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REVIEW ARTICLE

Optimization for green container shipping: A review and future research directions

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ABSTRACT

Maritime freight transportation is one of the least emissions-producing transportation alternatives in terms of transported tonnage per distance. However, it produces a high amount of emissions as around 80% of international freight transportation is conducted through seas and 20% of maritime transportation is conducted through container shipping. This makes it crucial to reduce emissions in container shipping. In this regard, this study reviewed previous studies on the environmental optimization of container shipping and identified various future research directions. The results showed that in the sea segment of environmental optimization of container shipping, decisions which require further attention include resource allocation, emission reduction technology choice, disruption recovery, freight rate optimization, and shipment scheduling. The decisions that require future research in the port segment are related to internal transportation and handing operations in container terminals (i.e., yard crane deployment, yard truck deployment, yard truck scheduling, yard container stack allocation, yard container retrieval), renewable energy source installation, and emission reduction technology choice. Vessel scheduling and speed optimization decisions are the most frequently studied decisions in the sea segment, but they are rarely considered for inland shipping of containers. In the sea-port combined segment of container shipping, future studies are required in quay crane scheduling, vessel scheduling, container route allocation, ship route allocation vessel deployment, and emission reduction technology choice. The least studied decision in the door-to-door segment of container shipping includes hub location-allocation, empty container relocation, ship route allocation, vessel deployment, environmental taxation and subsidy scheme, emissions reduction technology choice, and speed optimization. It was also demonstrated that modeling of future studies should more frequently consider uncertainties and social sustainability parameters.

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Introduction

Maritime transportation of freight plays a crucial role in international trade as over 80% of it is carried through seas (UNCTAD, 2021). Means for freight transportation in seas highly depend on the characteristics of the goods to be carried. Therefore, maritime transportation consists of various sub-markets, and container shipping is one of them. Container shipping is conducted by standardized maritime container equipment in which freight is stuffed. That container equipment requires specialized container ships to carry them and specialized container terminals at seaports to transfer them between ships and shore. The adoption of containers in maritime transportation grew fast because of their convenience and efficiency in handling and transferring them between different modes of transport. This growth in container transportation has led container shipping companies to increase their transportation capacity by ordering more and bigger ships. The increased adoption of containerization has brought the environmental impacts of container ships under scrutiny.

Like any other industry, reducing emissions in the maritime transportation sector has become important as the effects of climate change show themselves more and more. Maritime freight transportation is one of the least emissions-producing transportation alternatives in terms of transported tonnage per distance because of its high-capacity transportation capability. Although it produces a low amount of emission per unit transported, it produces a high amount of emission as most of the international trade is conducted by maritime transportation. For this reason, in 2018, IMO member states agreed to reduce the total annual GHG emissions resulting from ships by at least 50% by 2050 compared to 2008. Because around 20% of maritime freight transportation consists of container shipping (UNCTAD, 2021), container shipping must also comply with the emissions target of IMO.

Achieving the emissions target set by IMO requires a holistic approach that includes planning container shipping activities at strategic, tactical, or operational levels in addition to the adaptation of new technologies such as scrubbers, and new propulsion systems working with LNG or ammonia or fuel cells (Lagemann et al., 2022). Planning those activities requires an analytical approach to derive a benefit from it because the application of ad hoc planning might result in financial loss without environmental benefits (Dulebenets et al., 2021). In that manner, optimization modeling is widely used for the environmental planning of container shipping. However, there are still areas that need to be explored to reach the emissions target of the container shipping industry. To determine research gaps and the status of scientific knowledge in the area of environmental optimization in container shipping, there is a need for an in-depth literature review and analysis of future research opportunities. Several previous studies performed reviews in the area of container shipping optimization, but they mostly neglect the environmental aspect. They can be grouped under four headings: the studies that reviewed container shipping optimization studies in the seaborne transportation segment (J. Chen, Ye, Zhuang, et al., 2022; Christiansen et al., 2020; Dulebenets et al., 2021; Mansouri et al., 2015; Meng et al., 2014; Psaraftis & Kontovas, 2013; S. Wang & Meng, 2017; H. Yu et al., 2021); the studies that reviewed container shipping optimization studies in the container terminal segment (Abdelmagid et al., 2022; Yu et al., 2022); the studies that reviewed container shipping optimization studies in the inland transportation segment (R. Chen et al., 2022; Lam & Gu, 2013); the studies that reviewed door-to-door container shipping optimization studies (Caris et al., 2008; Rajkovic et al., 2016). Few of the review studies in the area investigated the environmental optimization of container shipping. Lam & Gu (2013) provided a review of the studies in the area of hinterland container flow optimization with green concerns. Psaraftis & Kontovas (2013) reviewed the studies that modeled speed optimization for energy efficiency in the sea leg of container shipping. In a very similar vein, Yu et al. (2021) investigated the studies that provided voyage optimization modeling to reduce environmental emissions of container shipping. In another study on the sea leg of container shipping optimization, Dulebenets et al. (2021) reviewed studies on the optimization of container liner shipping vessel schedules and distinguished the ones that provide an environmental perspective. The current study differentiates from those studies by providing a comprehensive literature review that considers environmental optimization in every segment of container shipping (i.e., sea, port, and inland). A handful of the previous studies provided optimization modeling that combines two or more segments, for example, some studies combined vessel speed optimization with berth allocation. In this regard, the current study aims to review the studies which focused on environmental optimization in each segment of container shipping by analyzing the status of the scientific contributions and providing insights regarding future research opportunities. The results of the analysis will provide scholars with prominent research directions to investigate the most under-researched research subjects related to the environmental optimization of container shipping.

Material and Method

This study reviewed the scientific studies on the environmental optimization of container shipping. To ensure the research conducted in the studies has a certain level of quality and is peer-reviewed, the review only considered the ones published in Web of Science indexed journals particularly indexed in the core collection: SCI-Expanded, SSCI, and ESCI. A systematic review method was adapted in this study. The systematic review is a literature review approach which has a clear research question and uses a systematic approach for identifying, selecting and analyzing studies (Moher et al., 2009; Snyder, 2019). To be systematic in the search process, we used a combination of three groups of keywords in three orders. The keywords in the first order included three keywords that specified the optimization aspect ("optimize", "optimizing", and "optimization"), and the keywords in the second order also included three keywords that specified the environmental aspect (“green”, “environmental”, and “emissions”), and the keywords in the last order included six keywords that specified the container shipping aspect ("container shipping", "liner shipping", "container terminal", "container port", "container transport", and "container transportation"). For example, one of the searches included a combination of those keywords in the keyword groups as "optimize green container shipping". A total of 54 searches were performed in the keywords, abstract, and title sections of the articles because the total combination of the keywords in the three groups is 54 (3×3×6).

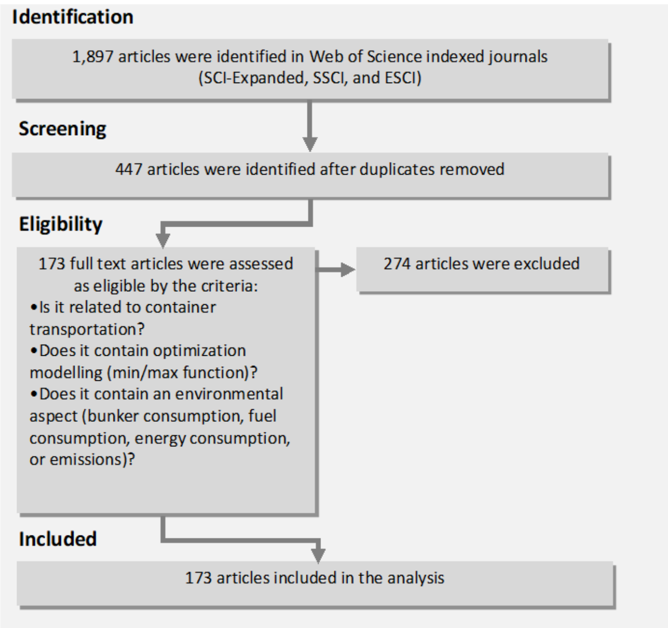

Figure 1. Article inclusion/exclusion process

Article inclusion/exclusion workflow was visualized in Figure 1. The workflow process visualization was done according to Moher et al. (2009). The search results included 1,897 items including duplicates. After the duplicates in the results were removed, 447 scientific articles remained. However, there were still unrelated articles present in the results. Therefore, each paper was further evaluated considering if it is in the area of container shipping and if it performed an optimization modelling (has a max/min function), and if it includes environmental optimization (bunker consumption, fuel consumption, energy consumption, or emissions) in its objective function or its constraints. The oldest research article dated back to 2009. Because the oldest article which satisfies the incision criteria is only 14 years old, a year limit was not included. After the elimination of the articles that do not satisfy those criteria, 173 articles were finally included in for the analysis.

The articles were grouped under the segments of container shipping they considered. The research in some of the articles considered more than one segment. Five groups of articles were constructed according to the container shipping segment considered in their research: environmental optimization in the sea segment of container shipping; environmental optimization in the port segment of container shipping; environmental optimization in the inland segment of container shipping; environmental optimization in the sea-port (includes combination both sea and port) segment of container shipping; and environmental optimization in door-to-door (includes sea, port, and inland) container shipping. Decisions considered by each included research article was identified along with other aspects. Some terms used in those decisions were kept general. For example, quay crane includes mobile harbor crane and gantry crane and yard truck includes terminal truck, automated guided vehicles and straddle carriers (straddle carriers can transport containers in a container terminal and stuck them at a container yard). Under these five groups, the following sections will evaluate the current status of the scientific contribution and future research directions.

Results and Discussion

Environmental Optimization in the Sea Segment of Container Shipping

Table 1 summarizes the environmental optimization studies related to the sea segment of container shipping. The studies evaluated five aspects: the decisions considered in their research, the type of uncertainty if their research includes stochasticity, the modeling approach, decision level, and parameters considered in their objective functions. Before further elaboration, it needs to be clarified that in the context of this study vessel scheduling decisions include the determination of arrival times and departure times of vessels and service frequency on liner services, on the other hand, vessel deployment decisions include the determination of the number of vessels should be allocated to liner services.

Table 1 shows that 74 studies focused on the sea segment of container shipping. It is more than one-third of the total 173. This indicates that environmental optimization studies on container shipping mostly consider the sea segment. As it comes to the decisions considered in those studies, speed optimization is the most studied decision after vessel deployment and vessel scheduling decisions are the ones that were studied most.

As it is shown in Table 1, several of the articles considered single decisions. X. Li et al. (2022), Lu et al. (2023), X. Li et al. (2020), Y. Zhao et al. (2020), Lee et al. (2018), and Wong et al. (2015) included speed optimization as a single decision. X. Li et al. (2022) minimized fuel consumption. Y. Zhao et al. (2020), Lee et al. (2018), and Wong et al. (2015) minimized fuel consumption and time while X. Li et al. (2020) and Lu et al. (2023) minimized fuel consumption and other costs. None of them considered uncertainties. L. Chen et al. (2018) and Du et al. (2015) studied ship route allocation as a single decision. L. Chen et al. (2018) optimized fuel consumption, costs, and time without considering uncertainties. Du et al. (2015) only optimized fuel consumption and considered the fuel consumption of ships as an uncertain input. M. Liu et al. (2022) and Trapp et al. (2020) optimized container route allocation. M. Liu et al. (2022) minimized emissions and costs while considering transportation demand as an uncertain input. Trapp et al. (2020) minimized emissions, costs, and transit time without including stochasticity. Zhen et al. (2017) considered the bunkering decision as a single decision to optimize fuel consumption. They included ship fuel consumption and fuel price as uncertain inputs. M.-M. Yu & Chen (2016) evaluated resource allocation decisions while optimizing efficiency and they considered emission production as one of their constraints.

Several of the studies shown in Table 1 included a combination of two decisions. Zacharioudakis et al. (2011), S. Wang (2016), S. Wang & Wang (2016), and Xing et al. (2019) considered speed optimization and vessel deployment decisions together. Xing et al. (2019) optimized fuel consumption and other costs while Zacharioudakis et al. (2011), S. Wang (2016), S. Wang & Wang (2016) optimized ship time in addition to fuel consumption and costs. None of those studies included stochasticity. Zhen, Hu, et al. (2020) and W. Zhao et al. (2021) considered ship route allocation and speed optimization together. Zhen, Hu, et al. (2020) optimized only fuel consumption, on the other hand, W. Zhao et al. (2021) minimized the time and navigational risks. Both of them neglected uncertainty. C. Li et al. (2015) and Y. Liu et al. (2022) studied disruption recovery and speed optimization together while overlooking uncertainties. C. Li et al. (2015) minimized fuel consumption and time. Y. Liu et al. (2022) minimized costs in addition to those parameters. Qi & Song (2012), S. Wang et al. (2015), and Reinhardt et al. (2020) studied vessel scheduling and speed optimization together. Reinhardt et al. (2020) optimized only fuel consumption. Qi & Song (2012) and S. Wang et al. (2015) minimized the shipping time in addition to fuel consumption. Qi & Song (2012) included port times as uncertain inputs for their model. Y. Liu et al. (2021) studied speed optimization and container route allocation together and minimized emissions and costs. Dong & Tae-Woo Lee (2020) considered speed optimization together with freight rate optimization while minimizing fuel consumption, costs, and shipping time. R. Tan et al. (2020) integrated speed optimization with bunkering and minimized bunker consumption and costs. J. Chen, Ye, Liu, et al. (2022) studied emission reduction strategy choice and ship route allocation and optimized emission production and costs. Their study considered uncertain transportation demand. X. Zhang et al. (2020) studied shipment scheduling and container route optimization to minimize both emissions and costs. M. Zhu et al. (2018) studied ship route allocation and vessel deployment together while considering carbon tax as an uncertain input, they optimized both emissions and costs. Matsukura et al. (2010) considered ship route allocation and container route allocation together to optimize emission production. Wu et al. (2023) and R. Tan et al. (2022) integrated emission reduction technology choice and speed optimization by optimizing emissions and other costs.

Table 1 shows that several studies included a combination of three decisions. A handful of them considered vessel scheduling, vessel deployment, and speed optimization decisions together (Dulebenets & Ozguven, 2017; Giovannini & Psaraftis, 2019; Song et al., 2015; S. Wang et al., 2014; W. Ma et al., 2022; Sun et al., 2022). Dulebenets (2022), Jiang et al. (2020), Dulebenets (2018a), Dulebenets (2018b), Dulebenets & Ozguven (2017), Dulebenets, Golias, et al. (2017), Dulebenets

(2016), Giovannini & Psaraftis (2019), and S. Wang et al. (2014) optimized fuel consumption, costs and time while Song et al. (2015) optimized fuel consumption, cost and time reliability and Alharbi et al. (2015), W. Ma et al. (2022) and Sun et al. (2022) only optimized fuel consumption and other costs. None of those studies included uncertain inputs in their modeling. A few studies considered speed optimization, bunkering and vessel deployment decisions (S. Wang & Meng, 2015; M. Liu et al., 2020; Y. Wang et al., 2018; Wu et al., 2022a). M. Liu et al. (2020) and S. Wang & Meng (2015) optimized fuel consumption, costs, and time, on the other hand, Y. Wang et al. (2018) and Wu et al., (2022a) only optimized fuel consumption and other costs. Except Wu et al., (2022a), all of them included uncertainty in their modeling. M. Liu et al. (2020) considered uncertain transportation demand, Y. Wang et al. (2018) considered fuel price as uncertain and S. Wang & Meng (2015) considered the speed of ships as uncertain input to their modeling. Cheaitou & Cariou (2019) and S. Wang & Meng (2012) studied speed optimization, vessel deployment, and container route allocation decisions altogether. While Cheaitou & Cariou (2019) optimized fuel consumption, costs, and time, S. Wang & Meng (2012) only optimized fuel consumption and costs. Both of the studies did not consider uncertainty in their modeling. Y. Zhao et al. (2021) also considered vessel deployment and ship route allocation together but they included emission reduction technology choice to optimize emissions and costs. Their model considered several uncertainties i.e., transportation demand, charter rate, fuel price, and ship technology renewal time for emission reduction. C. Wang et al. (2022) considered vessel deployment, ship route allocation, and vessel scheduling together. They optimized fuel consumption, costs, and shipping time. Wu et al. (2022b), Lan, Zuo, et al. (2023), and Zhuge et al. (2021) studied vessel deployment and ship route allocation together in the context of speed optimization by minimizing fuel consumption and other costs. Y. Yu et al. (2021) studied container route allocation, and ship route allocation with speed optimization by optimizing fuel consumption and costs. S. Li, Tang, et al. (2023) and Abioye et al. (2019) studied disruption recovery in vessel scheduling by optimizing ship speed. S. Li, Tang, et al. (2023) optimized fuel consumption and other costs and Abioye et al. (2019) optimized fuel consumption, other costs, and shipping time. S. Zhao et al. (2022) and Aydin et al. (2017) studied ship bunkering by considering vessel scheduling and speed optimization. S. Zhao et al. (2022) optimized emissions and other costs. Aydin et al. (2017) optimized fuel consumption and ship time while considering port time as an uncertain input. Y. Zhao et al. (2023) integrated vessel deployment, emission reduction technology choice, and speed optimization while minimizing fuel consumption and other costs.

Some of the studies shown in Table 1 simultaneously consider four decisions. Lan, Tao, et al. (2023), Gao & Hu (2021), and Cariou et al. (2018) studied container route allocation, ship route allocation, vessel deployment, and speed optimization decisions simultaneously. Lan, Tao, et al. (2023) and Gao & Hu (2021) optimized fuel consumption with other costs. Cariou et al. (2018) minimized shipping time as well as fuel consumption and costs. Wen et al. (2022) studied disruption recovery, vessel deployment, vessel scheduling, and speed optimization simultaneously by optimizing fuel consumption, costs, and time reliability. De et al. (2021) studied ship bunkering together with vessel scheduling, disruption recovery, and speed optimization and their objective function included the minimization of fuel consumption and costs. W. Ma et al., (2021) also studied ship bunkering, vessel scheduling, and speed optimization but with ship route allocation. They optimized fuel consumption, costs, and shipping time. Two other studies related to the shipping bunkering decision was provided by C. Wang & Chen (2017) and Lin & Leong (2022). Their studies integrated vessel scheduling, vessel deployment, and speed optimization in bunkering. C. Wang & Chen (2017) optimized fuel consumption, other costs, and ship time. Lin & Leong (2022) optimized fuel consumption and other costs by considering uncertain fuel consumption. S. Wang et al. (2021) studied ship route allocation, vessel deployment, and speed optimization for emission reduction technology choice for the deployed container ships. Their model optimized emissions and costs. S. Wang et al. (2013) integrated vessel scheduling, vessel deployment, speed optimization, and shipment scheduling to optimize fuel consumption and costs. Pasha et al. (2021) studied ship route allocation, vessel scheduling, vessel deployment, and speed optimization by optimizing fuel consumption, other costs, and ship time.

Environmental Optimization in the Port Segment of Container Shipping

Table 2 summarized the environmental optimization studies related to the port segment of container shipping. The most studied decisions are berth allocation, scheduling, and deployment of quay and yard cranes. In the context of this study, scheduling decisions involve time factors and deployment decisions include the quantity of the deployed entity. As can be seen in Table 2 the majority of the studies considered a combination of two or more decisions.

Table 1: Studies on environmental optimization in sea segment of container shipping

Reference	Uncertainty									Decision										Modelling			Level			Objective					
	Transportation Demand	*Charter Rate*	*Fuel Consumption*	*Fuel Price*	*Carbon Tax*	*Renewal Time*	*Ship Speed*	*Port/Handling Time*	*Resource Allocation*	*Bunkering*	*Vessel Scheduling*	*Container Route Allocation*	*Ship Route Allocation*	*Vessel Deployment*	*Disruption Recovery*	*Emission Reduction Technology Choice*	*Speed Optimization*	*Freight Rate Optimization*	*Shipment Scheduling*	*Non-Linear*	*Linearized*	*Linear*	*Strategic*	*Tactical*	*Operational*	*Emissions/Energy/Fuel*	*Costs (Operational Costs, Handling Costs, Fixed Costs, etc.)*	*Time*	*Time Reliability*	*Navigational Risk*	*Efficiency*
S. Li, Tang, et al. (2023)											√				√		√				√			√	√	√	√				
Lu et al. (2023)																	√			√					√	√	√				
Y. Zhao et al. (2023)														√		√	√				√		√	√	√	√	√				
Lan, Tao, et al. (2023)												√	√	√			√					√		√	√	√	√				
Wu et al. (2023)																√	√				√		√		√	√	√				
Lan, Zuo, et al. (2023)													√	√			√			√				√	√	√	√				
S. Zhao et al. (2022)										√	√						√				√			√	√	√	√				
R. Tan et al. (2022)																√	√				√		√		√	√	√				
X. Li et al. (2022)																	√				√				√	√					
Wu et al. (2022b)													√	√			√			√				√	√	√	√				
Wu et al. (2022a)										√				√			√				√			√	√	√	√				
Sun et al. (2022)											√			√			√					√		√	√	√	√				
Lin & Leong (2022)			√							√	√			√			√				√			√	√	√	√				
W. Ma et al. (2022)											√			√			√			√				√	√	√	√	√			
J. Chen, Ye, Liu, et al. (2022)	√												√			√				√			√	√		√	√				
C. Wang et al. (2022)											√		√	√						√				√		√	√	√			
Dulebenets (2022)											√			√			√				√			√	√	√	√	√			
M. Liu et al. (2022)	√											√									√				√	√	√				
Y. Liu et al. (2022)															√		√			√					√	√	√	√			
Wen et al. (2022)											√			√	√		√			√				√	√	√	√		√		
Gao & Hu (2021)												√	√	√			√				√			√	√	√	√				
Y. Liu et al. (2021)												√					√				√			√	√	√	√				
Pasha et al. (2021)											√		√	√			√				√		√	√	√	√	√	√			
De et al. (2021)										√	√				√		√			√					√	√	√				
Y. Zhao et al. (2021)	√	√		√		√							√	√		√					√		√	√		√	√				
Zhuge et al. (2021)													√	√			√			√			√	√	√	√	√				
W. Ma et al., (2021)										√	√		√				√			√				√	√	√	√	√			
Y. Yu et al. (2021)												√	√				√			√				√	√	√	√				
S. Wang et al. (2021)													√	√		√	√				√		√	√	√	√	√				
W. Zhao et al. (2021)													√				√			√					√	√		√		√	
X. Li et al. (2020)																	√				√				√	√	√				
Zhen, Hu, et al. (2020)													√				√								√	√					
Reinhardt et al. (2020)											√						√				√			√	√	√					
Trapp et al. (2020)												√										√			√	√	√	√			
Dong & Tae-Woo Lee (2020)																	√	√		√					√	√	√	√			
M. Liu et al. (2020)	√									√				√			√				√		√	√	√	√	√	√			
X. Zhang et al. (2020)												√							√		√			√	√	√	√				
Jiang et al. (2020)											√			√			√				√		√	√	√	√	√	√			
R. Tan et al. (2020)										√							√					√			√	√	√				
Y. Zhao et al. (2020)																	√			√					√	√		√			
J. Yu et al. (2019)																√						√	√			√	√				
Xing et al. (2019)														√			√				√			√	√	√	√				
Giovannini & Psaraftis (2019)											√			√			√				√		√	√	√	√	√	√			
Cheaitou & Cariou (2019)												√		√			√			√			√		√	√	√				
Abioye et al. (2019)											√				√		√				√				√	√	√	√			
M. Zhu et al. (2018)					√								√	√								√	√			√	√				
Y. Wang et al. (2018)				√						√				√			√			√				√	√	√	√				
Lee et al. (2018)																	√			√					√	√		√			
Dulebenets (2018a)											√			√			√				√			√	√	√	√				
Dulebenets (2018b)											√			√			√				√			√	√	√	√				
L. Chen et al. (2018)													√									√			√	√	√	√			
Cariou et al. (2018)												√	√	√			√				√		√	√	√	√	√	√			
Zhen et al. (2017)			√	√						√										√					√	√					
C. Wang & Chen (2017)										√	√			√			√			√			√		√	√	√	√			

Table 1 (continued)

Reference	Uncertainty										Decision									Modelling			Level			Objective					
	Transportation Demand	*Charter Rate*	*Fuel Consumption*	*Fuel Price*	*Carbon Tax*	*Renewal Time*	*Ship Speed*	*Port/Handling Time*	*Resource Allocation*	*Bunkering*	*Vessel Scheduling*	*Container Route Allocation*	*Ship Route Allocation*	*Vessel Deployment*	*Disruption Recovery*	*Emission Reduction Technology Choice*	*Speed Optimization*	*Freight Rate Optimization*	*Shipment Scheduling*	*Non-Linear*	*Linearized*	*Linear*	*Strategic*	*Tactical*	*Operational*	*Emissions/Energy/Fuel*	*Costs (Operational Costs, Handling Costs, Fixed Costs, etc.)*	*Time*	*Time Reliability*	*Navigational Risk*	*Efficiency*
Dulebenets & Ozguven (2017)											√			√			√				√			√	√	√	√	√			
Dulebenets, Golias, et al. (2017)											√			√			√							√	√	√	√	√			
Aydin et al. (2017)								√		√	√						√			√					√	√		√			
M.-M. Yu & Chen (2016)									√													√		√							√
S. Wang & Wang (2016)														√			√			√				√	√	√	√	√			
S. Wang (2016)														√			√			√				√	√	√	√	√			
Dulebenets (2016)											√			√			√				√		√	√	√	√	√	√			
Wong et al. (2015)																	√			√					√	√		√			
S. Wang et al. (2015)											√						√					√			√	√		√			
S. Wang & Meng (2015)							√			√				√			√				√		√		√	√	√	√			
Song et al. (2015)								√			√			√			√			√			√		√	√	√		√		
C. Li et al. (2015)															√		√			√					√	√		√			
Du et al. (2015)			√										√								√			√		√					
Alharbi et al. (2015)											√			√			√				√			√	√	√	√				
S. Wang et al. (2014)											√			√			√				√			√	√	√	√	√			
S. Wang et al. (2013)											√			√			√		√	√				√	√	√	√				
S. Wang & Meng (2012)												√		√			√				√			√	√	√	√				
Qi & Song (2012)								√			√						√			√					√	√		√			
Zacharioudakis et al. (2011)														√			√			√				√	√	√	√	√			
Matsukura et al. (2010)												√	√									√		√	√	√					

Several of them considered a single decision. Nadi et al. (2022), Xu et al. (2022), Caballini et al. (2020), Fan et al. (2019), Do et al. (2016), and G. Chen et al. (2013) studied inland truck appointments systems as a single decision in seaport container terminals. Xu et al. (2022) and Fan et al. (2019) optimized emissions, costs, and truck times. Xu et al. (2022) included uncertain truck arrival times in their modeling. Nadi et al. (2022) and G. Chen et al. (2013) optimized only truck times while Caballini et al. (2020) optimized time and time reliability. Do et al. (2016) optimized only emissions while considering uncertainty in truck arrival times. Dulebenets, Moses, et al. (2017), Zhen et al. (2016), and Golias et al. (2009) studied berth allocation in seaport container terminals as a single environmental optimization decision. Dulebenets, Moses, et al. (2017) and Zhen et al. (2016) optimized emissions, costs, and ship time while Golias et al. (2009) optimized only emissions and time and none of them considered uncertainty. S. Chen & Zeng (2021) and J. He, Huang, & Yan (2015) studied yard crane scheduling as a single optimization decision by optimizing emissions and crane time. Kanellos (2019) studied electricity grid allocation in seaport container terminals as a single decision by optimizing emissions and costs and considering electricity price as an uncertain input parameter. D. Liu & Ge (2018) studied crane deployment in seaport container terminals and optimized costs considering emissions as a constraint. L. Li et al. (2018) studied renewable electricity source installation considering uncertain electricity supply and minimized installation costs. H. Li & Li (2022) studied quay crane scheduling optimizing energy usage. Duran et al. (2022) and Abu Aisha et al. (2020) optimized container terminal yard layouts. Duran et al. (2022) minimized emissions while Abu Aisha et al. (2020) optimized emissions and the monetary costs. Tao et al. (2023) studied optimum yard container stack allocation by minimizing travelled distances.

A great deal of the studies on environmental optimization in the port segment of container shipping considered a combination of two decisions.

Table 2. Studies on environmental optimization in port segment of container shipping

Reference	Uncertainty								Decision															Modeling Level						Objective						
	Counts of Handled Containers	*Ship Arrival Time*	*Truck Arrival Time*	*Electricity Supply*	*Electricity Demand*	*Workload*	*Electricity Price*	*Port/Handling Time*	*Berth Allocation*	*Quay Crane Deployment*	*Quay Crane Scheduling*	*Yard Layout Optimization*	*Yard Crane Scheduling*	*Yard Crane Deployment*	*Yard Truck Deployment*	*Yard Truck Retrofitting for Emission Reduction*	*Yard Truck Scheduling*	*Yard Container Stack Allocation*	*Yard Container Retrieval*	*Electricity Grid Allocation*	*Renewable Electricity Source Installation*	*Inland Truck Scheduling*	*Emission Reduction Technology Choice*	*Non-Linear*	*Linearized*	*Linear*	*Strategic*	*Tactical*	*Operational*	*Emissions/Energy/Fuel*	*Costs (Operational Costs, Handling Costs, Fixed Costs, etc.)*	*Time*	*Time Reliability*	*Workload*	*Distance*	*Container Throughput*
Duan et al. (2023)													√				√									√			√	√						
Zheng et al. (2023)											√		√				√									√			√	√						
Tao et al. (2023)																		√							√				√	√						
Duran et al. (2022)												√												√				√		√						
Niu et al. (2022)													√				√					√				√			√	√						
H. Li & Li (2022)											√															√			√	√						
H. Yu, Huang, et al. (2022)											√		√					√								√			√					√	√	
Zhen, Lin, et al. (2022)				√							√		√				√			√					√				√							√
Y. Zhang, Liang, et al. (2022)				√	√				√		√		√							√					√				√	√		√				
J. Yu et al. (2022)									√	√	√									√						√			√	√	√	√				
Q. Zhang et al. (2022)						√									√	√										√	√		√	√	√	√				
Zhen, Jin, et al. (2022)	√														√	√										√	√		√	√	√	√				
Nadi et al. (2022)																						√		√					√			√				
Xu et al. (2022)			√																			√		√					√	√	√	√				
Duan et al. (2021)									√		√													√					√	√	√	√				
S. Chen & Zeng (2021)													√													√			√	√		√				
Zhen et al. (2021)		√				√			√		√														√				√	√	√	√				
Karakas et al. (2021)															√			√								√			√	√		√				
Zhong et al. (2020)											√						√									√			√			√				
Abu Aisha et al. (2020)												√													√				√	√	√					
Feng et al. (2020)			√																√			√				√			√	√		√				
Caballini et al. (2020)																						√				√			√			√	√			
D. Yu et al. (2019)						√							√	√										√			√		√	√		√				
Y. Yang et al. (2019)													√				√	√								√			√	√		√				
W. Wang et al. (2019)				√	√															√	√					√	√		√		√					
Peng et al. (2019)		√							√											√						√			√	√	√					
M. Ma et al. (2019)													√									√		√					√	√		√				
X. Li, Peng, et al. (2019)					√															√	√			√			√		√		√					
Kanellos (2019)							√													√						√			√	√	√					
Fan et al. (2019)																						√				√			√	√	√	√				
T. Wang et al. (2018)									√	√	√														√		√		√	√	√	√				
D. Liu & Ge (2018)										√														√			√			√						
L. Li et al. (2018)				√																	√			√			√				√					
H. Yu et al. (2017)															√		√									√									√	
Dulebenets, Moses, et al. (2017)									√																	√			√	√	√	√				
Zhen et al. (2016)									√																√				√	√	√	√				
Peng et al. (2016)		√	√					√						√									√	√			√			√						
He (2016)									√	√	√															√	√		√	√		√				
Do et al. (2016)			√																			√				√			√	√						
Schmidt et al. (2015)					√															√			√							√						
J. He, Huang, & Yan (2015)													√												√				√	√		√				
J. He, Huang, Yan, et al. (2015)											√		√				√								√				√	√		√				
Q.-M. Hu et al. (2014)									√	√	√													√					√	√	√	√				
G. Chen et al. (2013)																						√		√					√	√		√				
Golias et al. (2009)									√																	√			√	√		√				

Niu et al. (2022) and Duan et al. (2023) integrated yard crane scheduling and yard truck scheduling decisions by optimizing energy consumption. Q. Zhang et al. (2022) and Zhen, Jin, et al. (2022) studied yard truck deployment problem for yard truck retrofitting with low-emission technologies by optimizing emission, costs, and truck times. They both considered uncertainty in their input parameters. Q. Zhang et al. (2022) included workload Zhen, Jin, et al. (2022) included transportation demand as an uncertain parameter. Duan et al. (2021) and Zhen et al. (2021) studied berth allocation and quay crane scheduling simultaneously by optimizing emissions, costs, and crane times. Only Zhen et al. (2021) included uncertain parameters, i.e., ship arrival time and workload, in their modeling. W. Wang et al. (2019) and X. Li, Peng, et al. (2019) studied renewable electricity source installation and electricity grid allocation in container terminals by optimizing costs and they both considered uncertainty. W. Wang et al. (2019) included electricity demand and supply uncertainty while X. Li, Peng, et al. (2019) only included electricity demand uncertainty in their modeling. Karakas et al. (2021) integrated the yard truck deployment problem and yard container stack allocation and optimized emissions and time. Zhong et al. (2020) studied quay crane scheduling and yard truck scheduling together by optimizing their operation time. Feng et al. (2020) integrated the problem of yard container retrieval from the container stack into inland truck scheduling considering truck arrival time uncertainty. They optimized both emission and total time. D. Yu et al. (2019) integrated yard crane deployment problem and yard crane scheduling problem. They optimized time and emissions by considering uncertainty in crane workloads. Peng et al. (2019) studied berth allocation and electricity grid allocation for cold ironing. They optimized emissions and costs by considering ship arrival time uncertainty. M. Ma et al. (2019) integrated the modeling of yard crane scheduling into inland truck scheduling to optimize emissions and times. H. Yu et al. (2017) studied yard truck deployment and yard truck scheduling by optimizing the traveled distances of trucks. Peng et al. (2016) integrated yard crane deployment and emission reduction strategy choice modeling to optimize emissions. Their modeling considered uncertainties in ship arrival times, truck arrival times, and handling times. Schmidt et al. (2015) also studied emission reduction strategy choice but they integrated it with electricity grid allocation. They optimized emission production by considering uncertainties in electricity demand.

Some of the studies shown in Table 2 integrated three decisions in their modeling. T. Wang et al. (2018), He (2016), and Q.-M. Hu et al. (2014) studied the integration of berth allocation, quay crane deployment, and quay crane scheduling. Q.-M. Hu et al. (2014) and T. Wang et al. (2018) optimized emissions, costs, and time while He (2016) optimized emissions and time. None of them considered uncertainties. Modeling of H. Yu, Huang, et al. (2022) included quay crane scheduling, yard crane scheduling, and yard container stack allocation simultaneously. They optimized traveled distances and workload allocated to each crane. Y. Yang et al. (2019) modeled yard crane scheduling, yard truck scheduling, and yard container stack allocation to optimize time and emissions. The model proposed by J. He, Huang, Yan, et al. (2015) and Zheng et al. (2023) integrated quay crane scheduling, yard crane scheduling, and yard truck scheduling. J. He, Huang, Yan, et al. (2015) optimized energy consumption and time, while Zheng et al. (2023) optimized only energy consumption.

Table 2 shows that few of the studies integrated four decisions in their modeling. Zhen, Lin, et al. (2022) simultaneously modeled quay crane scheduling, yard crane scheduling, and electricity grid allocation with yard truck scheduling to maximize the container throughput of the container terminal by considering emissions as constraints. Their model included uncertainties in electric supply. Y. Zhang, Liang, et al. (2022) also modeled quay crane scheduling, yard crane scheduling, and electricity grid allocation but integrated them into berth allocation. They optimized time and emissions by considering uncertainties in electricity supply and demand. The model proposed by J. Yu et al. (2022) integrated quay crane scheduling, quay crane deployment, and electricity grid allocation with berth allocation to optimize emissions, costs, and time without considering uncertainties.

Environmental Optimization in the Inland Segment of Container Shipping

Table 3 demonstrates summaries of the environmental optimization studies related to the inland segment of container shipping. The table shows that hub location-allocation and container route allocation are the most studied decisions. Similar to the previously evaluated container shipping segments, the environmental optimization studies in the inland segment mostly integrates two and more decision. However, some of the studies considered single decisions. Digiesi et al. (2019), Tsao & Linh (2018), Y. Chen et al. (2018), Maia & Couto (2013), Sun (2020), and Dai & Yang (2020) studied hub location allocation as a single decision in inland container shipping. Digiesi et al. (2019) and Dai & Yang (2020) only optimized emissions and costs while Y. Chen et al. (2018) and Maia & Couto (2013) optimized time as well as emissions and costs. On the other hand, Sun (2020) optimized time reliability in addition to emissions and costs. Tsao & Linh (2018) included social sustainability variables i.e., noise and accidents in addition to emissions, costs, and time. Only two of them included uncertainty in their modeling. Sun (2020) included uncertainties in transportation time and handling time while Dai & Yang (2020) included transportation demand uncertainty in their modeling. W. He et al. (2021), Shiri & Huynh (2018), Schulte et al. (2017), and Heilig et al. (2017) modeled inland truck scheduling in their studies. Shiri & Huynh (2018) optimized only time considering emissions as a constraint while Schulte et al. (2017) optimized emissions and time. W. He et al. (2021) and Heilig et al. (2017) optimized emissions, costs, and time simultaneously. None of them considered uncertainty in their modeling. S. Zhu et al. (2021) modeled tug scheduling for container barges as a single decision in inland shipping to optimize emissions. S. Li, Wu, et al. (2023) studied optimum emission reduction technology choice by optimizing fuel consumption and the other costs while considering the uncertainties in emission production, transportation demand and transportation capacities.

Table 3. Studies on environmental optimization in inland segment of container shipping

Reference	Uncertainty							Decision									Modeling			Level			Objective									
	Emissions	*Transportation Demand*	*Number of Available Vehicles*	*Costs*	*Capacity*	*Transportation Time*	*Port/Handling Time*	*Hub Location Allocation*	*Vessel Scheduling*	*Barge Tug Scheduling*	*Empty Container Relocation*	*Container Route Allocation*	*Inland Truck Scheduling*	*Emission Reduction Technology Choice*	*Speed Optimization*	*Shipment Scheduling*	*Non-Linear*	*Linearized*	*Linear*	*Strategic*	*Tactical*	*Operational*	*Emissions/Energy/Fuel*	*Costs (Operational Costs, Handling Costs, Fixed Costs, etc.)*	*Time*	*Time Reliability*	*Noise*	*Accidents*	*Infrastructure Deterioration*	*Trucker Rest Time*	*Unemployment*	*Immigration*
J. Ma et al. (2023)		√						√				√							√	√			√	√								
Omran et al. (2023)		√						√				√							√	√			√	√								
S. Li, Wu, et al. (2023)	√	√			√									√					√	√			√	√								
Pourmohammad-Zia et al. (2023)			√									√	√						√			√	√	√	√							
Z. Tan et al. (2022)														√	√		√			√		√	√	√								
Kurtuluş (2022)								√				√						√		√		√	√	√								
S. Zhu et al. (2021)										√									√			√	√									
Ambrosino & Sciomachen (2021)								√				√							√	√		√	√	√	√		√	√	√			
W. He et al. (2021)													√						√			√	√	√	√							
Pian et al. (2021)								√				√							√	√		√	√	√	√							
Sun (2020)						√	√					√						√				√	√	√		√						
Wong et al. (2020)								√			√	√							√	√		√	√	√	√							
Dai & Yang (2020)		√										√							√			√	√	√								
Tsao & Thanh (2019)		√		√	√			√				√							√	√		√	√	√	√						√	√
Digiesi et al. (2019)												√					√		√			√	√	√								
Tsao & Linh (2018)												√					√					√	√	√	√		√	√				
Z. Tan et al. (2018)						√	√		√						√		√				√	√	√		√							
Sun et al. (2018)					√							√				√		√				√	√	√	√							
Shiri & Huynh (2018)													√				√					√			√							
Irannezhad et al. (2018)											√	√							√			√	√	√								
Y. Chen et al. (2018)												√							√				√	√	√							
Schulte et al. (2017)													√									√	√	√								
Heilig et al. (2017)													√				√					√	√	√	√							
Fazili et al. (2017)												√	√			√			√			√	√	√						√		
Shi et al. (2016)												√		√				√		√		√	√	√								
Palacio et al. (2016)								√				√							√	√		√	√	√								
Sun & Lang (2015)												√				√		√				√	√	√	√							
Palacio et al. (2015)					√			√				√							√	√		√	√	√								
Maia & Couto (2013)												√							√	√		√	√	√	√							
Kim et al. (2013)								√				√					√			√		√	√	√	√							

Environmental optimization studies in the inland segment of container shipping mostly combine two decisions in their modeling. The modeling approach of J. Ma et al. (2023), Omran et al. (2023), Kurtuluş (2022), Ambrosino & Sciomachen (2021), Pian et al. (2021), Tsao & Thanh (2019), Palacio et al. (2016), Palacio et al. (2015), and Kim et al. (2013) integrated container route allocation into inland container hub location-allocation. Kurtuluş (2022), Palacio et al. (2016), and Palacio et al. (2015) optimized emissions and costs while Pian et al. (2021) and Kim et al. (2013) optimized time in addition to emissions and other costs. J. Ma et al. (2023) and Omran et al. (2023) also optimized emission and the other costs while considering the uncertainty in transportation demand. Tsao & Thanh (2019) and Ambrosino & Sciomachen (2021) optimized social sustainability parameters i.e., noise, accidents, infrastructure deterioration, unemployment, and immigration in addition to emissions, costs, and time. Only two of those studies considered uncertainties: Palacio et al. (2015) considered capacity uncertainty while Tsao & Thanh (2019) considered uncertainties in transportation demand, costs, and capacities. Sun et al. (2018) and Sun & Lang (2015) combined shipment scheduling and container route allocation in inland container transportation to optimize emissions, costs, and time. Sun et al. (2018) also considered uncertainties in capacities. Z. Tan et al. (2022) combined emission reduction strategy choice and speed optimization in inland container shipping to optimize emissions and costs. Z. Tan et al. (2018) integrated vessel scheduling and speed optimization in inland container shipping. They optimized emissions and time while considering uncertainties in transportation times and port times. Irannezhad et al. (2018) integrated empty container relocation in container route allocation to optimize emissions and costs in inland container transportation. Shi et al. (2016) modeled container route allocation and emission reduction strategy choice to optimize emission production and costs. Pourmohammad-Zia et al. (2023) integrated container route allocation and inland truck scheduling while considering the uncertainties in available number of trucks. They optimized emissions, other costs and transportation time.

Only two studies in environmental optimization combined three decisions. Wong et al. (2020) integrated hub location allocation, empty container relocation, and container route allocation to optimize emissions, costs, and time. Fazili et al. (2017) combined shipment scheduling, container route allocation, and inland truck scheduling to optimize emissions, costs, and trucker rest times. They provided the only research in this review that considers trucker rest time as a parameter in their modeling.

Environmental Optimization in Sea-Port Segment of Container Shipping

Table 4 summarizes the environmental optimization studies that integrated both the sea and port segments of container shipping. It is illustrated in the table that most of the studies considered berth allocation and speed optimization simultaneously while two of them included additional decisions in their modeling. Z.-H. Hu (2020), Venturini et al. (2017), and Du et al. (2011) included only berth allocation and speed optimization decisions. Z.-H. Hu (2020) and Du et al. (2011) optimized emissions and time while Venturini et al. (2017) optimized costs as well as emissions and time. Alvarez et al. (2010) included vessel scheduling decisions to berth allocation and speed optimization decisions. They optimized emissions, costs, and time while considering uncertainties in truck arrival times. Zhen, Wu, et al. (2020) integrated five more decisions i.e., vessel scheduling, container route allocation, ship route allocation, vessel deployment, and emission reduction strategy choice to berth allocation and speed optimization decisions. They optimized emissions, costs, and time. J. Qi & Wang (2023) integrated bunkering, bunkering hub location, emission reduction technology choice and speed optimization decisions while optimizing fuel consumption and the other costs.

Environmental Optimization in Door-to-Door (Sea-Port-Inland) Container Shipping

Studies related to environmental optimization in door-to-door container shipping were summarized in table 5. The table shows that the most studied decision is the container route allocation decision. Similar to the studies in the other segments, the environmental optimization studies in this segment of container shipping mostly consider two or more decisions. On the other hand, some of the studies consider only a single decision. S. Liu (2023), M. Li & Sun (2022), Z. Yang et al. (2021), X. Li, Kuang, et al. (2019), Q. Ma et al. (2018), Martínez-López et al. (2016), and Chang et al. (2010) studied container route allocation as a single decision in door-to-door container shipping. S. Liu (2023) optimized emissions, the costs, transportation time, and quality. M. Li & Sun (2022) optimized emissions, the costs, and transportation time while considering the uncertainties in transportation demand and emission costs. Z. Yang et al. (2021) and X. Li, Kuang, et al. (2019) optimized emissions and costs while Q. Ma et al. (2018) optimized costs and quality by considering emissions as constraints. On the other hand, Martínez-López et al. (2016) and Chang et al. (2010) optimized time in addition to emissions and costs. Q. Hu et al. (2022) studied the environmental subsidy scheme as a single decision to optimize emissions. Sáinz Bernat et al. (2016) studied empty container relocation as a single decision in door-to-door container shipping considering uncertainties in transportation demand and empty container supply to optimize emissions, costs, and time.

Table 4. Studies on environmental optimization in sea-port segment of container shipping

Reference	**Uncertainty**	**Decision**										**Modeling**			**Level**			**Objective**		
	Truck Arrival Time	*Bunkering*	*Bunkering Hub Allocation*	*Berth Allocation*	*Quay crane Scheduling*	*Vessel Scheduling*	*Container Route Allocation*	*Ship Route Allocation*	*Vessel Deployment*	*Emission Reduction Technology Choice*	*Speed Optimization*	*Non-Linear*	*Linearized*	*Linear*	*Strategic*	*Tactical*	*Operational*	*Emissions/Energy/Fuel*	*Costs (Operational Costs, Handling Costs, Fixed Costs, etc.)*	*Time*
J. Qi & Wang (2023)		√	√							√	√		√		√		√	√	√	
Z.-H. Hu (2020)				√							√	√					√	√		√
Zhen, Wu, et al. (2020)				√		√	√	√	√	√	√		√		√	√	√	√	√	√
Venturini et al. (2017)				√							√			√			√	√	√	√
Du et al. (2011)				√							√	√					√	√		√
Alvarez et al. (2010)	√			√	√						√			√			√	√	√	√

Table 5. Studies on environmental optimization in door-to-door container shipping

Reference	**Uncertainty**			**Decision**										**Modeling**			**Level**			**Objective**			
	Emissions cost	*Transportation Demand*	*Empty Container Supply*	*Hub Location Allocation*	*Empty Container Relocation*	*Container Route Allocation*	*Ship Route Allocation*	*Vessel Deployment*	*Environmental Taxation Scheme*	*Environmental Subsidy Scheme*	*Emission Reduction Technology*	*Speed Optimization*	*Shipment Scheduling*	*Non-Linear*	*Linearized*	*Linear*	*Strategic*	*Tactical*	*Operational*	*Emissions/Energy/Fuel*	*Costs (Operational Costs, Handling Costs, Fixed Costs, etc.)*	*Time*	*Quality*
(S. Liu, 2023)						√										√			√	√	√	√	√
(M. Li & Sun, 2022)	√	√				√										√			√	√	√	√	
Q. Hu et al. (2022)										√					√		√			√			
Y. Zhang, Atasoy, et al. (2022)						√							√			√			√	√	√	√	
Martínez-López (2021)						√	√	√						√			√			√	√	√	
Z. Yang et al. (2021)						√								√			√			√	√		
K. Chen et al. (2020)						√			√	√				√			√		√	√	√		
Martínez-López & Chica (2020)						√	√	√				√		√			√	√	√	√	√	√	
Martínez-López et al. (2019)						√					√			√			√		√	√	√	√	
X. Li, Kuang, et al. (2019)						√										√			√	√	√		
Martínez-López et al. (2018)						√					√			√			√		√	√	√	√	
Q. Ma et al. (2018)						√										√			√		√		√
Tran et al. (2017)						√	√									√			√	√	√	√	
Sáinz Bernat et al. (2016)		√	√		√									√					√	√	√	√	
Martínez-López et al. (2016)						√								√			√		√	√	√	√	
Lam & Gu (2016)					√	√										√	√		√	√	√	√	
M. Zhang et al. (2013)				√		√										√	√		√	√	√		
Chang et al. (2010)						√										√			√	√	√	√	

Table 5 shows that several of the environmental optimization studies in door-to-door container shipping combined two decisions. Martínez-López et al. (2019) and Martínez-López et al. (2018) integrated container route allocation and emission reduction strategy choice for container ships in door-to-door container shipping to optimize emissions, costs, and time. Y. Zhang, Atasoy, et al. (2022) combined container route allocation and shipment scheduling to optimize emissions, costs, and time. Tran et al. (2017) integrated container route allocation and container ship route allocation and optimized emissions, costs, and time. Lam & Gu (2016) integrated empty container relocation in container route allocation and optimized emissions, costs, and time. M. Zhang et al. (2013) studied inland container hub allocation and container route allocation to optimize emissions and costs.

Table 5 demonstrates that only two of the studies combined three decisions. Martínez-López (2021) combined container route allocation, container ship route allocation, and vessel deployment to optimize emissions, costs, and time. On the other hand, K. Chen et al. (2020) integrated environmental taxation and subsidy scheme in container route allocation and optimized emissions and costs.

As illustrated in Table 5, only Martínez-López & Chica (2020) combined four decisions. They integrated ship route allocation, vessel deployment, and speed optimization in container route allocation and optimized emissions, costs, and time.

Research Directions Through Years

Figure 2 show the change in research direction trough years. It can be seen in the first graph in the figure that the number of research articles in the environmental optimization of sea segment of container shipping has been consistently increased in the later years. Lately, vessel speed optimization, vessel deployment and vessel scheduling decisions took increased attention of the scholars in the area. This is understandable considering the increased environmental concerns in the shipping industry because those decisions can have a big impact on environmental performance of container shipping. By optimizing the speed of container vessels, bunker consumption can be reduced thus the amount of emission production. Vessel scheduling and number of the vessels deployed can also have a big impact on vessel speed and bunker consumption. Emission production can be high in a container service with a tight schedule and few container vessels because vessels must speed up to catch up with the schedule.

The second graph in Figure 2 show the yearly change in research direction in port segment in the research area. Similar to the sea segment, number of research in the port segment has been increased in the later years. Researchers mostly focused on quay crane scheduling and yard crane scheduling in the recent years. By optimizing quay crane and yard crane scheduling, energy consumption of those equipment per handled container as well as yard truck and inland truck waiting times can be improved thus emission production can be reduced. The third graph in Figure 2 shows the development of research through the years in inland segment of the research area. The graph show that number of research articles has not been increased in the recent years. It was consistent throughout the years. In the recent years, researchers focused on hub location allocation and container route allocation decisions. Locations of inland container hubs can have a significant impact of emission production because by selecting optimum locations, total travelled distances can be reduced. Additionally, container route allocation include transportation mode choice and emission production can be reduced by using environmentally friendly alternatives to road transportation of inland containers.

Fourth graph in figure 2 shows the yearly change in research direction in the research articles which considered both sea and port segment of container shipping. Even though there are few research articles that consider both sea and port segment, the number of articles has been increased in the recent years. The recent articles mostly focused on berth allocation and speed optimization decisions. Those two decisions are closely related because with optimum berth allocation, waiting times of container vessels can be minimized therefore excess time can be used to reduce optimum speeds of container vessels. The last graph in figure 2 illustrates the yearly change in the number of research articles according to considered decisions on the door-to-door segment of container shipping. The graph shows that there is not much increase in the number of research articles in the area. The number of research articles are fairly consisted throughout the years. Most studied optimization decision in the recent years shown in the graph is container route allocation. The container route allocation decisions in the door-to-door container shipping include selection of transportation modes thorough different routes. It is understandable that this decision become popular among researchers in the area of environmental optimization in container shipping because choice of a low emission producing transportation alternative can increase the environmental performance of container shipping.

Figure 2. Change in research directions through years

Future Research Directions

Even though environmental optimization in container shipping widely researched area, there is still a need for further research. Expanding the research in environmental optimization of container shipping to reduce emissions has become more important as the negative effects of climate change are more frequently seen. In this regard, this study identified various future research directions in the area. Table 6 shows the decisions considered by each segment of environmental optimization studies in the research area. The future research directions were identified in terms of the number of research articles focused on each identified optimization decisions, uncertainty modelling and objective function. The number of research articles on the considered decisions were illustrated in Table 6 according to the container shipping segment. As it can be seen in the table that some decisions were well studies in one or more segment but not in the other segments.

Table 6. Number of research articles on the considered decisions

	Sea	Port	Inland	Sea-Port	Door-to-Door
Barge Tug Scheduling			1 (%2)		
Berth Allocation		11 (%13)		5 (%25)	
Bunkering	12 (%6)			1 (%5)	
Bunkering Hub Allocation				1 (%5)	
Container Route Allocation	11 (%6)		22 (%44)	1 (%5)	16 (%52)
Disruption Recovery	6 (%3)				
Electricity Grid Allocation		8 (%9)			
Emission Reduction Technology Choice	7 (%4)	2 (%2)	3 (%6)	2 (%10)	2 (%6)
Empty Container Relocation			2 (%4)		2 (%6)
Environmental Subsidy Scheme					2 (%6)
Environmental Taxation Scheme					1 (%3)
Freight Rate Optimization	1 (%1)				
Hub Location Allocation			10 (%20)		1 (%3)
Inland Truck Scheduling		9 (%10)	6 (%12)		
Quay Crane Deployment		5 (%6)			
Quay Crane Scheduling		13 (%15)		1 (%5)	
Renewable Electricity Source Installation		3 (%3)			
Ship Route Allocation	19 (%10)			1 (%5)	3 (%10)
Shipment Scheduling	2 (%1)		3 (%6)		1 (%3)
Speed Optimization	61 (%33)		2 (%4)	6 (%30)	1 (%3)
Vessel Deployment	39 (%21)			1 (%5)	2 (%6)
Vessel Scheduling	28 (%15)		1 (%2)	1 (%5)	
Yard Container Retrieval		1 (%1)			
Yard Container Stack Allocation		4 (%5)			
Yard Crane Deployment		2 (%2)			
Yard Crane Scheduling		12 (%14)			
Yard Layout Optimization		2 (%2)			
Yard Truck Deployment		4 (%5)			
Yard Truck Retrofitting for Emission Reduction		2 (%2)			
Yard Truck Scheduling		8 (%9)			
Total	186 (%100)	86 (%100)	50 (%100)	20 (%100)	31 (%100)

Research Direction Towards Uncertainty Modelling

Uncertainty is the often-neglected aspect of environmental optimization studies in container shipping. Compared to different segments, uncertainty is more frequently included in the models of the studies in the port segment of container shipping but still over half of the reviewed studies on port segment neglected uncertainties as illustrated in Table 1-5. Future studies in different segments can include different uncertain inputs in their modeling.

Future studies related to environmental optimization in the sea segment of container shipping can include uncertainties in sailing times, port times, and fuel/energy consumption. Uncertainties in those parameters were rarely considered by previous studies although they can be highly volatile caused of various factors such as weather conditions, sea currents, worker strikes, and oil prices.

Future studies on environmental optimization in the port segment of container shipping can also include various neglected uncertain parameters i.e., count of containers handled, electricity supply, and demand. Transportation demand depends on economic conditions and can be highly volatile. Strategic environmental optimization decisions with high fixed costs in the port segment of container shipping must consider uncertainties in the number of containers handled to avoid big financial losses. Uncertainties in electricity supply and demand are important aspects for future studies on cold ironing and electrification of container handling equipment to reduce emissions of container terminals. Additionally, the studies related the renewable energy source installation in ports must consider those uncertainties in their modeling to ensure reliable energy supply and effective usage of financial resources.

Uncertainty was seldom considered by the environmental optimization studies in the inland segment of container shipping. Future studies can include uncertainties in transportation demand and transportation times. Considering uncertainties in transportation demand for inland container shipping is critical for studies that evaluate expensive infrastructure installment in hinterlands of ports. Additionally, considering uncertainties in transportation time is critical for accurate emission calculation and calculation of external social costs because congestion in inland transportation networks is a frequently occurring phenomenon that needs to be dealt with.

In the sea-port combined segment of container shipping, only one study included uncertainty in its research. Future studies that will focus on environmental optimization in the sea-port integrated segment of container shipping can include uncertainties in ship arrival times, inland truck arrival times, and workloads because volatilities in those parameters can highly impact costs and emission production.

Similar to the sea-port segment, only one study in environmental optimization of the door-to-door container shipping segment considered uncertainty in their modeling. In door-to-door container shipping, uncertainties in transit times in different segments (i.e., sea, port, and inland) can have a huge impact on the container route selection and hub location-allocation. Therefore, they can affect emission production and total costs. In addition to uncertainties in transit times, uncertainties in transportation demand also affect container route allocation and hub location allocation because high demand means lower unit transportation costs and lower emissions per unit of containerized freight transported.

Research Directions for Sea Segment of Container Shipping

The most under-researched decisions in environmental optimization models in the sea segment of container shipping include resource allocation, emission reduction technology choice, disruption recovery, freight rate optimization, and shipment scheduling. Future studies can integrate those decisions in their modeling to expand the research in the area. Resource allocation in the sea segment can be combined with research allocation in inland container shipping networks and resources of the container shipping companies can be allocated to reduce emissions in the whole door-to-door container shipping chain. Consideration of emission reduction strategy choice for future studies on environmental optimization is crucial because the adaptation of an analytical approach for investing and application to an emission reduction strategy can deliver more effective results. Those emission reduction technologies can include but are not limited to scrubber installation, retrofitting ship engines for alternative low-emission fuels (ammonia, LNG, and hydrogen fuel cells, etc.), an adaptation of wind-assisted sailing systems, or wave-assisted sailing systems. Disruption recovery is another decision that is under-researched for environmental optimization. Measures for recovering disruptions such as increasing ship speed can produce high emissions. Therefore, future studies can focus on environmental optimization in disruption recovery to minimize emissions resulting from container ship operations. Future studies on freight rate optimization can be helpful for the determination of environmental tax caps in container shipping because shipping companies eventually will reflect environmental taxes to their customers inside their freight rates. Shipment scheduling decisions are another important area for future research in environmental optimization. Shipment scheduling decisions including the determination of timing and frequency of containerized freight shipments can have a huge impact on companies' carbon footprint since bigger shipments mean less emission per ton of shipped containerized freight.

Research Directions for Port Segment of Container Shipping

The evaluation of previous environmental optimization of the port segment of container shipping revealed the least researched areas as decisions related to internal transportation and handing operations in container terminals (i.e., yard crane deployment, yard truck deployment, yard truck scheduling, yard container stack allocation, yard container retrieval), renewable energy source installation, and emission reduction technology choice. Optimization of internal transportation and handling operations can have a big impact on energy consumption thus emission production in container terminals. Future studies can focus on this area by providing environmental optimization models for internal transportation and handling operations of container terminals. The problem of renewable energy source installation in the seaport areas lately gained importance because ports can require a high amount of energy for their operations and there are usually industrial clusters located around ports that require a high amount of energy for their operations. Therefore, ports can be established as focal energy production and distribution points for the industry by investing and establishing renewable energy production infrastructures such as wind tribunes, wave tribunes, or facilities that produce electricity from organic waste. Future studies related to environmental optimization can model decisions related to the number, location, and energy distribution of renewable energy source installations in ports. Another under-researched area for environmental optimization related to container terminals is the emission reduction strategy choice. From a financial point of view, the selection of emission reduction technology can have a big importance and must not be decided in an ad hoc manner. For example, what kind of zero-emission technology should a container terminal invest in such as retrofitting internal transportation and handling equipment for electrification, battery usage, fuel cell usage, or alternative fuel usage e.g., ammonia or LNG usage for hydrogen production with a carbon capture technology.

Research Directions for Inland Segment of Container Shipping

The review of this study showed the decisions seldom considered by previous environmental optimization studies in the inland segment of container shipping include vessel scheduling, barge tug scheduling, empty container relocation, emission reduction strategy choice, speed optimization, and shipment scheduling. Vessel scheduling and speed optimization decisions are the most frequently studied decisions in the sea segment, but they are rarely considered for inland shipping of containers. Because inland shipping is performed in inland waterways and rivers, it has different operational dynamics than seaborne container shipping. For example, inland navigation can be affected by such factors as river currents, draft, and air draft limitations, dam crossings, etc. For this reason, future studies can model vessel scheduling and speed optimization in inland container shipping for optimizing emission production. Barge tug scheduling is also an under-researched decision. Inland container shipping through barges is common practice in Europe and China. Therefore, there is a need for future studies on environmental optimization in the area. Empty container relocation is well studies area in general, but studies mostly focused on the sea segment and often neglected empty container relocation in inland container transportation. Empty containers for inland container transportation are stored in inland hubs and the demand and supply of empty containers highly depend on the demand for export and import containerized freight transport. In this regard, future studies can provide a modeling perspective for empty container relocation in inland container transportation, especially in combination with inland container route allocation and inland container hub location. The emission reduction strategy choice in the inland segment of container shipping is another decision that requires more future research for environmental optimization. The emission reductions strategies for inland container transportation can include but are not limited to the adaptation of emission reduction technologies by inland container ships and container barge tugs such as scrubbers, fuel cells, batteries, or zero emission propulsion technologies as well as electrification of rail lines or retrofitting inland transportation trucks with zero-emission technologies. An ad hoc decision approach to the adoption of those technologies can result in inefficiencies in the usage of financial resources, therefore, there is a need for future studies on optimization modeling in the area. Shipment scheduling for environmental optimization in the inland segment of container shipping also requires further research. Shipment scheduling includes deciding on the timing and frequency of containerized freight shipments. Shipments with low frequency and bigger baches produce less emission as per tonnage transported but increase inventory holding cost. Future studies on optimization modeling for shipment scheduling can provide help for trade-offs between costs and emissions.

Research Directions for Sea-Port Segment of Container Shipping

The decisions that require further research in the sea-port segment of container shipping include quay crane scheduling, vessel scheduling, container route allocation, ship route allocation vessel deployment, and emission reduction technology choice. Most of those decisions are well-researched in the other segments but all the studies in the sea-port combined segment of container shipping only included berth allocation and speed optimization decisions. Consideration of quay crane scheduling can have a big impact on berth allocation decisions and speed optimization is highly affected by vessel scheduling and vessel deployment decisions. Future environmental optimization studies in the sea-port segment of container shipping can integrate those decisions to provide more accurate and comprehensive modeling perspectives. Container route allocation and container ship route allocation decisions are highly related since containers allocated to a shipping route require the allocation of container ships in the services of the container lines. And ship route allocation decisions impact vessel scheduling and vessel deployment decisions. Therefore, future environmental optimization studies in the sea-port segment must also integrate container route and ship route allocation decisions into their models. As in the other segments, emission reduction technology choice is seldom considered in the sea-port segment. Future studies on emission reduction technology choice in the sea-port segment can integrate decisions on emission reduction technologies in the sea segment (e.g., scrubber installation, retrofitting ship engines for alternative zero-emission fuels, wind-assisted sailing systems, or wave-assisted sailing systems) to decisions on emission reduction technologies in the port segment (e.g., retrofitting internal transportation and handling equipment for electrification, battery usage, fuel cell usage or alternative fuel usage).

Research Directions for Door-to-Door Segment of Container Shipping

Almost all the research in environmental optimization in the door-to-door segment of container shipping considered container route allocation decisions. There is a need for further research that includes other decisions i.e., hub location-allocation, empty container relocation, ship route allocation, vessel deployment, environmental taxation and subsidy scheme, emissions reduction strategy choice, and speed optimization. Two of the least studied decisions, i.e., hub location-allocation and vessel deployment, in the door-to-door segment are well-studied in other segments. However, they should be considered by environmental optimization studies in the door-to-door segment. Hub locations can impact transportation costs and choice of transportation modes as well as emission production. Vessel deployment is rarely explicitly considered by the models in the door-to-door segment since consideration of vessel deployment can highly increase model complexity and solvability. However, vessel deployment decisions can have a big impact on the amount of emission production. Emission reduction strategy choice is another area in the door-to-door segment that needs further research. Emission reduction technology choice in the sea segment is highly related to vessel deployment decisions. The choice of emission reduction technologies in the sea, port, and inland segments of container shipping can be integrated with the models of the door-to-door segment. Empty container relocation and ship route allocation decisions in the door-to-door segment also require more research. The two decisions are very related and can be integrated into container route allocation for environmental optimization in door-to-door container shipping. Future studies can also consider modeling environmental taxation and subsidy provision since the determination of environmental taxation and subsidies by optimization modeling can ensure policy effectiveness. Speed optimizations is another under-researched decision in the door-to-door segment however it is well studied in the sea segment. Speed optimization in the door-to-door segment requires a different perspective than speed optimization in the sea segment because in door-to-door segments it is highly integrated with transportation mode choice and shipment scheduling. Therefore, future environmental optimization studies that consider speed optimization in door-to-door container shipping should integrate mode choice decisions and shipment scheduling in their modeling.

Research Directions towards Combination of Environmental and Social Sustainability

The result of this review reveals that objective functions of the previous study in the environmental optimization of container shipping mostly included parameters related to fuel/energy consumption, emissions, costs, and time. Those parameters are related to economic and environmental sustainability. Future studies can quantify and include social sustainability parameters such as noise production, accidents, quality, immigration, employment, and personnel rest times. One of the interesting and very important social sustainability parameters considered in one of the previous studies was the trucker rest times (Fazili et al., 2017) which is crucial for the safety and health of the truckers. For example, future studies in the sea or port segment can integrate similar parameters in their studies because working conditions and overworking of port and ship personnel were one of the most criticized realities in the shipping sector and it got worse and under scrutiny during the Covid-19 pandemic.

Conclusion

Around 80% of international freight transportation is conducted through seas and 20% of maritime transportation is conducted through container shipping (UNCTAD, 2021). Therefore, total emissions produced by container shipping constitute a high share of total industrial emission production. This makes it crucial to expand the research to reduce emissions in container shipping. In this regard, this study provided a review of previous studies on the environmental optimization of container shipping and identified various future research directions. The review grouped the environmental optimization studies under five segments: sea, port, inland, sea-port combined, and door-to-door container shipping.

Under each segment of container shipping, the decisions that require future research on environmental optimization were revealed. In the sea segment of environmental optimization of container shipping, decisions which require further attention include resource allocation, emission reduction technology choice, disruption recovery, freight rate optimization, and shipment scheduling. The decisions that require future research in the port segment are related to internal transportation and handing operations in container terminals (i.e., yard crane deployment, yard truck deployment, yard truck scheduling, yard container stack allocation, yard container retrieval), renewable energy source installation, and emission reduction technology choice. Vessel scheduling and speed optimization decisions are the most frequently studied decisions in the sea segment, but they are rarely considered for inland shipping of containers. In the sea-port combined segment of container shipping future studies required in quay crane scheduling, vessel scheduling, container route allocation, ship route allocation vessel deployment, and emission reduction technology choice, although they were well-researched in the other segments. The least studied decision in the door-to-door segment of container shipping includes hub location-allocation, empty container relocation, ship route allocation, vessel deployment, environmental taxation and subsidy scheme, emissions reduction technology choice, and speed optimization. The hub location-allocation and vessel deployment are well-studied in other segments.

Additionally, the review showed that uncertainties in modeling approaches and objective function parameters related to social sustainability require the attention of scholars in the area. The analysis provided in previous studies in this review demonstrated the level of scientific rigor regarding environmental optimization of container shipping to the scholars that plan to provide research in the area. The future research directions on environmental optimization in container shipping revealed in this study will provide a guide for scholars in the area to investigate the most under-researched subjects.

Compliance With Ethical Standards

Conflict of Interest

The author declares that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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