB terminals	Labor availability for all vessels across terminals.
Within-Case	POLA/LB	Use of BEX for port stakeholders to coordinate and cooperate.
Cross Case	POLA/LB vs. Rotterdam	Ship movement data comparing different operational models across ports.
Cross Case	POLA/LB vs. Vancouver and European ports	Comparison across ports of loaded vs. empty containers.

The level of analysis for this study is mainly at the port level because I am interested in uncovering the drivers of complexity and efficiency of port operations. However, I also examine efficiency across terminals within ports (within-case analysis) to extract the drivers of complexity and efficiency based on the different operations across terminals. The POLA/LB is the base case, while the case studies of the Port of Rotterdam and Port of Vancouver are used for comparison and benchmarking to validate propositions based on an analysis of their similarities and differences. The rationale for this design is two-fold. First, I have strong familiarity of the POLA/LB so I can bring that knowledge to bear in the depth of the study. Second, it allows for a deeper dive into the POLA/LB, which was the most negatively affected of the three case sites by the pandemic. The rationale for the selection of the other two ports, based on the differences and similarities between them, is covered in the next section.

The combined POLA/LB has 15 container terminals. Several terminals in the POLA/LB have undergone automation over the past several years. The ACTs were compared against each other and then against the other non-automated terminals. Currently, the combined ports are at risk of losing market share to East Coast ports due to the Panama Canal expansion and continued gains by the Prince Rupert container-rail port located in the North Coast Regional District of British Columbia. Therefore, understanding how PCSs and container terminal automation has affected the operation of POLA/LB in general, and during the COVID pandemic shock specifically, can offer insights into theory and practice of port efficiency more broadly.

A core element of the case study is the Business Exchange (BEX), which is administered by one of the two POLA/LB railroads. The BEX is the only shared data platform utilized by all the POLA/LB container terminals and by both railroads in the two-port San Pedro Bay complex. The analysis on the use of BEX at the POLA/LB provides insights that lead to prescriptive theoretical propositions on how PCSs enable coordination and cooperation, leading to efficiency in port operations.

In this case study, I compare the operation across ports during the COVID-19 pandemic to a base operation period before the pandemic. The within-case and cross-case design, together with a comparison before and after the pandemic, provides key insights on the drivers of complexity and efficiency on port operations including technological factors and how maritime ports can be improved to handle shocks like the pandemic.

Cross-Case Study of Ports and Terminals

The cross-case study across ports and terminals allowed in-depth exploration of similarities and differences across different cases to build theory. The main case study analysis was for POLA/LB and it included non-automated versus automated terminals and their reaction to supply chain disruption. The cross-case analysis across ports is complementary but important to develop theoretical propositions. Differences and similarities were evaluated and from this analysis the theoretical propositions emerged. The ports selected have similarities and differences, which create enough variance across cases to develop theoretical propositions.

The Port of Vancouver, Canada's largest port, was used to compare loaded versus empty containers across ports. It was chosen because it is similar to POLA/LB in that both are on the West Coast of North America. The Port of Vancouver receives container vessels before POLA/LB due to the shorter distance from East Asian ports to the West Coast of North America. Vancouver has four non-automated container terminals and is served by three Class I railroads and one regional short line railroad, each with extensive on-dock rail facilities. In contrast, POLA/LB has two railroads operating in the combined ports. As far as differences between the ports, the combined POLA/LB handles significantly greater volumes than Vancouver. Also, vessels arriving at POLA/LB have a shorter transit to their berth than Vancouver due to its location on the Fraser River. The Port of Vancouver does not have a PCS but does provide data on its website in a similar fashion to the data shared by PCSs.

The Port of Rotterdam, Europe's largest port, was selected for the cross-port analysis of ship movements and port efficiency. Rotterdam's port and industrial area are managed and operated by the Port of Rotterdam Authority. Rotterdam's PCS, Portbase, offers over 40 different services for all the links in the logistics chain. The port has nine ACTs. Container vessels calling on Rotterdam typically make stops at multiple container terminals to avoid exceeding the container capacity of a single terminal. By contrast, at POLA/LB most container ships unload and reload at one terminal. Rotterdam utilizes truck, rail, and barge for inland transport, while POLA/LB uses just truck and rail.

Rotterdam has deep sea and short sea terminals to handle containers destined for different geographic locations. Short shipping occurs in the short sea terminals. It is the maritime transport of goods over relatively short distances within the European Union, as opposed to the intercontinental cross-ocean deep sea shipping (EU Commission, 1999). The short sea operation is for smaller ships on a special schedule that is not analogous to any POLA/LB operation. In this study, I focus on Port of Rotterdam's deep sea terminal operation.

POLA/LB Case Study Preliminaries

For the import business, marine container terminals at the POLA/LB unload containers from container ships to rail and truck transportation for further transport to inland destinations. They accept rail and truck container traffic for export business and load it on container ships. Competition exists between marine terminals in the POLA/LB, but the combined ports also compete against other domestic and international ports. In the aggregate, efficiency is an important goal for POLA/LB to compete against other ports.

Over 10 years ago, the BEX was developed and administered by the railroads for use in the POLA/LB. This in contrast to other ports, where PCSs are developed and managed by the ports themselves. Ten marine terminals and two railroads use it in the two ports. The BEX has gone through many iterations and upgrades. The BEX was designed to optimize container movement from the container terminals to the railroads and does not cover truck transportation. Marine terminals track containers, so PCS developers focus on containers. The marine terminal's primary goal is to quickly move containers from the ship to a truck or train and off the property. Tracking of railcars is necessary for a railroad. Marine terminals tolerate tracking railcars as a necessary inconvenience to move the containers from their property. Future improvements to the BEX may include full integration of container and railcar tracking.

Process-wise, seven days per week, conference calls occur at specific times with the following stakeholders on each call: Marine terminals, ocean carriers, and railroads. Each terminal is covered on separate calls to keep conversations private since the terminals are competitors. The purpose of the conference calls is to discuss BEX inputs made by terminals and railroads such as a forecast of arrivals of container trains and container vessels, and the related number of containers. These metric and forecasts are reviewed, and operational decisions are agreed upon. The ocean carriers are not always present when their terminals' conference call takes place since their attendance is not mandatory. The two railroads are competitors but are on the same conference calls to operationally coordinate train movements in and out of the two ports. All rail tracks are shared, so the two railroads cannot simultaneously arrive at the same terminal at the same time. The BEX does not produce its own data, it just aggregates data produced by marine terminals, ocean carriers, and railroads.

The Efficiency Problem

With unlimited resources, terminals and land transportation companies could provide unlimited equipment and crews to move containers to and from marine terminals. A marine terminal would order excess labor each shift to ensure coverage of all moves. Unfortunately, unlimited resources are not available. Inland carriers such as rail operators and road haulers and marine terminals at the POLA/LB, and at other ports for that matter, are expected to optimize efficiency with limited resources while still accomplishing the daily tasks needed to move containers rapidly.

Compared with other U.S. ports, labor cost at POLA/LB is exceptionally high due to a significant union presence and the high cost of living in Southern California. The two unions with the most substantial presence are the ILWU and the Teamsters. Both are opposed to terminal automation because it can result in a net loss of jobs. Labor unions have concerns about the cited benefits of automation and whether these benefits will be achieved. They have used tactics such as strikes or work slowdown to demonstrate their resistance to automation. The marine terminals have offered to retain jobs through retraining in operation, maintenance, and repair of automated equipment. This opposition does not only apply to automated cranes and autonomous vehicles but also to other computerized systems.

The POLA/LB has undergone several attempts to merge the two ports to achieve the benefits of a unified leadership while reducing redundant positions. According to the former Los Angeles Port Director, these attempts failed because the two port directors were not involved in the negotiations (Knatz, 2018). Both ports have independent governing organizations. The Port of Los Angeles is a department of the City of Los Angeles (also known as the Los Angeles Harbor Department) and is governed by the Los Angeles Board of Harbor Commissioners. The

Port of Long Beach has a similar organization. There is one neutral organization which spans the two ports: the Alameda Corridor Transit Authority (ACTA). The two ports formed ACTA to build and operate a freight rail corridor which runs partially underground from the ports to the major railyards near Downtown Los Angeles.

As the demand for international trade increases, a significant investment is needed to increase operational efficiency and physical capacity. However, available land for port expansion is often limited. Environmental concerns make it difficult to expand onto accessible land. It appears that the only viable solution is to increase terminal efficiency. There are various ways this can be accomplished. There are currently two labor shifts utilized daily at most terminals. A third shift could be added, but labor costs are prohibitively high. Container movement can be expedited by adding newer cranes that can pick up more containers per lift. Truck ingate and outgate technology can be improved to speed up the flow of trucks. Increasingly, the terminals are looking to technology and automation to increase efficiency and decrease labor costs.

Container technology has evolved significantly from the days of slinging crates off ships and loading with forklifts into trucks or boxcars. Today, it is imperative to move the freight fast because companies like Amazon, UPS, and FedEx offer timely delivery. Technology such as automated cranes controlled by the Terminal Operating System (TOS) has streamlined container flow through the terminal. A TOS is a vital system for maritime ports because it aims to control the movement and storage of various cargo types in and around the port. In the POLA/LB, all the marine terminals use their own TOS to track containers and control the automated cranes.

Data Collection and Analysis

Data was collected to capture different dimensions of the same phenomenon across terminals and ports. Secondary data is the primary source of data. Where necessary, interviews were used to complement the secondary data. I was not authorized to explicitly report the data from the interviews, but I was able to effectively use it to complement or validate my own inside knowledge of the POLA/LB operation and to complement data from the other two ports.

Five terminals at the POLA/LB were not included because they did not have rail access or were multipurpose terminals providing cruise line, bulk, and automotive delivery services. Similarly, terminals from Port of Rotterdam were excluded because they were short sea operations that moved smaller vessels and covered regional routes, so they were not good comparisons to the POLA/LB operation.

Table 3 shows anonymized POLA/LB terminals used from the dataset along with the number of berths per terminal. Each terminal's number of berths varies between three and six and is assumed to not affect the loading/unloading dwell for a specific vessel. For instance, a terminal with four berths and only one vessel occupying one berth would not garner all the cranes in the terminal to increase the loading/unloading rate because a fixed number of cranes can fit alongside one vessel depending on its length. A similar assumption is made for a terminal with three berths and three vessels occupying those berths. The loading / unloading rate per vessel is assumed to be unaffected by the terminal having all its berths occupied. The total length of a terminal's berth is a significant factor in determining the terminal's ability to receive the largest container vessels. For instance, the terminal manual-Z may only have three berths, with each berth being twice the length of terminal manual-Y.

Table 3

POLA/LB Berths

Terminal	Number of Berths
Automated	5
Automated - 1	4
Manual S	6
Manual T	3
Manual U	3
Manual V	4
Manual W	5
Manual X	5
Manual Y	6
Manual Z	3

Four areas of port operations were examined: container ship movement, longshoremen labor, container availability and imbalance, and inter-organizational coordination. The container ship movement depicts the extent of the congestion. The labor analysis explores the effects of labor shortages as a contributor to the bottleneck and the extent to which available port berths were underutilized. The container analysis looks at the ratio of empty and loaded containers and the effects of surplus/deficit containers. The actions taken by the port stakeholders using the BEX were used to gauge its impact on inter-organizational coordination and cooperation.

Ship Movement: Data Collection and Descriptive Summary

An important data point to determine the efficiency of a port is the ship movement in the port's vicinity and inside the port. Ship movement data were collected from the Automatic Identification System (AIS), which tracks data from ship transceivers via coastal AIS receiving stations and satellites. When satellites supplement AIS signatures, the system is known as Satellite-AIS (S-AIS). Ship transceivers provide position, course, and speed to the S-AIS, allowing real-time vessel tracking and ship movement history. Several eCommerce companies use vessel tracking, apply algorithms, and integrate complementary data sources to provide the shipping, trade, and logistics industries with actionable insights into shipping activity.

Container ship movement data was obtained from the Marine Exchange of Southern California, a non-profit organization dedicated to the development and efficient flow of maritime commerce throughout Southern California. The Marine Exchange collects its data from several sources, including ship AIS and ship logs. This data covered only container ships arriving at the POLA/LB. Of interest was the pandemic shock reaction of the eight non-automated terminals and the two automated terminals.

I collected data on two ship movements. The first was total days at the marine container terminal berth and the second was the time at anchor before repositioning to the berth. A berth is a port location where a vessel stops for loading and unloading. These two data points serve as a proxy to evaluate the efficiency of container movement from the vessel through the terminal to land transportation. The most efficient terminals minimize or avoid having their container vessels wait at anchor before arriving at the berth, which is made possible by expeditious container flow through the terminal to available land transportation such as rail or truck away. I also collected container capacity for each vessel measured in twenty-foot equivalent units (TEU). A TEU is a measure of volume in units of containers that are 20 feet in length. For example, large container ships can transport more than 20,000 TEU. This would equate to 20,000 twenty-foot containers or 10,000 forty-foot containers. The TEU metric was used to analyze the relationship between vessel size and unloading time, also known as *dwell*.

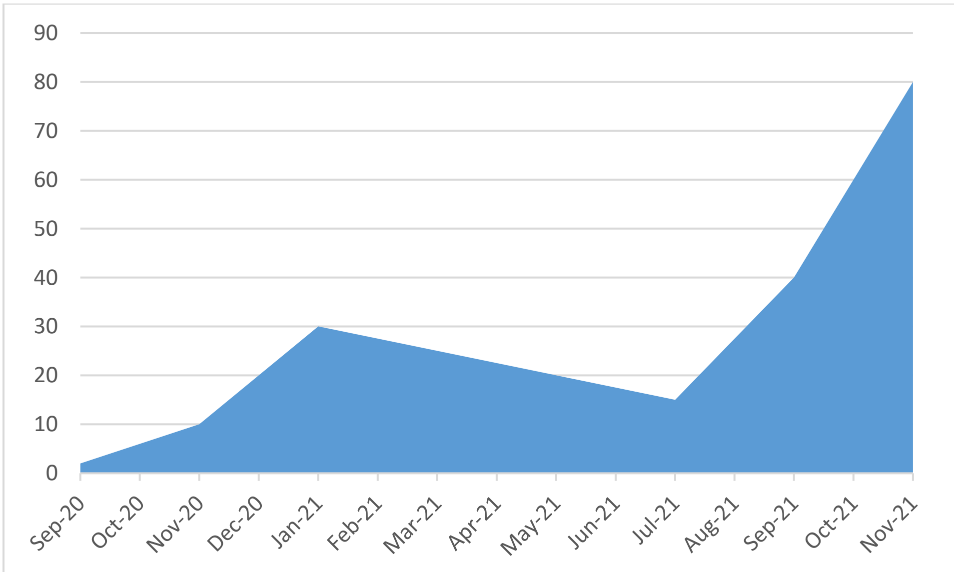
Container movement inside the marine terminals was not analyzed for two reasons. First, the container dwell, or total time in the terminal, was proprietary and was not available. Second, the container dwell information inside the terminal was complex, varied, and outside the scope of this study. When a vessel is unloaded in the terminal, each container is moved into ground stacks. One area of the terminal may have many truckaway stacks separated by trucking company and destination. Another area holds all the rail containers. These are separated by rail company and destination. In an optimal situation, a container may move from the vessel and depart on ground transportation in just a few days. In the worst cases, containers may languish for over a month. The reasons for each container's dwell are often varied and includes labor availability, customs hold, and billing issues.

Data pertaining to the container movement out of the terminal to land transportation was not collected due to its proprietary nature. However, from a complexity perspective, it is a significant contributor to container dwell within the terminal and to the total transit time of the container movement from origin to destination. Expeditious container departure from the terminal is critical to avoid terminal congestion as evidenced by the massive container stacks during the pandemic

The data covered two time periods: September 2019 through December 2019 and September 2021 through December 2021. The 2019 timeframe was selected as the baseline because it was the most recent year before the COVID-19 pandemic. The 2021 period was chosen to represent the highest point of congestion in terms of the number of anchored vessels off the POLA/LB. Figure 2 shows an earlier peak of 40 vessels in February 2021, with a slow decline through June 2021. By July of 2021, the rate of vessels anchoring was increasing dramatically and remained near 100 vessels through the end of 2021.

Figure 2

Vessels at Anchor at POLA/LB in 2020-21



Note. Source: Marine Exchange of Southern California and Vessel Traffic Service LA/Long Beach

The POLA/LB dataset had the following fields: vessel name, berth, attribute (e.g., arrival, departure), attribute date and time, and activity (e.g., load, unload, refuel). For each vessel, berth dwell was calculated by subtracting the departure date/time from the arrival date/time. Anchor time was calculated in a similar fashion. The data was then categorized by terminal type: automated, automated-1, and manual. They were then further segmented by month.

The Port of Rotterdam dataset and POLA/LB data set had two major differences. The Port of Rotterdam dataset did not have the activity column, so the specific vessel operation being performed at the berth (i.e., loading, unloading, refueling) was unknown. Additionally, the number of containers delivered to each terminal was unknown. It was only known how much time the vessel spent at each terminal. Data was only used from the five deep sea terminals. The short sea terminal data was not used because it employs small vessels of approximately 1000

TEU, sailing on a fixed schedule to and from the United Kingdom. As such, the data is not comparable to the POLA/LB terminals.

Historically, the September through December period also encompasses the peak season, when stores obtain inventory for the holiday shopping season. The 2021 peak season added further stress to an already weakened supply chain. An overview of the vessels arriving at the POLA/LB during the period of data collection is shown in Table 4. The terminals are categorized by level of automation and based on the operational model, namely the layout of the terminal and number of stops each vessel has at the terminal. The manual terminals comprise all the non-automated terminals. The automated category represents a terminal using automated equipment with an operational model that requires larger container vessels to partially unload at that specific automated terminal and return to anchor awaiting more room at the terminal. The automated -1 category represents a terminal using automated equipment in which vessels completely unload at that specific automated terminal. The POLA/LB data analyzed includes one automated terminal, one automated-1 terminal, and eight manual terminals.

Table 4

2019 and 2021 Total Vessels Arriving at POLA/LB

Terminals by Level of Automation	2019	2021
Automated	29	35
Automated - 1	36	51
Manual	599	497
Total	664	583

The purpose of looking at ship arrival and departure data is to gain an understanding of the throughput and efficiency of the marine terminal system, which includes the container vessel, container terminal, and land transportation. An optimized scenario would mean a vessel arrives and avoids anchoring. It immediately ties up to an available berth and quickly unloads all its containers. The containers are then swiftly transported by land. In an inefficient scenario, vessels cannot unload at the berth because there is no room to stack the containers. Newly arriving vessels must anchor because all available berths are full. Terminals can reach container capacity for several reasons including ineffective land transportation. Therefore, the ship movement and TEU capacity data are used as a proxy to gauge the overall efficiency at both the port level and at the marine terminal level.

Efficiency Analysis

I assumed that each vessel arrived carrying its full TEU complement of containers. In the last sub-section of the analysis, I partially address the drawback of this assumption, which shows that the results hold while accounting for vessel size. Under normal operating conditions shipping companies have the incentive to load and unload at full capacity. This is not an unreasonable assumption, especially given that this assumption should not affect the relative comparison between automated and non-automated terminals.

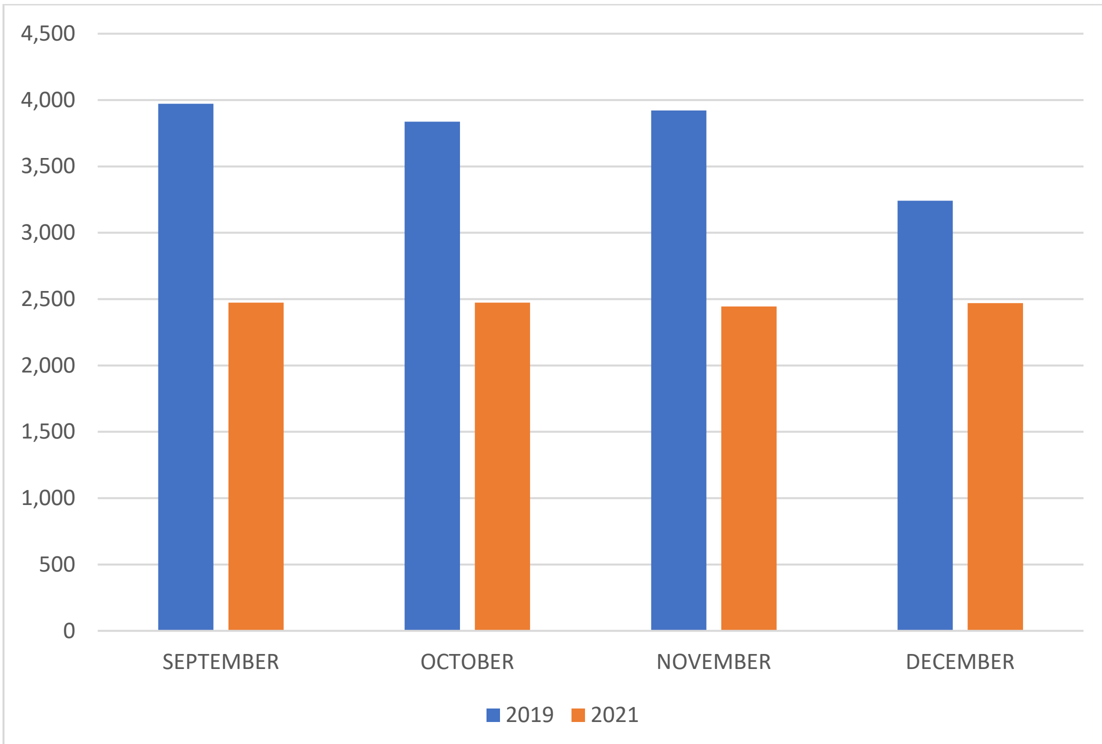
For the POLA/LB, any vessel which discharged at more than one terminal was excluded since the number of containers going to each terminal was unknown. For 2019, two vessels, or less than 1%, were excluded. For 2021, four vessels, or less than 1%, were excluded. At the Port of Rotterdam, all vessels made stops at multiple terminals and were included in the analysis.

The TEU per day metric is calculated by dividing the full capacity TEU by the number of days in the month. This metric considers the difference in unload versus load time in a large versus a small container vessel. For instance, a 15,000 TEU vessel may take five days to unload and reload, while a 3,000 TEU may be finished in one day.

Figure 3 compares the average TEU unloaded per day across all terminals, showing a 25% reduction in 2021 compared to 2019. It does not include any time the vessel spent at anchor, only at the berth. Fall 2021 was a significantly less efficient period for POLA/LB than Fall of 2019, driven by the COVID pandemic.

Figure 3

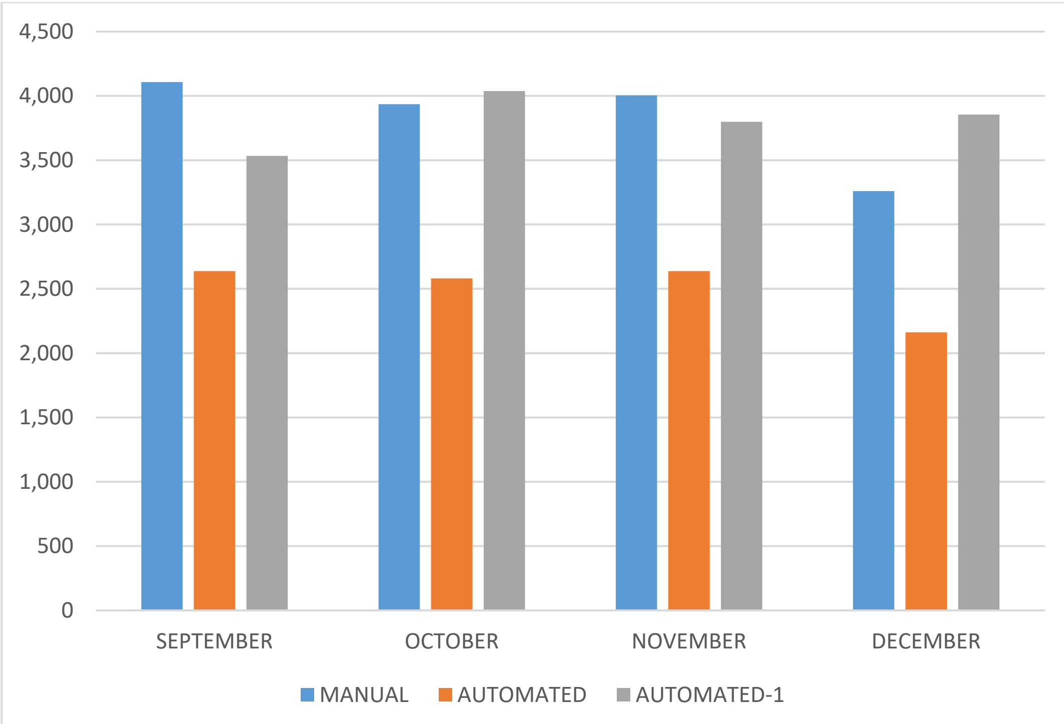
2019 and 2021 POLA/LB total TEU per Day Across Terminals



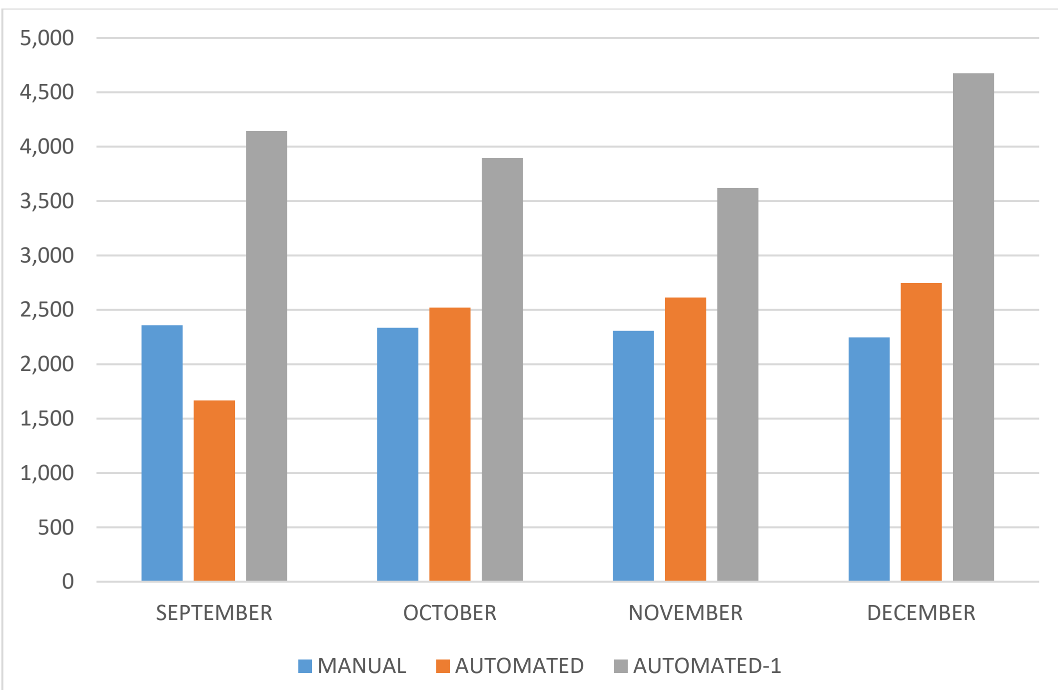
Dissecting the data between automated and non-automated terminals provides further granularity to illustrate performance differences enabled by automation. Panel 1 and Panel 2 of Figure 4 show the 2019 and 2021 TEU unloaded per dwell day on average for each terminal category, respectively. A dwell day is the time a container remains at a terminal berth from arrival to departure.

Figure 4

2019/2021 POLA/LB Average TEU per Vessel Dwell Day



Note. 2019. For the 8 manual terminals, the TEU reported is the average.



Note. 2021. For the 8 manual terminals, the TEU reported is the average.

In 2019, the manual terminals had a significantly higher average unload rate than the automated terminal and slightly higher than the automated-1 terminal. It should be noted that automated-1 terminal had not finished all three phases of the Middle Harbor Project construction by the end of 2019. In 2021, the automated-1 terminal's performance significantly exceeded both the automated and manual terminals in terms of TEU per vessel dwell day. The finding that automated-1 did significantly better than the automated terminals suggests that automation alone does not necessarily lead to more efficiency. Other contextual factors determine whether automation will lead to higher efficiency.

The Effects of Anchoring

Figure 5 shows the average days per vessel for each category and distinguishes berth days from anchor plus berth days. In this context, a low number is desirable. Note that there is not a significant change in total days across the three categories. Also, very few vessels went to anchor in 2019 for any category of terminal. This is consistent with normal maritime operations in which anchoring is unnecessary and avoided when terminals can accept vessels on arrival.

In contrast, during Fall 2021 the POLA/LB overall reached a high level of congestion. By September 2021, the number of vessels at anchor was at record levels, approaching 100 vessels. Once all available anchoring locations became occupied, vessels were assigned drift areas farther out to sea. While designated anchorages are limited for any given coastline, the space for ships to safely drift offshore is not. For this analysis, this drift time is rolled up under anchor time.

Figure 6 shows the difference in performance in the Fall of 2021 based on the level of automation. The most significant difference is seen at the automated and manual terminals due to significant anchoring and increase in berth time. November was the worst month, with vessels across terminal categories spending an average of nearly 20 days at anchor and berth.

Figure 5

2019 POLA/LB Anchor and Berth Days by Level of Automation

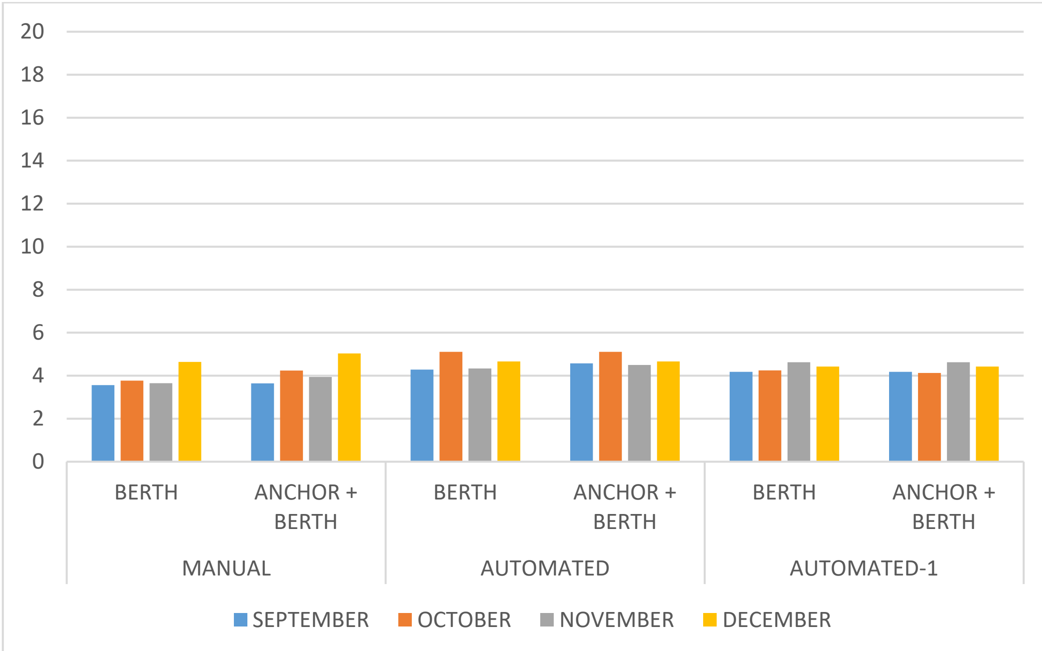
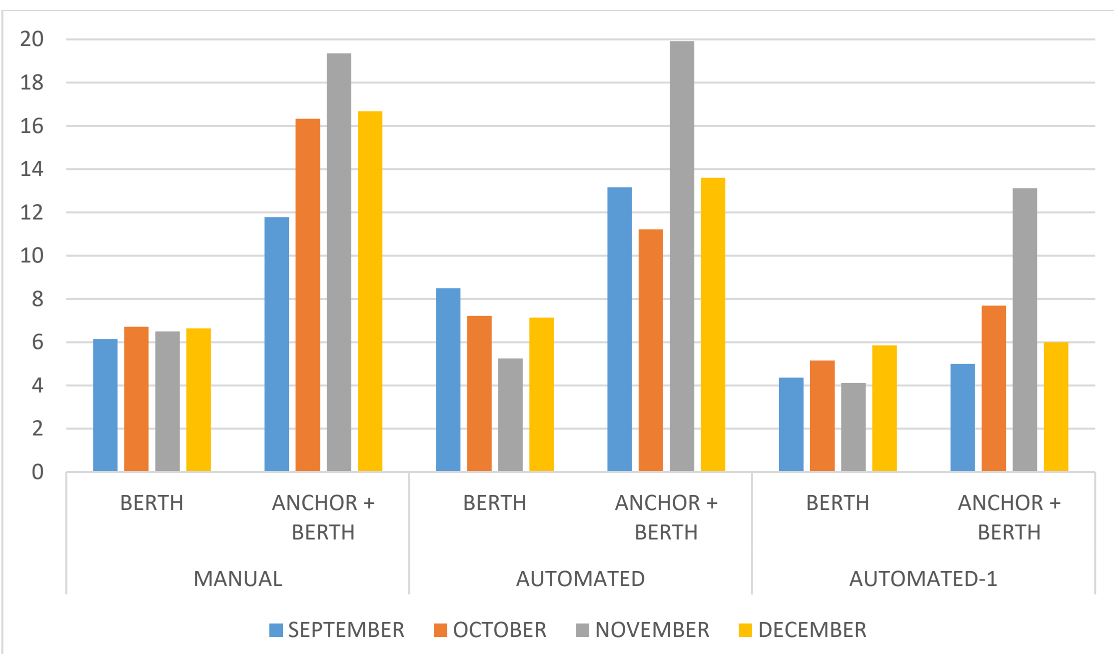


Figure 6

2021 POLA/LB Anchor and Berth Days by Level of Automation

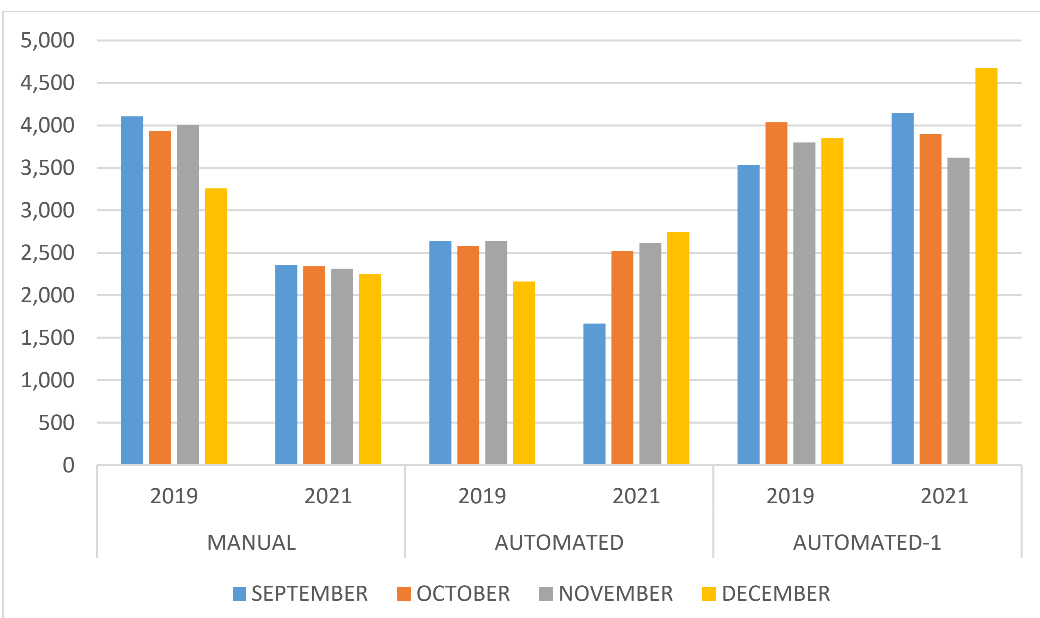


Conversely, the vessels arriving at the automated-1 terminal did not significantly increase berth days relative to 2019 and spent little time at anchor, except for November. Potentially skewing the data is the likelihood that some of these automated-1 vessels may not have been initially designated for the automated-1 terminal but were diverted due to berth availability. It is uncertain whether this action by automated-1 was anomalous and is an area for further study, but an intuitive plausible explanation is that lower congested terminal helped relieve higher congested terminals provided they shared the same ocean carrier alliance.

With so much unproductive time spent at anchor, container ship captains would ideally want a quick unload and reload once they shifted from the anchorage to the berth. Likewise, a short turnaround time would allow another vessel to shift from anchor to the berth that much sooner, thus helping to alleviate the anchoring bottleneck. Unfortunately, this was not the case in the Fall of 2021, when the manual terminals experienced an average decline in berth unloading rate of 35% in TEU per day compared to 2019 (Figure 7).

Figure 7

2019 and 2021 POLA/LB Berth Unloading Rate (TEU/day)



In this context, higher is better. The automated terminal experienced a 4% increase in TEU per day and the automated-1 terminal had the best performance, increasing 6% over 2019. The November decline coincides with a peak in the shortage of longshoremen labor and will be addressed in the next section.

In 2019, the automated-1 terminal's efficiency was impeded by the Middle Harbor construction project. However, by the Fall of 2021, all three phases of the Middle Harbor Project construction were complete, resulting in a much newer and larger terminal with double the original acreage. Therefore, the 6% increase in unloading rate observed in 2021 may have been on an artificially lower base. This nuance non-withstanding, the inefficiency in observed in 2021 for the manual and automated terminals because of the pandemic disruption is observed both in a higher berth and anchoring time, which is partially explained by a lower berth unloading rate.

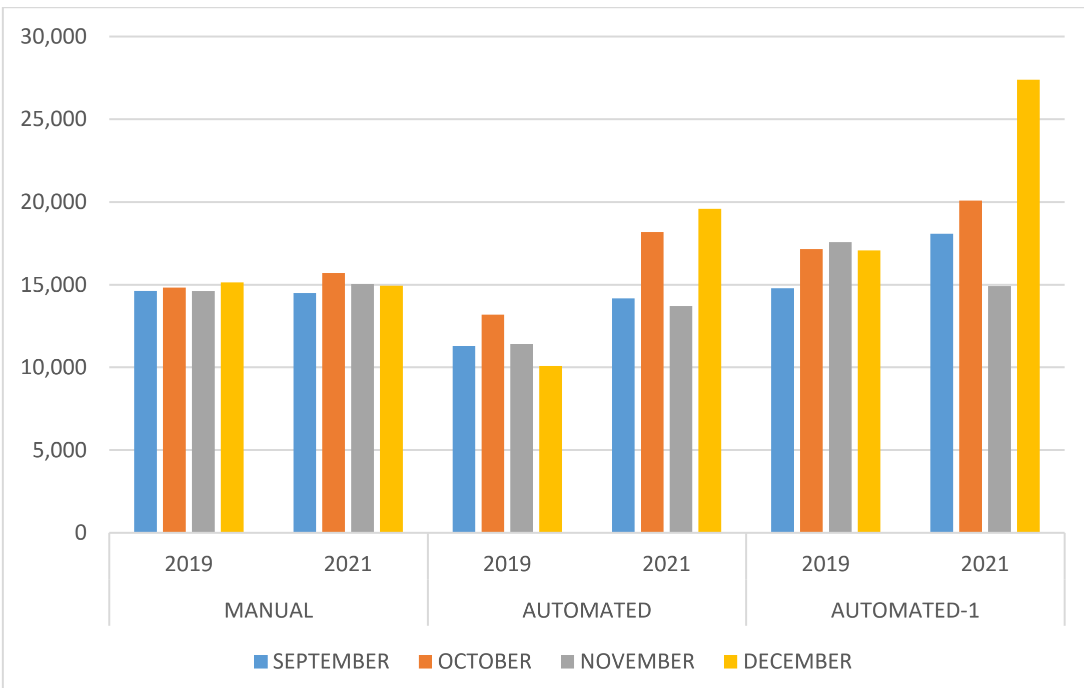
Controlling for Vessel Size

Since 2015, ocean carriers in the freight forwarding industry have undergone significant changes, consolidating carriers to gain economies of scale, capture additional market share, and lower overall costs. Larger vessels require fewer crew members per TEU, but they necessitate additional resources such as deeper port channels and longer berths. Vessel unloading time (berth dwell) increases with vessel size, which can lead to increased port congestion.

Considering the industry trend toward larger container vessel size, I analyzed the effects of vessel size on berth efficiency. Unloading larger vessels requires additional resources such as cranes, trucks, chassis, and labor. Therefore, a larger vessel accumulates more berth dwell than a smaller vessel. However, a terminal may still increase its overall container unload rate by utilizing larger vessels in the aggregate. One 20,000 TEU vessel can be loaded and unloaded quicker than two 10,000 TEU vessels because several operations are not dependent on vessel size. For instance, it may take one hour on average to attach lines from a vessel to the pier to secure it against movement. The two 10,000 TEU vessels would total two hours while the one 20,000 TEU vessel would take one hour. Figure 8 depicts the TEU per vessel in 2019 vs. 2021 to illustrate the change in size of the average container vessel calling on POLA/LB. There is an increase in vessel size for the automated terminals, while that of the manual terminals remained relatively unchanged.

Figure 8

2019 and 2021 POLA/LB TEU per Vessel by Level of Automation

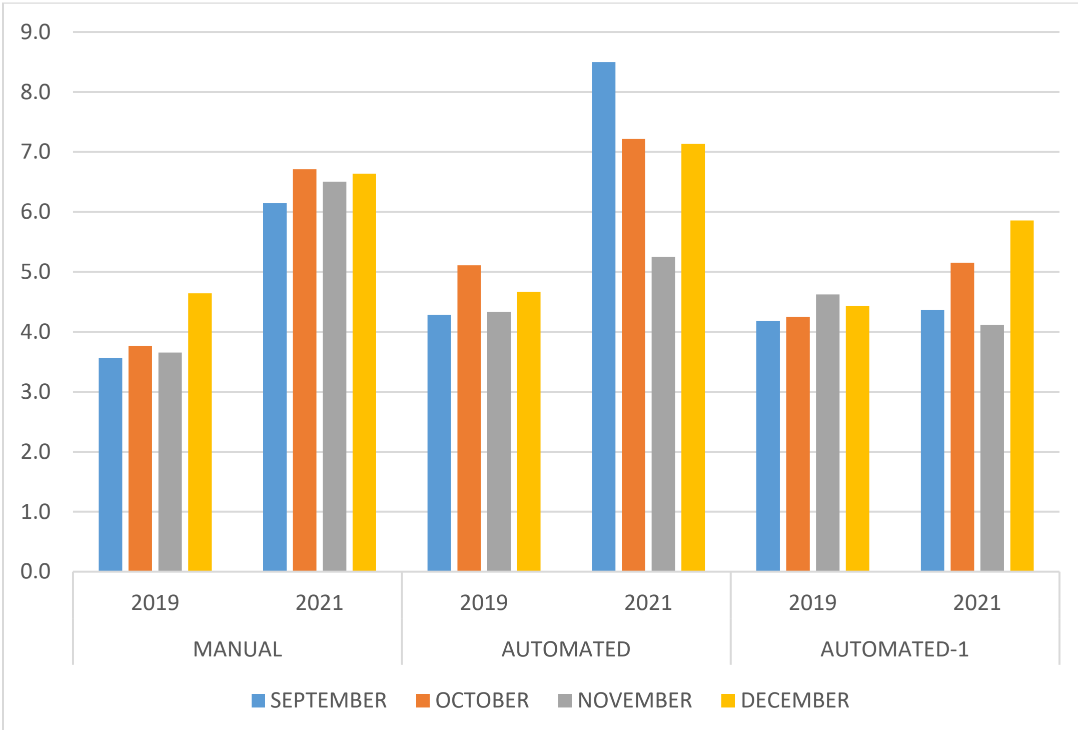


Note. The TEU per vessel is doubled in the figure since each vessel unloads and loads during each port call. December spike is seasonal.

Figure 9 depicts the berth dwell days per vessel in 2019 vs, 2021, which shows the average number of days a vessel spends at the berth and does not include delays while at anchor. The automated terminal average berth dwell increased 43% and the manual terminal dwell increased by 67%. In contrast, the automated-1 terminal dwell increased by only 8%, establishing it as the best performing terminal.

Figure 9

2019 and 2021 POLA/LB Berth Dwell Days per Vessel by Level of Automation



To gauge whether the POLA/LB increase in dwell is driven by the increase in TEUs, level of automation, and year, a multiple regression was run to predict vessel dwell from TEUs, controlling for the level of automation (Manual is the base category, and added dummy variables for Automated and Automated-1) and a dummy variable for Year (2019 = 0, 2021 = 1). The model performed well as a predictor of vessel dwell, indicating that our analysis was focusing on the correct variables for the case study, $F(4, 977) = 192.51$, $p < .0005$, $R^2 = 0.441$. The fitted regression model is represented in equation (1) and in Table 5.

$$Dwell = 0.71 + 0.000427 * \text{TEU} + 2.04 * Automated - 1.47 * Automated\text{-}1 + 2.58 * Year \qquad (1)$$

Table 5

Regression with Vessel Dwell as Dependent Variable – POLA LB

Variable	Coef.	St. Error	Confidence Interval (95%)	
TEU	0.0004***	0.0002	0.00039	0.00047
Automated	2.04***	0.32	1.41	2.67
Automated-1	-1.47***	0.28	-2.01	-0.93
Year	2.58***	0.15	2.28	2.88
Constant	0.71***	0.18	0.35	1.06

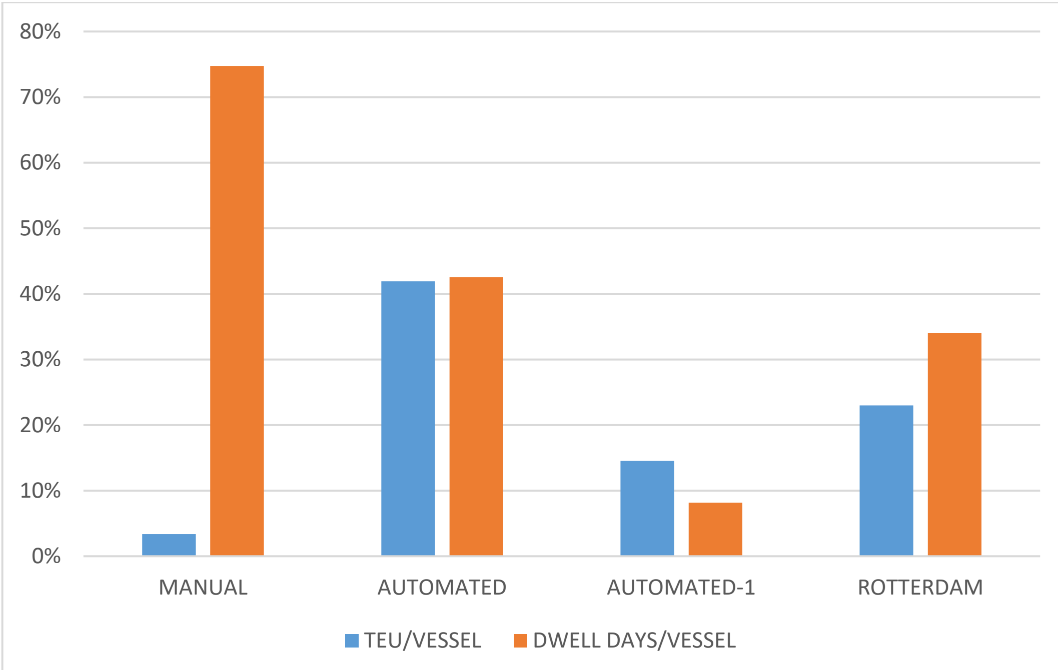
One interesting finding is that the automated coefficient turned out to be positive. This is consistent with the notion that automation alone does not necessarily improve efficiency, especially when the system is not very congested. So, there are probably cost reduction measures that also enter the equation on whether automation is viable. But during congested periods and when other operational factors are considered, automation can lead to more efficiency.

Comparison to Port of Rotterdam

Figure 10 compares the POLA/LB to Port of Rotterdam's performance in terms of Average TEU and berth dwell per vessel. In general, a larger container vessel should take longer to unload at the berth, resulting in more dwell days. First, I examined POLA/LB numbers. From 2019 to 2021, the automated terminal average container vessel size increased 42% and the average berth dwell commensurately increased 43%. However, during the same period, the manual terminal's dwell increase of 75% cannot be attributed to container vessel size because the average size only increased by 2%. In contrast, the automated-1 terminal appears to have countered this trend. Its average container vessel size increased by 15%, yet the average berth dwell only increased by 8% on average for September through December of 2021.

Figure 10

2021 Increase in Average TEU and Dwell per Vessel – POLA/LB and Rotterdam



Next, I examined analogous data for the Port of Rotterdam, comparing Fall 2021 to Fall 2019. The Port of Rotterdam experienced a 23% overall growth (TEU) in deep sea vessels' average TEUs and an increase of 34% in vessel dwell for anchoring and berthing. This is not a direct comparison since the POLA/LB analysis includes unloading at the berth while the Rotterdam figures represent a wider snapshot of overall vessel dwell from arrival to the port until departure, but it provides a rough comparison of efficiency relative to the increase in TEUs.

Berth Dwell. Table 6 shows dwell time growth in 2021 vs 2019 for POLA/LB and the Port of Rotterdam. Overall, the POLA/LB had a 58% increase in berth dwell, compared to Port of Rotterdam at 34%. The analysis by terminal category offers contrasting insights as to why. First, for comparable automated terminals at POLA/LB and Port of Rotterdam, berth dwell increased by at 43% and 36%, respectively. The operational disruption from the COVID-19 pandemic affected both ports in a similar order of magnitude, when comparing terminals which have a similar level of automation and a similar operational model that allows for multiple terminal stops.

Table 6

POLA/LB and Rotterdam Dwell Time Increase per Vessel – 2021 vs. 2019

Dwell Time	Terminal Category	POLA/LB	Rotterdam
Berth Only	Automated	43%	36%
	Automated-1	8%	n/a
	Manual	67%	23%
	Sub-total	58%	34%
Anchoring Only	Sub-total	2688%	171%
Berth + Anchoring	Total	191%	39%

On the other hand, the POLA/LB automated-1 berth dwell increased by 8%, so relative to other terminals at POLA/LB and Port of Rotterdam, it was better able to handle the operational disruption from the pandemic. Its combined high automation and one-stop operation, which are not both present in other terminals, likely contributed to this relatively better performance. The POLA/LB automated-1 terminal was more efficient during the COVID-19 pandemic relative to the automated terminal and manual terminals. The automated-1 terminal capitalized on the advantages of larger vessels. In contrast, other automated terminals often did not unload large vessels at one time. Instead, the vessels would partially unload and return to anchor while the containers were cleared from the terminal. Alternatively, vessels would be partially unloaded at an automated terminal and then shifted to another terminal to finish unloading, which is analogous to Rotterdam's operational model.

Regarding the manual terminals, POLA/LB had the highest increase in berth dwell per vessel across terminal categories for both POLA/LB and Port of Rotterdam at 75% with only a 2% TEU increase, which helps explain why overall the POLA/LB efficiency decrease was higher than Port of Rotterdam. However, the Port of Rotterdam's manual terminal had a lower dwell increase of 23% relative to the automated terminals at 36%, and lower relative to POLA/LB manual terminals at 67%. This exception to the pattern of automated terminals performing better can be explained by the fact that the Port of Rotterdam's manual terminal was less congested during the COVID-19 pandemic. It had a TEU decrease of 6.1% in 2021 vs. 2019, whereas the TEUs for the automated terminals increased by 6.5%.

Anchoring. In 2019, anchoring as a share of total dwell time was 7% for both ports. But in 2021, the average vessel spent 60% of its total dwell time at anchor in POLA/LB, while Port of Rotterdam performed better at only 13%. This is the product of a very high average anchoring dwell time increase per vessel from eight hours to 223 hours in POLA/LB (the equivalent percent increase is 2688%). In contrast, the average Rotterdam vessel anchored 3.5 hours in 2019 and it went up to 9.5 hours in 2021, or 171%.

It is important to note that in Port of Rotterdam, the order magnitude in the increase in anchoring was well within one day, while at the POLA/LB it went from eight hours to almost 10 days. Therefore, anchoring is the main driver of the difference in efficiency between POLA/LB and Port of Rotterdam, with berth plus anchoring increases of 191% and 39%, respectively. The anchoring effect from the COVID-19 pandemic for the POLA/LB was the most visual as numerous vessels anchored for days and it also shows in the order of magnitude relative to other berth and anchoring dwell increases across the two ports.

The POLA/LB vs Port of Rotterdam cross-case analysis shows that the average vessel dwell increased as a consequence of the pandemic-induced supply chain disruption, which is to be expected, due to increased congestion. However, it appears that the dwell increase was mitigated by either terminal automation or a simpler operational model like one terminal stop per vessel. The POLA/LB's automated-1 terminal exhibited both.

Generally, the primary cause of a container ship going to anchor is the lack of an available berth. As the two ports reached capacity based on lower efficiency in terms of time at berth, all berths eventually became occupied, and any new arriving vessel would have to spend time at anchor awaiting a berth time or slot. The data shows that automated-1 terminal was the exception to this loss in efficiency. However, this analysis does not account for inefficiencies due to unused terminal unloading capacity. The subsequent analysis shows that all berths were not occupied when many ships were already at anchor, which can be explained by labor issues.

Analysis of Labor Issues

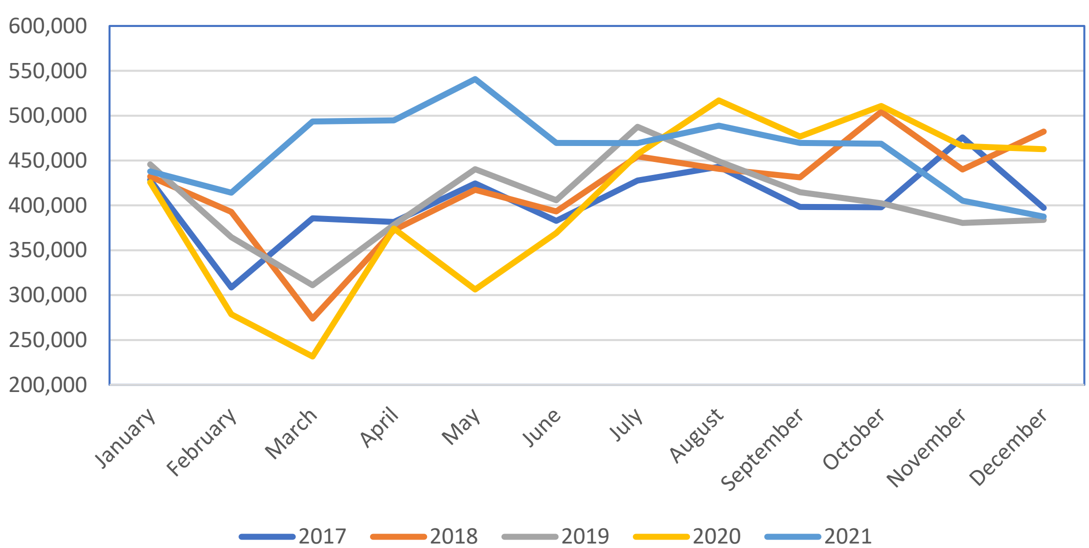
During the COVID-19 pandemic, labor shortages were often seen as the cause for supply chain woes, as echoed in the popular press. This shortage happened because many workers were sick from infection or were working from home to avoid becoming infected, based on interviews with industry experts. To verify this claim, I collected data for a labor analysis from the Pacific Maritime Association (PMA). The PMA's mission is to provide labor relations, human resources, and administrative services to its member companies.

The PMA membership consists of 70 ocean carriers and terminal operators who operate at the 29 West Coast ports. The primary workforce to load and unload vessels is composed of longshoremen. The ILWU represents waterfront employees on the U.S. and Canadian Pacific Coast, Hawaii, and Alaska. Nearly 15,000 ILWU workers are employed at West Coast ports. Longshore workers handle the loading and unloading of ships, among other related duties. The PMA submits daily orders for waterfront labor at 29 ports and works in partnership with the ILWU to dispatch workers on day, afternoon, and night shifts. Data was obtained through dispatch summaries compiled by PMA Allocators for the POLA/LB regions. Three dispatch summaries are compiled daily for the first, second, and third shifts. The third shift is seldom utilized; therefore, only the first and second shift summaries were evaluated.

Figure 11 shows the total import container volume at the POLA for the 2017-2021 timeframe. The five-year view is superimposed to illustrate the seasonal cycles. The annual seasonal downturn in February and March is attributed to the Lunar New Year. Transpacific trade is often affected by the Lunar New Year holiday, reducing goods production and factory orders in many East Asian countries that export to the United States. It is evident that 2021 was an exceptional year. For March, April, and May of 2021, the POLA witnessed a dramatic year-over-year increase in imports of 113%, 32%, and 77%, respectively. The Port of Long Beach endured similar increases during the same period.

Figure 11

Port of Los Angeles Total Imports (TEUs)



Note. Source: Port of Los Angeles

This spike in volume coincided with the initial increase in anchored vessels for the two ports, as depicted in Figure 2. The combination of anchoring of vessels with the March-May volume spike provided a suitable starting point to investigate the impact labor had in tackling the volume spike. The peak anchoring time took place in the Fall of 2021. This period was also evaluated by analyzing labor dispatch summaries.

My analysis of the data employed a reduction and averaging of the twice-daily dispatch reports. When a container vessel arrives at a terminal berth, it is unloaded and reloaded. The terminal requests longshoremen labor gangs each day until the unloading and loading are completed. The PMA assigns labor gangs to fulfill these requests. From a labor perspective, the POLA/LB complex would achieve hypothetical capacity by having every berth filled with a vessel and each vessel having enough labor gangs to satisfy each terminal's labor requests. The maximum number of vessels is dictated by vessel length. For instance, a terminal may have three berths but can accommodate four vessels if two are short. In September 2021, the ports surged and accommodated 40 vessels on multiple days. For this reason, 40 vessels serve as a full occupancy level for all available berths. Note that there are more than 40 berths in POLA/LB but the total vessels occupying those berths varies due to vessel length.

Table 7 summarizes longshoreman labor assigned by PMA to each vessel at a berth in a terminal in March, April, and September of 2021. A shorted vessel occurs when, for example, four gangs are requested to unload a vessel, but only two are available. Berth dwell increases for the shorted vessel because unloading and loading take longer for the shorted vessel. By September, nearly 13 vessels per day on average went without enough longshoremen.

Table 7

POLA/LB Longshoremen Labor Averages - 2021

	Mar-21	Apr-21	Sep-21
Vessels with NO labor gang assigned	3.4	2.5	4.6
Vessels with SHORTED labor gang assigned	1.6	1.7	1.6
Vessels IDLE	5.9	4.8	6.7
Total vessels	10.9	9	12.9
Vessels with ALL labor gangs assigned	21.1	20.5	22.2
Total vessels occupying berths	32	29.5	35.1
Labor gang availability	66%	69%	63%
Labor gang availability with all 40 berths occupied	53%	51%	56%
Vessels at anchor or drifting	24	19	53

Note. Longshoremen gangs are also assigned to other non-container vessels and other sections of the container terminal such as rail and are not represented in this data. Source: Pacific Maritime Association.

Labor gang availability decreased from 66% in March to 63% in September. If all 40 berths were occupied, the percentages would drop to 53% and 56%, respectively. During this time, the average number of vessels at anchor or in drift areas climbed from 24 to 53. While the change in labor gang availability is minor, the overall low percentage of occupied berths shows underutilization of all available resources. Since the POLA/LB was not at capacity, any pre-pandemic volume spikes were absorbed without resorting to sending excess container vessel traffic to anchorage. However, the March to May volume spike signaled the beginning of anchoring for the two ports since they were essentially at full capacity for labor gangs that unloaded and loaded vessels. A backup commenced once labor could not keep up with the daily vessel quotas. Each vessel remained at the berth longer, forcing arriving vessels to anchor.

The idle vessel upward trend is an additional area of concern. There is little incentive to occupy all available berths if labor is insufficient to fulfill the daily terminal requests. Any vessels without labor would sit idle while accumulating dockage and other expenses that may be avoided at anchor. The average idle vessels increased from 5.9 in March to 6.7 in September.

With 40 available berths, a steady-state number of vessels is idle at the berth on any given day. The reasons for idling and not loading or unloading vary and include maintenance, refueling, and railcar shortage, among others. A terminal with a vessel at the berth that could not fill its labor gang request for several days likely opted to go idle to save on other labor costs.

By Fall 2021, vessels were also idled for non-labor reasons such as overall terminal congestion. Per CAS theory, these emergent phenomena materialize, stemming from complex causality. With so many empty containers stacked on the ground, terminals had no place to unload the loaded containers from the vessel. Thus, the loaded import containers became trapped for weeks at a time. During this time, the terminals also started refusing inbound trains carrying empty containers for export to East Asian countries. Instead, the terminals held out those empty container trains and waited for trains with loaded containers. This train selectivity by the terminal further delayed the vessel's departure, increased the overall ship dwell at the berth, and inhibited any attempts to decrease the number of anchored vessels.

The Container Imbalance Problem

The currency of intermodal transportation is the container. I examined historical container volumes for POLA/LB, including loaded and empty containers and their impact on complexity and efficiency. A cross-port analysis was conducted to compare and contrast POLA/LB with the Port of Vancouver and European ports. The analysis showed that container imbalance contributed to the poor performance of POLA/LB during the COVID-19 pandemic.

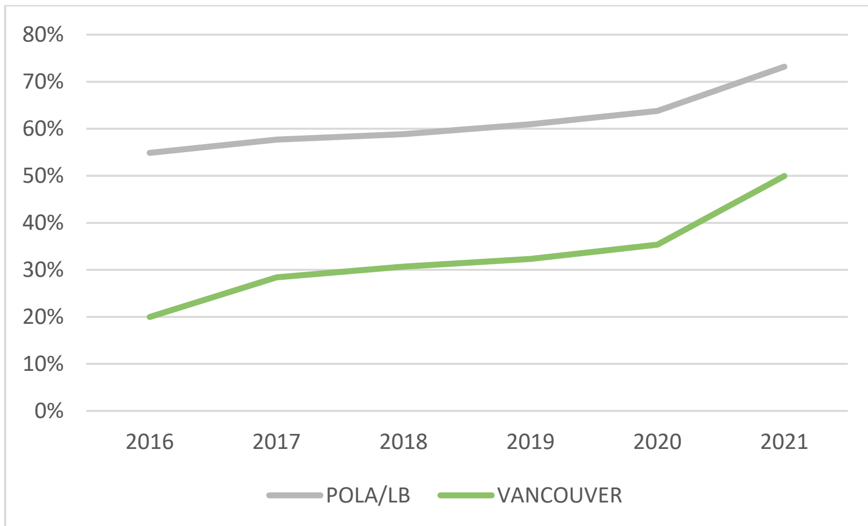
The data was obtained from the POLA/LB public statistics. It covered the monthly loaded and empty containers for import and export. An efficient logistics system would have ships, trains, and trucks loaded during their inbound and outbound legs. To maximize utilization, a container vessel coming from East Asian countries should have all loaded containers when it arrives in the U.S. Likewise, it should depart the U.S. with all loaded containers. The railroads also seek to achieve all loaded miles. Unfortunately, the situation for the railroads is much more daunting when there is an imbalance. Railroads are required to provide their customers with empty railcars so they can load their containers. A balanced system would have loaded railcars on the outbound and inbound legs to the terminal. If there is no backhaul of inbound containers, the railroads still must provide empty railcars for which they do not generate revenue.

Another important scenario emerges when empty containers are returned to the marine terminals by rail for export. This results in some railroad revenue but contributes to an empty container imbalance being loaded on vessels for their return leg to East Asian ports. The U.S. trade deficit is also exacerbated by this imbalance of loaded versus empty containers because empty containers are being shipped to East Asian ports instead of containers filled with U.S. produced goods which were waiting to be shipped. Recent data published by the POLA/LB shows a steady rise in the percentage of empty containers being loaded on vessels for their return leg to East Asian ports. For the Port of Los Angeles, in August 2021, an all-time high of 78% empty container ratio was recorded with its corresponding 22% loaded export container rate indicating that only one in four containers was loaded with goods.

Figure 12 compares the percentage of empty containers versus loaded containers for the POLA/LB and the Port of Vancouver, Canada. Vancouver has similarities to the POLA/LB in that a significant percentage of their container traffic flows inland by rail. In 2021, their empty container ratio was a more modest 50%, up from 35% in 2020, compared to 74% for POLA/LB. For Europe, a different picture emerges for loaded vs empty containers. Figure 13 depicts the volume of containers handled in the main European ports from 2005 through 2019 (the data from 2020 and 2021 were not available). Even with overall container volumes rising, the percentage of empty containers remained relatively stable at less than 20%, reflecting a greater proportion of export goods compared with POLA/LB.

Figure 12

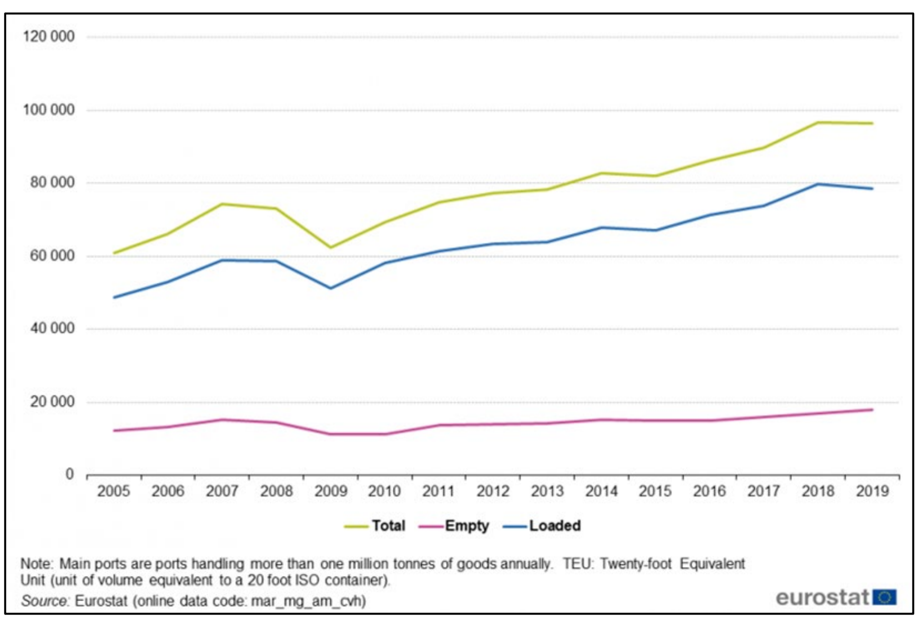
Empty Export Container Percentages for POLA/LB and Port of Vancouver



Note. Source: POLA/LB and Port of Vancouver

Figure 13

Volume of Containers Handled in Main European Ports, 2005-2019



In theory, when evaluating the marginal profit obtained from one container, an ocean carrier will maximize profit (and utilization) by moving loaded containers to the U.S. and loaded containers back to East Asian ports. The equation changes in a tight market or in an extreme scenario like the COVID-19 pandemic. In this situation, the carrier considers other variables like the dwell for that container in terms of the time a container remains in the U.S. to be unloaded, reloaded, and placed in an outbound vessel t, and the time it takes enroute to East Asian ports.

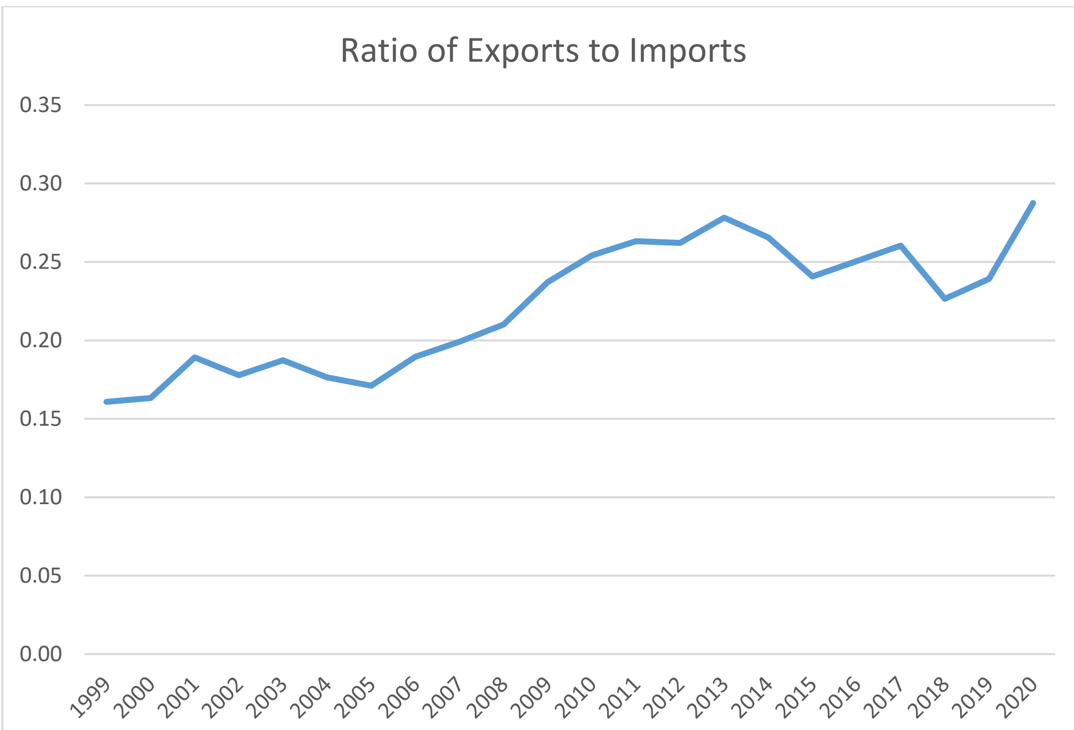
The Trade Deficit Structural Effect. One of the inherent causes of the imbalance of loaded versus empty containers for POLA/LB is the U.S. trade deficit. The balance of trade of the U.S. progressed into a substantial deficit from the late 1990s, especially with China and other East Asian countries. Economists have rejected the idea that bilateral trade deficits are detrimental in and of themselves. However, from a supply chain point of view, the U.S. trade deficit with China has important implications on container utilization. The U.S. trade deficit with China has grown steadily over the last 20 years. Excluding services and focusing only on goods is a more reliable measure of container movement for this analysis since services are unrelated to the discussion. The trade deficit has gone from $68 billion in 1999 to a peak of $417 billion in 2018. In 2020, it moderated to $309 billion. The U.S. trade deficit with other East Asian countries pales in comparison when considering China with Japan ($56 billion), Taiwan ($30 billion), South Korea ($25 billion), Hong Kong ($16 billion), and Singapore ($4 billion) (Bureau of Economic Analysis, 2022).

Figure 14 depicts the ratio of imports to exports to and from China. From 1999 to 2020, the ratio increased from 0.16 to 0.29. A ratio of 0.29 represents a trade imbalance where imported Chinese goods is 3.5 times larger than U.S. exports to China. The impact on shipping containers is worth considering. In a hypothetical situation where there were zero U.S. exports to

China and $309 billion in Chinese imports, each container ship arriving in the U.S. from China would be loaded with 100% loaded containers. Since there would be zero U.S. exports, each ship would depart for China with 100% empty containers. From a supply chain management perspective, this situation would lead to a poor utilization of containers and ships with economic and environmental consequences. As previously mentioned, utilization is maximized when the transportation conveyance (i.e., ship, train, truck, boat) is fully loaded to and from the origin.

Figure 14

U.S. Trade Balance with China



Note. Ratio is based on dollar value. Source: https://www.bea.gov.

The current deficit ratio of 0.29 would mean that every container vessel from China would arrive in the U.S. with 100% loaded containers and would continue to depart to China with a significantly larger percentage of empty versus loaded containers. Indeed, poor utilization of these assets is taking place and the trend continues to be troublesome. When a container terminal loads a vessel, it takes the same amount of labor to load an empty container as it does for a full container. This roughly 70/30 loaded to empty container ratio is consistent with the POLA/LB data depicted in Figure 11, although the numbers in that figure are in dollars. Nevertheless, it does signal that the ratio of import-export directionally influences the container imbalance.

While there are other causes for this supply chain mismatch, the inherent China trade deficit represents a significant headwind to supply chain optimization. As of August 2021, both ports had vessels depart for China with as few as 25% loaded containers and 75% empty containers. In 1996, the POLB experienced a 16% empty to loaded percentage. By 2020, the ratio had grown to 63%; in other words, 63 of every 100 containers leaving POLB were empty. POLA experienced a similar trend. In essence, POLA/LB is a gathering point for exporting from the West Coast because it exports significantly more than it imports. Recall, however, that 74% of those exports were empty containers in 2021 (Port of Long Beach, 2022; Port of Los Angeles, 2022).

The Interoceanic Structural Effects. On the way to East Asia, a container may have several weeks of free time upon arrival in East Asian ports. Free time is time offered by the ocean carrier before demurrage and detention charges begin. The free time adds significantly to the typical two-week vessel transit to East Asia. Free time is not applicable if the container is empty, hence the allure of keeping it empty for the return leg to East Asia. The container can be placed immediately back in export inventory.

Container ship routing from East Asia to North America is also a factor in container imbalance. Vessels transiting the Pacific Ocean will navigate via the great circle route since it is the shortest geographic distance between two points on a globe. At 24 knots, the 5630 nautical mile transit from Shanghai to Los Angeles would take a little under 10 days. In contrast, the Shanghai to Vancouver transit is 750 nautical miles less at 4880 nautical miles, a 1.3-day transit savings each way. Vessels take advantage of this routing by first arriving in Vancouver and partially unloading. They may make multiple stops in other ports such as Oakland on their way south. Arriving at POLA/LB for their final unload results in a completely unloaded ship and would allow for a reload of containers consolidated from all sources. The vessel could then depart straight to Shanghai without the multiple northwest coast stops.

The Inland Structural Effect. The trade deficit effect on container imbalance is manifested or exacerbated by U.S. inland economic phenomena. By way of example, railroads have specialized railcars for moving automobiles. A significant percentage of Asian automobiles are transported from the U.S. West Coast to many large cities via rail. Railroads looked for a loaded backhaul to fill these railcars for their transit back to the West Coast. In the early part of the 21st century, as U.S. automotive factories closed, fewer automobiles were available for this western transit. Other options were considered to fill these railcars including used cars and farm equipment. These options were tested and abandoned because of the complexities of changing the supply chain at the destination. The result was that automotive railcars would transit empty back to the West Coast if no domestic automobile factories were nearby.

The Inland COVID Effects. During the COVID-19 pandemic, absence of available containers was an alarming result for agriculture exporters. The lack of containers resulted in the farmers' inability to export their crops to East Asia. Loaded imported containers from East Asia became much more profitable for the ocean carrier at approximately $6,000 per container movement on average, versus $3,500 for export containers, causing some container vessels that unload their East Asian goods in Southern California to omit their scheduled Seattle port stop

(Roberts, 2021). The Seattle port call would have picked up loaded agricultural export containers. The ocean carriers would rather have the empty containers from POLA/LB rather than adding another week to the voyage to pick up loaded agricultural exports.

As the COVID-19 pandemic surged at the beginning of 2020, many businesses closed and unemployment rose. However, in the U.S. consumers kept buying things, especially online. The economic impact payments supplemented this spending. Spending shifted from services like restaurants and theaters to tangible goods, which increased U.S. demand for imports. As imports rebounded and then surged, the need for containers also increased. Much of this demand for goods was fulfilled by East Asian manufacturers. In response, ocean carriers prioritized shipments out of East Asia for American markets, exacerbating the structural container imbalance. The ocean carriers decided not to hold their vessels in U.S. ports waiting for loaded containers from U.S. exporters. They opted for the more lucrative business originating in East Asia. Getting the empty containers back to East Asia became the priority. The justification for the rapid departure was to reduce the overall vessel transit time compared to waiting for the loaded export container.

The imbalance of containers started in March 2020 when empty containers accumulated at the POLA/LB due to blank sailings. A blank sailing happens when an ocean carrier cancels a port call when the demand for space on vessels is low. Sweeper ships were used by shippers such as Maersk to help reposition the containers to East Asia as factories in China began to reopen. Sweeper ships are dedicated vessels sent by international carriers for specific purposes. In this case, their purpose was to reposition empty containers from the Southern California ports to China.

The Container Imbalance Effect on Operational Complexity and Efficiency. In August 2021, the Port of Los Angeles endured a 60% increase in empty containers compared to August 2020. This 60% increase in the inbound/outbound ratio signified enormous stress on the ports and was a harbinger of further congestion during the peak holiday shipping season at the end of 2021. In port operations, the container availability index (CAx) is an indication of how many full containers were imported vs. exported, and a value of 0.5 indicates container balance. At the time, the CAx was 0.9 for the POLA (xChange, 2022). This is the highest level of the container availability index at the port since 2019. The disproportionate number of empty containers in the POLA/LB resulted in a shortage in East Asia, where they were needed for loading. At the peak of the congestion in November, the two ports suffered from an empty container overabundance, which contributed to the gridlock. The excessive amounts of empty containers combined with the dozens of ships at anchor meant more delays in delivering goods to market. It also meant higher spot rates, demurrage, and detention charges.

For most of the summer of 2020, the POLA was relatively balanced with a value of approximately 0.5. During September, the CAx increased dramatically to 0.8, signaling too many empty containers. It remained there for October and then decreased to 0.25, indicating a shortage of containers. Going from a container availability of balanced to surplus to shortage reveals an over-correction in the supply chain. By April 2021, the CAx was back to the 0.9 range, signaling surplus empty containers. The balance of containers was in a constant state of flux, further contributing to the ports' inability to surge with the supply disruption. A significant inefficiency emerged based on the system’s inability to transport full containers, a shortage of container availability where they were needed to transport goods and severe space congestion at the POLA/LB because of large stacks of containers in and around the port.

The Role of PCSs

I evaluated the impact of the BEX as a coordination platform to deal with a disruptive situation such as the COVID-19 pandemic on the supply chain, determining POLA/LB supply chain vulnerabilities and the impact of supply chain resilience to face these situations. As a cross case analysis, I then compared the BEX to the Port of Rotterdam's Portbase PCS. The information contained in BEX is consolidated rail, vessel, and terminal planning data and is only available to authorized users due to its proprietary nature. Instead, the hierarchical container ship movement validates its use as a proxy to ascertain the overall efficiency of container movement through the container terminal to the land transportation. Aydogdu and Aksoy (2015) used a similar process to model PCS where shipboard data was used along with other operational metrics. In relation to other PCSs at other ports, the BEX does not have the enabling technology and sophistication of PCSs such as the Port of Rotterdam's Portbase, which is a non-profit subsidiary of Rotterdam and Amsterdam's ports and offers 40 major services. BEX's main attribute is the multi-party coordination that takes place using the BEX rail, vessel, and terminal planning data.

Table 8 contrasts BEX pre-COVID operations with those that occurred during the pandemic. Multiple steps were taken to alleviate the shipping bottleneck. The media scrutiny and pressure from internal and external sources increased the need to take positive actions.

Table 8

BEX Operations During Normal Operations and the Pandemic

	Pre-COVID	During COVID
Inbound train arrival data	X	
Forecasting	X	
Diversions	*	X
Ship adjustments	*	X
Labor adjustments	*	X
Empty railcar interchange	*	X
Port policy	X	X

Note. * = Rarely used; only for exceptions.
Source: Documented observations

Labor issues and the BEX. Prior to the COVID-19 pandemic, regarding the daily ordering of labor gangs, the BEX data assisted the decision-making process and the daily BEX conference calls enabled decision execution. Although labor availability is part of BEX functionality, labor's impact is reflected in forecasted and actual train releases by each terminal. Marine terminals sought to increase efficiency by minimizing their labor costs, only ordering longshoremen labor when needed. A single shift reduction amounts to tens of thousands of dollars in labor savings. The terminals had the option to reduce labor or go idle if no ships were available and if there were no arriving or departing trains. The terminals made labor decisions on committing to hire longshoremen labor gangs after coordinating vessel and train arrivals during daily BEX conference calls. All stakeholders were entrusted with honoring their commitments.

During the COVID-19 pandemic, the shortage of labor gangs was one of the primary reasons vessels could not be unloaded at the terminals. This contributed to the mass anchoring off the coast. The POLA/LB operations were significantly affected by a labor shortage for all the trades. The lack of available longshoremen gangs for unloading the vessels was notable. Non-automated terminals require a larger labor force than automated terminals. The labor shortages were discussed on daily BEX conference calls and adjustments were made to operations to account for labor shortages. Terminals frequently declined railcars for loading because the containers were still on the vessels waiting to be unloaded.

The railroads were facing the same labor problems. A significant part of the workforce percentage was affected by COVID-19 infections, resulting in a shortage of qualified engineers and conductors. With the economy's downturn in the spring of 2020, the railroads furloughed many engineers and conductors to keep labor costs down. Many of these employees did not return due to COVID-19 or found employment elsewhere. Both railroads actively recalled all furloughed employees. New hiring became a priority, but it can take up to six months to train a new conductor and even longer to train an engineer. Although not a direct BEX input, traincrew shortages were discussed on BEX conference calls and adjustments were made to the BEX to port rail operations in the form of adjusted train arrival and departures.

BEX Reaction to Port Policy Changes. During normal pre-COVID-19 operations, port policy was rarely discussed during BEX conference calls. This was because the port policies rarely changed. Any new changes were implemented by each respective stakeholder independent of BEX operations.

In late October 2021, the POLA/LB threatened to institute a dwell penalty on dwelling containers to mitigate the operational bottlenecks at the port. The concept was to speed up the departure of empty containers lingering in marine terminals to combat congestion, adding pressure for carriers to pick up empties for transport back to East Asia. By assessing fines to ocean carriers of $100 per container, increasing in $100 increments per container per day until the container leaves the terminal. A similar policy was placed against railroads and truckers for import loaded containers (Port of Long Beach, 2022; Port of Los Angeles, 2022).

Although the dwell policy was delayed several times, it had the chilling effect of causing terminals to delay incoming trains until they could clear their existing container inventories. The delays would be reflected in the BEX as delayed estimated arrival times. Terminals would also delay unloading inbound trains to avoid starting the clock for dwelling containers. Similarly, this type of delay would be a BEX input by the terminal. In essence, the railcars became a storage platform for the containers inside the terminal. The drawback for the railroads was the loss of use of the railcars until they were unloaded. This unintended consequence of a threatened policy was that port stakeholder decisions were based on expected consequences of the policy, instead of the search for solutions to the congestion and bottlenecks.

BEX Reaction to Empty Container Surplus. Prior to the pandemic, the unequal empty container ratio had little effect on port congestion, although it did contribute to operational complexity. During the height of the POLA/LB container congestion, the vast number of containers in the port limited each terminal's ability to move containers from one stack to another. As a BEX data input, loaded export trains were prioritized over empty container trains because the loaded containers would quickly depart on the next vessel for East Asia. The terminal also recognizes more revenue from handling the moves of loaded containers (as does the railroad). As annotated in the BEX, the empty containers would be ground stacked and held while awaiting an opportune ride. This storage of containers took up precious marine terminal acreage. Terminals did not have an incentive to take inbound trains with empty reposition containers. The result for the railroads was devastating. The inbound empty container trains had to be temporarily stored on a railroad siding while awaiting their appointed arrival date. Scarce railcars and locomotives were tied up, resulting in shortages of both to support the railroad networks in other locations. BEX rail estimated time of arrival would be adjusted accordingly.

For the ocean carriers, a congested port results in inbound container vessels having to anchor. This is not the case for the railroads. Railroads operate with more active trains than rail terminals to land them to achieve greater capacity, like a juggler with five balls in the air and only two hands. Eventually, stopped trains needed to be stored on the mainline resulting in a severe impediment to the rail network. As depicted in the BEX data, the delayed arrival of the inbound trains resulted a shortage of railcars for the container terminals. Without railcars, the terminals were forced to set back their next release of loaded railcars and adjust their BEX forecast accordingly.

BEX Reaction to Diversions by the Railroads and Ocean Carriers. Prior to the pandemic, the use of diversions was limited. If a terminal became too congested and could not receive its inbound train traffic, the railroads would coordinate with the ocean carrier to divert the rail traffic to a less congested sister container terminal. Such diversions would be negotiated offline but reflected in and coordinated through the BEX process. Therefore, the BEX was used for execution of port operations. There are complexities involved with diversions that need to be worked out in advance. Vessel diversions are more intricate than train diversions. Vessels arriving at a different port require new overland routing for rail and truck. On the rail side, long-term service contracts would be needed. Railroads would need to find a complementary backhaul to match the new routing so that the movements would be loaded in both directions. A rail diversion would be handled in the BEX by annotating the new arrival terminal. The terminal receiving the new train would adjust their BEX forecast.

Similarly, the railroads would seldomly limit traffic through embargo. An embargo is a temporary method of controlling traffic movements when in the judgment of the serving railroad there is likelihood of congestion, accumulation, or other interference with operations such as track, bridge, or other physical impairments that warrant restrictions. Container ship diversions happened independent of the BEX process.

During the pandemic, the use of railroad diversions and embargoes increased. For instance, the Union Pacific Railway began a seven-day halt on shipments to its Chicago Global IV intermodal facility, citing a shortage of chassis and drayage capacity that had clogged the facility with containers. Likewise, the ocean carriers diverted some vessels resulting in unintended consequences, as in the case of Oakland. The Port of Oakland saw no backlog of containers on its docks, yet several ocean carriers skipped Oakland in the Fall of 2021 (Port of Oakland, 2021). Excessive delays in Southern California required the immediate return of some ships to East Asia without stopping in Oakland. In the case of diversions, the BEX process would delete the incoming vessel from the terminal forecast. As a system of record, the BEX provides a history of forecasts. The terminals would plan for less labor and the railroads would adjust their forecasts for railcar supply.

BEX and Port Automation. During the pandemic, little intervention was needed for the fully automated-1 terminal since obtaining longshoremen labor gangs was less of an issue. The only procedural difference during BEX coordinating meetings regarded the separate railyards for automated terminals. Rail arrival and departure were coordinated on the BEX. The fully automated terminal did not allow railroad crews to deliver their trains during automated operations while the fully automated-1 did. The fully automated-1 terminal's larger footprint allowed it to conduct parallel automated operations and rail operations simultaneously. No changes in these procedures during the pandemic other than the labor shortage often precluded the automated terminal from unloading while the automated-1 was able to capitalize on the situation due to the reduced uncertainty of labor during a system under stress.

Port of Rotterdam's PCS: Portbase

I compared my study and analysis of the BEX with the Port of Rotterdam and its PCS Portbase. Although not conducted during a pandemic, the Port of Rotterdam case studies provided a suitable comparison with the BEX's governance and composition of participating stakeholders.

Theoretically, PCSs and inter-organizational processes can enable coordination and cooperation to counter the undesirable emergent complexity in ports. de Oliveira et al. (2021) found that the Port of Rotterdam was the most efficient port among ports from 17 different countries. The researchers used the Quality of Port Infrastructure (QPI) index from the World Economic Forum and determined that Rotterdam and the other top nine countries are governed by post-industrial governing coalitions. This type of coalition has decentralized port governance and sanctions the involvement of foreign companies, although they infrequently allow private-owned terminals (de Oliveira et al., 2021).

The BEX was designed to address rail operations in an out of the POLA/LB terminals while Portbase was created as a more generalized PCS with significantly more stakeholders. A case study by Nikghadam et al. (2021) analyzed the ways in which differences in governance may lead to disparate levels of success. They conducted a case study of the Port of Rotterdam looking at port calls and the amount of bilateral information sharing between terminals and tugboat pilots. They found that PCSs do not adequately supply answers to enable coordination between port service providers, such as pilot organizations and tugboat companies. Instead, they found that current PCS advantages exist in information sharing between PCS users instead of between port actors. Therefore, the more stakeholders independently join and govern a PCS, the higher the expected impact of the PCS. In that sense, Portbase's governance mechanism is better suited to address operational complexity than the BEX.

Chandra and van Hillegersberg (2018) conducted a case study in the Port of Rotterdam looking at the evolution of Portbase. Portbase has developed into a thriving PCS operator and organizer in European maritime port collaboration. The growth in the number of Portbase member companies and the financial stability of the port of Rotterdam are evidence of this success. This incomplete knowledge of inter-organizational governance has been aggravated by the intensifying complexity of collaborations. However, collaborations require prescribed governance to focus on members' concerns about data ownership, protection, and access. Mutual trust is a prerequisite for productive collaboration. However, joint agreements between organizations and their collaboration do not remove the competition between them (Chandra & van Hillegersberg, 2018).

In a port environment, the heterogeneity of actors is problematic. Organizational boundaries are indistinct and business processes are not well categorized. Portbase was designed for adoption by a large set of independent actors that acknowledge its services as beneficial for supporting their specific business processes. Portbase services are smart IT solutions designed to facilitate the efficient exchange of data in the logistics chain. Forty services are provided for 12 groups of stakeholders such as forwarders, exporters, and terminals. The services are categorized under specific processes such as ship calls, inland transport, cargo import, and export (Portbase, 2020).

Simoni et al. (2022) conducted a case study of Port of Rotterdam's digital strategy. They found that its 40 digital services effectively considered the complexity of the port system when creating the PCS's architecture and functions to fully evolve operations at both the individual operator and system levels. Portbase PCS's capacity to improve port stakeholder business processes is related to a portfolio of smart IT solutions. Their analysis found that most of the 40 services improve more than one of the dimensions of system quality, information quality, and service quality.

Although the Port of Rotterdam case studies do not cover the pandemic timeframe, they substantiate Portbase as an effective and highly regarded PCS. Further, they underscore the importance of an appropriate governance mechanism and the deliberate development of services that add value to stakeholders based on functionality that enables coordination. The Port of Rotterdam attributes part of its success in fending of the worst effects of the pandemic and other disruptions like Brexit to its digitalization efforts and to its Portbase PCS (Port of Rotterdam, 2021). This is evidenced by the vessel dwell at Port of Rotterdam having significantly less impact during the pandemic than POLA/LB.

Theorizing on Ports as Complex Adaptive Systems

I applied the findings from the cross-case analysis to develop theory on ports as complex adaptive systems and discuss the implications for practitioners and researchers. I leveraged CAS theory to develop theoretical propositions about the drivers of complexity and efficiency in port operations.

Descriptive Propositions on Ports' Operational Complexity

The POLA/LB automated-1 terminal was more efficient during the COVID-19 pandemic relative to the automated terminal and manual terminals. It was faster at unloading and it did not need to anchor its vessels, capitalizing on the economies of scale of larger vessels while only marginally increasing the berth dwell compared to the automated and manual terminals. The automated terminal, with its multidimensional operation, was often unable to unload large vessels at one time. Instead, the vessels would partially unload and return to anchor while the containers were cleared from the terminal. Alternatively, vessels were co-loaded and partially unloaded at the automated terminal and then shifted to another terminal to finish unloading.

The efficiency of the automated terminal was affected by its repeating pattern of partially unloading and anchoring, which forced it to compete for close anchorages with other terminals. Additionally, the complex relationship with other horizontally organized terminals increased the duration of co-loaded vessel transitions between terminals. A negative feedback loop resulted in idle vessels remaining at the automated berth waiting to shift to another terminal. Therefore, the automated terminal's berth dwell at POLA/LB increased by 43% in 2021 vs. 2019, while the automated-1 dwell increased by 8%.

The results are consistent with CAS theory in that any element in the system impacts and is impacted by the actions of others. Multifaceted behavior and structures materialize because of the repeating and cumulative patterns of the relations that exist between the component parts of the systems. In this case, comparing the automated terminals that can have more than one stop at the berth vs the automated-1 terminal that has a less complex operation with just one stop suggests that structural complexity is an important factor to consider. This leads to the first descriptive proposition.

> **Proposition 1: The Operational Complexity Proposition.** Container terminal accessibility and multiple intra-port vessel deliveries increase operational complexity.

The context can impact the function of a CAS. For POLA/LB, external factors affected efficiency. The annual post Lunar New Year seasonal downturn did not occur in February and March of 2021. Instead, a surge in volume ensued due to pandemic-driven changes in consumer buying patterns. The two ports had weathered several demand peaks and valleys over the previous years. Instead, in 2021 the surge impacted the ports when they were not in a state of equilibrium, including pandemic-driven labor shortages. For example, at one point, all longshoreman at the labor hall were sent home due to close contact from one COVID-19-positive individual. For that shift, no longshoremen were available for any POLA/LB vessels and this lack of labor combined with the increased demand substantially increasing operational complexity for those terminals.

The POLA/LB was affected by the pandemic and consumer spending patterns. Both factors increased complexity of the operation and together reduced port efficiency, increasing dwell by 58%. This increased complexity due to extraneous shocks was also observed at the Port of Rotterdam, but to a lesser extent. Nevertheless, both the POLA/LB and the Port of Rotterdam were not able to fully adjust operations to address these contextual changes. The dynamic situation suppressed the ports' systemic function of providing adequate labor to unload vessels.

The cross-case results show that port ecosystems as CASs are dependent on the context. Changing the context will have an impact on the function of the system. The environment suppresses or enhances possible systemic functions. Collaborative enterprises are affected by a wide range of contextual factors. For the ports, the pandemic and market demand patterns for goods were beyond the control of the inter-organizational authorities. The ports are radically open systems where the boundary line between the system itself and its environment is not clearly defined. This leads to the second descriptive proposition.

> **Proposition 2: The Extraneous Shock Proposition.** Transport demand and other extraneous shocks increase a port's operational complexity.

The dynamic relations that typify complex port systems often results in the relationship between two phenomena creating disproportionate effects. In the Fall of 2019, anchoring at the POLA/LB was negligible for the automated-1 and manual terminals. During the Fall of 2021, the manual terminals were forced to anchor their vessels disproportionately longer than the automated-1 terminal at 9.5 days and 3.0 days, respectively. Both employed the less complex single stop operation, yet the manual terminals berth unloading rate was significantly slower compared to the automated-1 terminal. The manual terminal dwell increased by 67%, yet its container vessel size only increased by 2%. In contrast, the automated-1 terminal experienced an average berth dwell increase of only 8%. At the same time, the automated-1 terminal capitalized on the economies of scale with its average container vessel size increasing by 15%. The unpredictability of volume spikes and uncertainty of pandemic-driven labor shortages resulted in nonlinear results for the automated-1 terminal versus the manual terminals.

In contrast, the Port of Rotterdam's congestion due to increased demand was a contributor to its 36% increase in berth dwell time in 2021 vs 2019, which is in line but still lower than the 43% berth dwell increase that the automated terminals in POLA/LB endured. Considering the complexities associated with the dependence on labor of the manual terminals at POLA/LB and other factors, the berth dwell time of these terminals increased by 67%. These results show that actions did not develop smoothly from one stage to the next in a sequential or logical way, but rather resulted in non-uniformity and disproportionality. Nonlinearity was a result of repeating feedback loops, which suppressed or magnified disturbances away from equilibrium. Such oscillations existed both internally and between the system and its environment. This is consistent with CASs, which are difficult to control due to uncertainty and unpredictability resulting from nonlinearity. This leads to the third descriptive proposition.

> **Proposition 3: The Non-linear Shock Effect Proposition.** Transport demand and other extraneous shocks decrease port efficiency disproportionately.

The COVID-19 pandemic made the situation unpredictable for POLA/LB due to many factors, including labor shortages, lockdowns, and changing consumer buying patterns. Over-reaction was one unfortunate hallmark of the ports' reaction to the COVID-19 pandemic.

Stakeholders often acted unilaterally to attempt to solve supply chain problems. This resulted in the needle swing to the far extreme, making the balancing act even more difficult. Repeating feedback loops occurred when ocean carriers, terminals, and railroads attempted to fix the problem, but they were unable to see the full effect of acting unilaterally.

As consumer demand dropped at the onset of the pandemic, railroads and container terminals found themselves needing to reduce labor and assets to minimize their costs. Per CAS theory, emergent phenomena manifest from complex causality. In POLA/LB, emergence occurred when the whole port system produced outcomes that differed categorically from those that the port actors produced individually. This emergent property of CAS was evident based on the connective structure of the port ecosystem. For example, as the operational complexity escalated, in 2021 POLA/LB terminals had too few containers and then were overflowing with containers, leading to a 60% increase in empty containers compared to the prior year.

The oversupply of containers caused an over-reaction and resulted in an undesirable emergent phenomenon. Cyclical container surpluses resulted in the same way that constructive wave interference occurs when wave amplitudes reinforce each other, building a wave of even greater amplitude. Likewise, container deficits arose in a similar fashion when simultaneous unilateral cancelling action left very few containers available. Complex causation resulted in significant oscillations in containers availability.

Meanwhile, railroads cycled between having too many active locomotives and railcars to having too few. Ocean carriers over-reacted to the railroads' failure to provide railcars by re-billing containers from rail to truck when the two railroads reached capacity. This change resulted in railroads not having enough work, forcing them to place railcars into storage. This system-wide behavior was amplified by feedback loops, leading to severe congestion and a tipping point in excess anchoring time.

The supply chain facilitates the balance of trade but does not cause its imbalance. The results show that emergence occurred when entities were observed to have systemic properties that were different and nonreducible to the properties of the constituent elements. Emergence occurred in a port setting when the whole port system produced outcomes that differed categorically from those that the port actors produced individually. An emergent property in a port was dependent upon the connective structure of the port system's elements. Complex causality arose from horizontal and vertical connections and was the result of circular and interrelational, nonlinear, and dynamic interactions. Emergent consequences resulted from unknown or poorly understood dependencies between port stakeholders. With complex causation, complex effects caused each member to see their own part of the cause of something, but none saw all the causes. This leads to the fourth descriptive proposition.

> **Proposition 4: The Emergent Factors Complexity Proposition.** Labor shortage, container imbalance, and other factors lead to emergent complexity in a port system under stress.

In 2019, anchoring was nominal at 7% of total dwell time for both POLA/LB and Rotterdam. For 2021, looking at POLA/LB anchoring only, the average vessel spent 60% of its total dwell time at anchor. Rotterdam performed better at only 13%. Between 2019 and 2021, the POLA/LB combined berth and anchor dwell increased by 191% while Rotterdam's increase was 39%. In absolute terms, the average Rotterdam vessel anchored 3.5 hours in 2019 and 9.5 hours in 2019 while the average POLA/LB vessel anchor time went from eight hours to 223 hours, respectively.

For the POLA/LB, multiple pathways of causality were evident when anchoring increased dramatically. Terminals slowed their unloading rate, there were not enough labor gangs to satisfy the daily demands, and all the berths were not used. The connective structure of the port system's elements created a situation conducive to anchoring. Some vessels remained at the berth for days with no labor gangs to unload due to inter-relational effects between terminals and the labor hall. Anchoring, as a key emergent phenomenon, occurred in POLA/LB as consequence of the actions that the port's stakeholders produced individually.

Anchoring is an outcome of port congestion. The Port of Rotterdam has a more multifaceted operation than POLA/LB, yet Rotterdam was able to avoid anchoring to the same extent as POLA/LB. Rotterdam's vessels spent 13% of their total port dwell time at anchor compared with 60% for POLA/LB. A significant factor that may have favored the Port of Rotterdam was its nine automated terminals, compared with two for the POLA/LB. Labor shortages were not as an acute a problem for Port of Rotterdam compared to POLA/LB, which is more dependent on manual terminals. This leads to the fifth descriptive proposition.

> **Proposition 5: The Anchoring Proposition.** Anchoring is a compounded emergent phenomenon in port operations experiencing a shock.

Prescriptive Propositions for Port Operations

The first five propositions associate port operations with CAS theory, to theorize on how extraneous shocks like the pandemic can escalate the complexity of the port system, which in turn affects efficiency. If this complexity and inefficiency are not handled properly, the port system can come to a halt. The key then, is to develop mechanisms to minimize the negative impact on efficiency. I develop prescriptive propositions next.

For the POLA/LB, automated terminals performed similarly to manual terminals in 2019. However, the automated terminals performed significantly better than the manual terminals in 2021. In this case, the positive effect of automation in enhancing port supply chain resilience is worth noting. Likewise, the Port of Rotterdam exploited the advantages provided by its nine automated terminals. Automated terminals are safer, quicker, more standardized, and require less labor. These benefits were magnified during the pandemic. Labor issues in manual terminals are bound to arise during port congestion. This leads to the first prescriptive proposition:

> **Proposition 6: The Container Terminal Automation Proposition.** Container terminal automation reduces the impact on efficiency of contextual complexity from exogenous shocks.

Ports must exercise all resources to ensure a positive reaction to supply chain disruptions. They need to have the ability to make the necessary changes to quickly adapt to different circumstances. Ports can minimize downtime and increase efficiency by maintaining flexible resources and periodically surging resources to ensure readiness. Ports need to evaluate their readiness to react and meet the demands of supply chain disruptions. In this way, ports can minimize the negative effects of emergent phenomena that stem from complex causality. Any one stakeholder can cause a bottleneck; therefore, ports need to quickly identify any limiting factors such as container shortages.

PCSs and inter-organizational processes can enable cooperation to counter the undesirable emergent complexity in ports due to shocks. Taking it a step further, active PCS-enabled cooperation facilitates resilience against supply chain disruption. Recall that the Port of Rotterdam attributes part of its success in fending of the worst effects of the pandemic and other disruptions like Brexit to its digitalization efforts and to its Portbase PCS (Port of Rotterdam, 2021).

Port supply chain governance implemented through PCSs stabilizes stakeholder dynamic interactions. During the pandemic, stakeholders used the BEX at the POLA/LB to coordinate ship schedule adjustments, labor adjustments, port policy, diversions, and empty railcar interchange. The intent was to limit dynamic interactions and complex causality. This was accomplished by sharing data and intentions through the BEX process to avoid individual stakeholders from acting unilaterally. To achieve this goal, all stakeholders need to be prepared to extend capabilities and resources to maximum capacity to avoid bottlenecks.

When compared to Portbase, the most significant shortcomings of the BEX entail governance and overall reach. Portbase, as a partially owned subsidiary, is governed by the Port of Rotterdam Authority which manages, operates, and develops the port. Comparatively, the BEX is operated by the railroads and has no governance authority or enforcement capability. Neither the POLA nor the POLB have any interaction or supervisory role in BEX proceedings.

Regarding overall reach, Portbase provides 40 services for 12 groups of stakeholders. In essence, Portbase provides a comprehensive suite of PCS services for all port stakeholders. In contrast, the BEX, by design, limits its interaction to rail-centered operations. For instance, the BEX has only indirect influence on the number of empty and loaded containers and longshoremen labor assignments. For the BEX to have been more successful in fending off the worst effects of the pandemic, it would have needed greater enforcement authority and greater reach to impact the complex causality prevalent in POLA/LB during the pandemic. This leads to the first prescriptive proposition.

> **Proposition 7: The PCS Complexity Reduction Proposition**. With distributed governance and wide stakeholder participation, PCSs can enable coordination to resolve structural and contextual complexity from shocks.

Supply chain disturbances from equilibrium can be reduced through governance to impose more transparency and stricter obligations. Port governance can impose fees and other restrictions to enforce compliance. The manifestations of poorly understood complex phenomena can be moderated by limiting one stakeholder's actions through cooperative working agreements and contractual provisions. Conversely, governance forces compliance when stakeholders need to act to prevent instability. Port authorities also have extensive administrative powers to implement policies, laws and regulations, and encourage port development and port improvement. As such, port authorities are accountable for growth and competitiveness of a port cluster by governing the port area, managing port activities, handling hinterland connections, and collecting real estate revenue (Tijan et al., 2021).

By late October 2021, world-wide attention on the Southern California anchoring situation warranted POLA/LB reputation as being emblematic of America's pandemic-driven supply chain disruptions. Port leaders received intense scrutiny by Congress and the White House. Resulting from scrutiny over the bottleneck problem, traditional port boundaries were transformed, causing increasing the complexity as a radically open system where the boundary line between the system itself and its environment is not clearly defined. Being integral to the identity of the systems, the POLA/LB environment witnessed non-linear growth in the number of anchored vessels as totals surged toward 100 vessels.

POLA/LB threatened to institute a dwell penalty on dwelling containers to mitigate the port bottleneck. Although the dwell policy was delayed several times, it had the chilling effect of causing terminals to delay incoming trains until they could clear their existing container inventories. This resulted in an undesirable emergent phenomenon. Terminals delayed unloading inbound trains to avoid starting the clock for dwelling containers. Railroads lost the use of the railcars until they were unloaded. This unintended consequence of a threatened policy was difficult for port stakeholders to deal with since actions were taking place based on rumors. This misalignment of incentives contributed to the inefficiency and congestion. Therefore, alignment of incentives is critical for ports to be efficient and to manage extraneous shocks successfully by minimizing the negative impact on efficiency. This leads to the final prescriptive proposition:

> **Proposition 8: The Incentive Alignment Proposition.** Port stakeholders must align incentives to cooperate to reduce the negative effects on efficiency of structural and contextual complexity.

Conclusion

The reaction of automated terminals to supply chain disruptions has renewed interest and attention, given the dramatic pandemic-related effects on port operations. To understand the factors that drive complexity and efficiency at the ports, I analyzed ship movement data, labor data, and container volume data at the POLA/LB as it reacted to the supply chain disruption during the COVID pandemic and compared and contrasted it to that of the Port of Vancouver and the Port of Rotterdam.

Four areas or port operations were examined: container ship movement, longshoremen labor, container availability and imbalance, and inter-organizational coordination through PCSs. The container ship movement depicted the extent of the congestion and considered container terminal automation. The labor analysis assessed whether labor shortages were a contributor to the bottleneck and to what extent available port berths were utilized. The container analysis looked at the ratio of empty and loaded containers and the effects surplus/deficit containers. I also compared the BEX in the POLA/LB to Portbase in the Port of Rotterdam to provide insights that led to prescriptive theoretical propositions on how PCSs can enable coordination and cooperation towards improving efficiency in port operations.

Port logistics activities comprise a complex network of interdependent port stakeholders that react and adjust dynamically to changes in the environment and within their systemic boundaries. Unfortunately, stakeholders typically try proactively to construct what they perceive to be advantageous to their own organization’s benefit. The results of this study reinforce that port operations, where various levels of vertical and horizontal structures interact, cannot merely be addressed in a reductionist fashion through a succession of unrelated and disconnected supply chain partners. Instead, supply chain decision-makers should acknowledge that contributors to port operations are interdependent when addressing the complexity of port operations.

From the cross-case analysis, CAS theory was an appropriate framework to understand the behaviors of supply networks and to develop both practical and theoretical implications for practitioners and researchers. Using the CAS lens, theoretical propositions emerged to frame port operations as a complex adaptive system and to show how ports can use technologies such as PCSs and automation to achieve higher efficiency, both in the absence and in the presence of extraneous shocks.

By comparing the effect of the COVID-19 pandemic on the POLA/LB, I found that port automation enabled the automated-1 terminal to achieve lower total dwell time compared to the automated terminal and manual terminals. Automated-1 terminals were able to handle larger ships more efficiently than manual terminals at the POLA/LB. Therefore, I propose that automation matters in times of emerging and increasing complexity because of extraneous shocks. However, the strength of this effect is moderated by operational complexity: container terminals with more complex vessel unloading patterns at both POLA/LB and Rotterdam were more likely to experience a decrease in efficiency due to an extraneous shock.

While port automation is not an antidote for more efficient port operations in all cases, it does provide advantages for ports experiencing a shock. This becomes more evident as ocean carriers pursue economies of scale in utilizing larger container ships with the resulting acute workload fluctuations for container terminals. In the Fall of 2019, there was limited evidence that automation increased efficiency in POLA/LB. However, in the Fall of 2021, the case study shows that terminal automation at the automated-1 terminal could be an effective measure to counteract expensive labor or labor shortages in a pandemic, and I theorize that it will be the case in the presence of other extraneous shocks, mainly because it reduces the impact of contextual complexity from shocks.

Complexity theory suggests that structural factors such as container terminal accessibility and multiple intra-port vessel deliveries increase operational complexity. Contextual factors such as transport demand and extraneous shocks also increase a port's operational complexity. While both contextual and structural factors are significant by themselves, it is also essential to consider the ramifications of their compounding effects. The dynamic relations that typify complex systems and the interplay of system components and drivers of complexity is non-linear. Labor shortage, container imbalance, and other factors lead to emergent complexity in a port system under stress. The cross-case analysis of POLA/LB and Port of Rotterdam suggests that a combination of contextual and structural forces triggered port congestion during the pandemic. The compounded emergent phenomenon in port operations experiencing shock materialized in the significant anchoring of vessels due to ports' inability to handle surges in vessel traffic.

To alleviate the emergent phenomenon of anchoring, port stakeholders must align incentives to cooperate to reduce structural and contextual complexity. PCSs and related embedded processes enable coordination to resolve structural and contextual complexity from shocks. It appears that the Port of Rotterdam, with its fully functional PCS, was able to handle the detrimental effects of the pandemic. For the POLA/LB, supply chain governance was implemented through the BEX to stabilize dynamic stakeholder interactions and limit complex causality. However, the BEX was constrained because its governance structure was centered around one main stakeholder—the railroads, and because its functionality was not as developed to facilitate coordination across all stakeholders.

I propose that transitioning to higher levels of automation and other technologies will make ports more resilient to supply chain disruptions when those systems are coordinated through PCS systems, but the effectiveness of the PCS will depend on its governance and functional design. Port stakeholders must focus on the future, not just on their short-term interests, and work to develop better processes that enable coordination and information exchange, leveraging technologies such as PCSs and automation.

Limitations and Future Research

Citing prior research studies would normally form the basis of my literature review to help lay a foundation for understanding the research problem. However, no previous BEX studies were available. Additionally, the information contained in BEX is consolidated rail, vessel, and terminal planning data and is only available to authorized users due to its proprietary nature. Instead, the hierarchical container ship movement validates its use as a proxy to ascertain the overall efficiency of container movement through the container terminal to the land transportation. Moreover, I was not authorized to explicitly report the data from the BEX interviews. However, limited access did not prevent me from following through on my study. Nevertheless, I was able to effectively use the information to complement or validate my own inside knowledge of the POLA/LB operation, and to supplement data from the other two ports.

Wide-ranging longitudinal effects of the COVID-19 pandemic were not measured due to limited time and resources and because the pandemic effects are still ongoing. The data covered two four-month snapshots in 2019 and 2021. Accordingly, future research comparing my findings to other periods of shocks across ports will be valuable.

Comprehensive information was unavailable for both the POLA/LB and Port of Rotterdam datasets. Namely, the actual number of unloaded containers was proprietary and unavailable. Instead, vessels were assumed to be fully loaded to maximize the efficient use of vessel container capacity. A promising field of research would evaluate actual container volumes unloaded at terminals across ports for a more accurate analysis. Also, the Port of Rotterdam ship movement data lacked a description of the activity for each record, which did not allow me to provide the same level of analysis of efficiency as with the POLA/LB data. It also precluded me from making comparative statistical analyses to compare efficiency drivers across ports. All these issues non-withstanding, allowed me to develop propositions to be tested in future empirical research.

CHAPTER 5. CONCLUSIONS AND IMPLICATIONS

Supply chain disruptions continue to be a significant challenge as the world economy recovers from the pandemic-related shutdowns that have strained global supply chains. Shocks challenge the adaptability and resilience of maritime ports. The reaction of ACTs to supply chain disruptions has renewed interest, given the dramatic scenes of ships anchored for weeks.

In this dissertation, I first provided a vision of how technology can improve port operations and enhance a port's ability to anticipate and handle shocks by improving coordination, cooperation, and information exchange across port stakeholders. I conducted an in-depth literature review on the use of PCSs, automation, and other emerging technologies to enhance port operations. Next, I considered the nuances in vertical and horizontal relationships between port stakeholders and the related potential impact of technology on coordination and cooperation. I then developed a vision on how technology can improve port operations in general and during pandemic-induced disruptions. This vision will help academics and practitioners perform research that advances theory and practice on the use of advanced technologies to improve port operations.

Synopsis of the Vision

The port of the future will adapt technologies such as automation, blockchain, and AI with integrated PCSs to structurally enhance port operations. These technologies can improve coordination, cooperation, resilience against shocks, and efficiency. As ports automate, PCSs will evolve to facilitate information exchange and communication, both horizontally and vertically. The role of PCSs needs to be advanced to facilitate greater integration of automation and IoT data to make the supply chain more efficient.

From Vision to Reality

To see how the vision has materialized or has yet to materialize, I used a complex adaptive systems lens to develop a qualitative cross-case study of the ports of Los Angeles, Vancouver, and Rotterdam. By embracing CAS theory, I created a comprehensive analysis of the critical tenets of complexity, from which I supported practical insights for the POLA/LB. Therefore, interventions can be established that are more likely to deliver positive results in terms of efficiency. The case study focused on comparison across ports and across terminals (within a port) to deduce the effect of automation and technology on port efficiency, both in daily operations and during the COVID-19 pandemic.

The case study started with an analysis of the reaction of the POLA/LB to the supply chain disruption caused by the COVID-19 pandemic. I compared the operation during the COVID-19 pandemic to a base operation before the pandemic. Then, I introduced an analysis of the Port of Rotterdam and the Port of Vancouver to perform cross-port comparisons. The within-case and cross-case design, together with a comparison before and after COVID-19, provides insights into the impact of automation, PCSs, and other technologies on the efficiency of port operations and how maritime ports can be improved to handle shocks. Data was also collected to capture different dimensions of the same phenomena across terminals and ports. I analyzed ship movement data, labor data, and container volume data at the POLA/LB as it reacted to the supply chain disruption during the COVID pandemic. I then compared and contrasted the POLA/LB data to that of the Port of Vancouver and the Port of Rotterdam.

From Reality Back to the Vision

Using the critical tenets of complexity and with a rigorous application of the case study method, I developed both theoretical propositions and practical insights to ground the vision of the port of the future based on current practices. The findings from the cross-case study suggest that automated terminals were more efficient during the pandemic than non-automated terminals, considering moderating factors uncovered in the study. These moderating factors being equal, I propose that transitioning to higher levels of automation, supported by emerging technologies like blockchain and the internet of things, will make ports more resilient to supply chain disruptions when those systems are coordinated through PCSs.

Port stakeholders must focus on the future, not just their short-term interests, and work to develop better processes that enable coordination and information exchange, leveraging technologies such as PCSs and automation. By comparing the effect of the COVID-19 pandemic on the POLA/LB and Rotterdam, I find that port automation does indeed have a significant effect on efficiency, with a strong correlation between the level of automation, changes in vessel size, and lower total dwell time. Automated terminals were able to handle larger ships more efficiently than manual terminals. However, the strength of this effect was moderated by operational complexity, in that container terminals with more complex vessel unloading patterns were more likely to experience a decrease in efficiency due to a system shock. The efficiency gains were also moderated by contextual factors like the availability of labor to handle increased congestion, and the degree of container imbalance in the system.

A port needs to consider what constitutes a shock and how local it must be to affect the port. To survive the battle and not lose the war, ports may need to expand the definition and geographic radius of influence of the shock. Planners need to consider three factors when looking at technologies and how much they provide resilience against shocks:

- How frequently does a shock need to occur to justify the expenditure?
- How big does it need to be to constitute a shock?
- How close does it need to be to influence a particular port?

System shocks such as Brexit, Ukraine, labor strikes, and weather events continue to materialize. As ports go through prolonged periods without a shock, there is a tendency to ignore investing in technologies that only provide benefits when a shock occurs. Quantifying the size and impact of a shock is not an easy proposition considering the butterfly effect by which small changes in initial conditions can emerge as large-scale and unpredictable variations in the system's future state.

In March 2021, the Suez Canal was blocked for six days by one of the largest container vessels in the world. The container vessel Ever Given ran aground from sandstorm-induced poor visibility and high winds. The resulting backup paralyzed the vital shipping route. The massive maritime traffic jam disrupted global trade as shippers were forced to reroute around the southern tip of Africa, adding weeks and increased costs to their voyages. For those port planners considering the probability of a shock affecting them, it was a wake-up call that they needed to look beyond local threats and reconsider the interconnectedness of global trade. It may weather one storm but may lose business overall.

From the POLA/LB case study, two sources of congestion and disruption have eased. First, COVID-19 related illness has decreased, allowing longshoreman labor to return to normal. Second, volume spikes have subsided, yet the logjam remains. This continued result reinforces that one issue may not cause a complex phenomenon, but multiple can. Once the tipping point occurs, it is hard to right the ship.

As the supply chain effects of the pandemic entered their third year, the complex interaction continued. Recently railroads have been faulted for not providing railcars. The actual problem is likely the inflationary price increase, forcing consumers to reduce purchases. While the causes of inflation are controversial, the result remains that stores do not want to replenish their inventories, leaving distribution centers with loaded containers. Railroad intermodal ramps back up because they are out of room to arrive and unload their container trains. Thus, the railcar shortage is not due to railroad mismanagement of their railcar fleet but the ocean carriers not ordering their distribution centers to pick up their containers from the railroad ramps.

At some point in 2021, with about 100 Vessels at anchor, the optics became untenable for the POLA/LB. Vessels were sent to drift circles, increasing fuel usage and danger for the crews. The anchoring emergent phenomenon transitioned to drift circles due to external, non-port-related concerns. Local neighborhoods were suffering from the anchored vessel emissions. Also, a vessel dragged its anchor and damaged an oil rig pipeline, causing a release. The two were exemplars of complex causality and an emergent phenomenon that can be well framed using CAS. CAS theory suggests that one single effort will not alleviate the emerging complexity to solve the problem, so coordination and cooperation between the shipping companies, the port terminals, and the ground transportation companies are necessary to effectively reverse the adverse compounding effects of the shocks on the ports.

As one final reflection, a port that does not invest in technology with the addition of coordination may suffer the tipping point consequences of an emergent phenomenon that is difficult to reverse. The consequences are not just operational because clients may decide to use other ports (e.g., the Panama Canal in the case of the POLA/LB).

This study revealed that, other things being equal, automated terminals are better off during extraneous shocks because they are better off handling operational complexities, including shortage of labor. If the other terminals that perhaps evaluated automation but put it off because it was too costly could go back in time, would they if it allowed them to recover the last two years? What would they pay to recapture the competitive advantage or the lost market share? Based on the vision and the case study in this dissertation, the main conclusion is that shocks and the potential negative consequences help make a case for long-term investment in automation aided by emerging technologies like blockchain, IoT, and AI to improve coordination and cooperation across stakeholders in the port ecosystem.

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APPENDIX A: IRB APPROVAL LETTER

Pepperdine University
24255 Pacific Coast Highway
Malibu, CA 90263
TEL: 310-506-4000

NOTICE OF APPROVAL FOR HUMAN RESEARCH

Date: November 10, 2021

Protocol Investigator Name: Kevin Dowgiewicz

Protocol #: 21-08-1639

Project Title: Leveraging Interorganizational Systems in the Era of Automation: A Cross-case Study of Port Operations

School: Graziadio School of Business and Management

Dear Kevin Dowgiewicz:

Thank you for submitting your application for exempt review to Pepperdine University's Institutional Review Board (IRB). We appreciate the work you have done on your proposal. The IRB has reviewed your submitted IRB application and all ancillary materials. Upon review, the IRB has determined that the above entitled project meets the requirements for exemption under the federal regulations 45 CFR 46.101 that govern the protections of human subjects.

Your research must be conducted according to the proposal that was submitted to the IRB. If changes to the approved protocol occur, a revised protocol must be reviewed and approved by the IRB before implementation. For any proposed changes in your research protocol, please submit an amendment to the IRB. Since your study falls under exemption, there is no requirement for continuing IRB review of your project. Please be aware that changes to your protocol may prevent the research from qualifying for exemption from 45 CFR 46.101 and require submission of a new IRB application or other materials to the IRB.

A goal of the IRB is to prevent negative occurrences during any research study. However, despite the best intent, unforeseen circumstances or events may arise during the research. If an unexpected situation or adverse event happens during your investigation, please notify the IRB as soon as possible. We will ask for a complete written explanation of the event and your written response. Other actions also may be required depending on the nature of the event. Details regarding the timeframe in which adverse events must be reported to the IRB and documenting the adverse event can be found in the *Pepperdine University Protection of Human Participants in Research: Policies and Procedures Manual* at community.pepperdine.edu/irb.

Please refer to the protocol number denoted above in all communication or correspondence related to your application and this approval. Should you have additional questions or require clarification of the contents of this letter, please contact the IRB Office. On behalf of the IRB, I wish you success in this scholarly pursuit.

Sincerely,

Judy Ho, Ph.D., IRB Chair

cc: Mrs. Katy Carr, Assistant Provost for Research

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