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A simulation-based research on carbon emission mitigation strategies for green container terminals

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ABSTRACT

This paper aims to solve the problem of how to quantify the impact of mitigation strategies on carbon emissions from port operations and shipping inside container terminals without real energy consumption data. In order to cope with complex stochastic processes in container terminals, the problem is carried out by establishing a carbon emission quantification simulation model. Firstly, the carbon emission formulation and mitigation strategies are introduced. Then, a container terminal operation simulation model is constructed considering four kinds of mitigation strategies as inputs: reduced speed in waterway channels, reduced auxiliary time at berth, on-shore power supply and alternative fuels, and increased working efficiency of port equipment. Finally, based on a real container terminal, this paper carried out a variety of simulation experiments and discovered that (1) Reduced speed from 24 to 8 knots can achieve a 48.4% reduction of carbon emissions from ships in waterway channels, and 32.9% from the whole container terminal. (2) Compared with diesel in waterway channels and at berth, the use of LNG can reduce carbon emissions by about 11% for the emissions from ships and 8% for the total emissions.

1. Introduction

Climate change and environmental pollution are one of the most pressing issues that need to be faced and resolved. Green port, referring to the one characterized by healthy ecological environment, reasonable utilization of resources, low energy consumption and pollution, is officially proposed in 2009 (Wan et al., 2017). Reducing carbon emissions and efficient use of port equipment in container terminals are vital to achieving the climate and environmental goal of green port construction (Peng et al., 2016). Emission mitigation strategies have been implemented in many container terminals, such as the port of Long Beach, Sydney ports, and Tokyo Harbor etc. For example, a shore power supply system was equipped in Venetial Harbor, leading to about 30% reduction of carbon emissions (Cai, 2010). Operation methods, such as reduced speed in waterway channels and reduced lay time at berth & anchor etc., were analyzed in the Port of Gothenburg, on the promise that GHG emissions would be 10% lower than the business as usual level to 2030 (Winnes et al., 2015). With a change from marine fuel to LNG, the carbon emission is reduced by 25% (Bengtsson et al., 2011). However, since the reduction of carbon emissions were calculated based on real operation data, it is hard to estimate how the green port approach influence emissions. Green port construction is a long, comprehensive, systematic and complex task and is a matter concerning the overall situation and long-term strategic perspective (Baily and Solomon, 2004). Therefore, considerable attention is generated on how to quantify the impact of mitigation strategies on the carbon emissions from port operations and shipping inside container terminals without real energy consumption data, which is the problem we aim to solve in this paper.

Efforts to reduce the environmental impact from ports mainly focus on visiting ships inside the ports, since almost half of emissions were attributed to ship movement (Villalba and Gemechu, 2011). The existing literature provides different approaches to reduce carbon emissions from port vessels, as summarized by the technologies and measures presented by (Bouman et al., 2017). Most of works related to the mitigation strategies focus on on-shore power supply (OPS), alternative fuels, reduced speed in waterway channels and reduced turnaround time at berth.

OPS, also known as shore-side electricity technology or "Cold Ironing", replaces the auxiliary diesel engines (AE) with electricity power supplied from shore. When a ship connects to OPS at berth, the air quality and noise in port cities can be improved and reduced (Styhre et al., 2017). Results showed that the total potential external health cost benefit of 60% of ships applying OPS (while 40% use AE-generated power) would amount to approx. € 2.8 million annually, a figure that excludes the benefit of reduced CO_2 emissions (Ballini and Bozzo, 2015).

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Alternative fuels cover all aspects related to replacing marine fuel oils with alternative energy, such as LNG, biofuels and methanol. NO_X and SO_2 emissions are reduced significantly when a shift from marine fuel to LNG happens, and the CO_2 emissions are reduced by 25%. However, the total emissions of CO_2-equivalents may not necessarily be decreased due to the leakage (Bengtsson et al., 2011). Adopting biofuels can cut down CO_2 emissions highest from the perspective of life cycle, but considering the systemic effects, such as land use change, it will produce more CO_2 emissions (Bouman et al., 2017). Methanol is another alternative fuel, which is just introduced to the market. From a life cycle perspective, adopting methanol is almost similar to that of usual marine fuels for the reducing global-warming (Brynolf et al., 2014).

Reduced speed in waterway channels relates to the operational speed of vessels in sailing period, as well as its design speed. A minor speed reduction can have a large impact on fuel consumption due to the cubic function between the speed and energy consumption. Generally, reduced speed is expected as the highest potential in carbon emission reduction (Buhaug et al., 2009). Du et al. (2011) and Wang et al. (2013) proposed optimization approaches to minimize fuel consumption by adjusting vessel speed in waterway. Then, Du et al. (2011) calculated the emissions from ships when travelling in waterway based on the widely-used emission factors. Later, an activity-based model is used to calculate fuel consumption and emissions of ships entering Kaohsiung Port, and results show that CO_2 emissions can be reduced by about 40% after decreasing the speed to 12 knots (Chang and Jhang, 2016).

Reduced turnaround time at berth is another means of reducing emissions, reducing lay time at berth and still carrying out the same amount of transport work. Only few studies focus on this issue. For instance, Winnes et al. (2015) analyzed and forecast ship emissions in the Port of Gothenburg for 2030, showing that the emissions at berth are most efficiently decreased with the reduction of ships' berthing time. Johnson and Styhre (2015) concluded that fuel consumption would be saved by 2%–8% by reducing unproductive waiting times, and the impact is calculated based on quantitative operational data from Voyage Reports etc.

The literature mentioned above shows that on-shore power supply, reduced speed in waterway channels, and reduced berthing time can help reduce CO_2-equivalents, while it's hard to say for the alternative fuels due to the leakage from the engine and incomplete burning etc. Only few studies calculate the reduction in CO_2 emissions caused by green approaches. Nonetheless, since the reduction of carbon emissions is calculated based on real operation data of many years, it is hard to estimate how the green port approach influence emissions with the change of parameters among mitigation strategies without real data.

The emissions from port equipment have been regarded as a problem recently and corresponding research has been studied. At present, the mitigation strategies for port equipment can be summarized in two aspects: equipment retrofit and working efficiency improvement. The studies on approaches of reducing carbon emissions through equipment retrofit are mainly focused on utilization of Automatic Guided Vehicles (AGVs) and energy replacement of diesel to electricity for yard cranes. Comparing the energy savings and CO_2 reduction of rubber-tired gantries (RTGs) and electric rubber tired gantries (ERTGs), it showed that ERTGs could save about 87% of energy and reduce CO_2 emissions by 68% (Yang and Chang, 2013). Besides, Geerlings and Duin (2010) indicated that the replacement of diesel cargo stevedoring equipment with electric equipment can reduce CO_2 emissions by 20%. Xiao and Lu (2012) proposed and analyzed a formula for calculating the energy consumption of quay cranes in container terminals based on a long-term real data, and developed an energy saving device used in cranes. On the other hand, the studies on reducing carbon emissions through improving working efficiency of equipment are mainly focused on scheduling optimization. Scheduling of handling equipment in container terminal has been studied, i.e., quay cranes, internal trucks and yard cranes. The results showed that the optimal tradeoff between time-saving and energy-saving can be achieved by reasonable scheduling of handling equipment.

Numerous approaches have been proposed to reduce carbon emissions in coastal areas and ports (Davarzani et al., 2015). But significant reduction in carbon emissions can be reached only by the replacement with renewable fuels (Styhre et al., 2017). Renewable energy plays an increasingly greater role within ports, as the ports are usually situated in the place that are particularly suitable for generating power from winds (Rotterdam; Kitakyushu), tide differentials (Dover; the Port of Digby), waves (Port Kembla; Mutriku), and in some cases geothermal energy (Hamburg). Furthermore, the ports often have available wide flat surfaces, such as storage areas and warehouses, that can be used for installation of solar panels (e.g. the Tokyo Ohi Terminal or in the Port of San Diego administration buildings), although such infrastructure might not always be suitable for large scale solar energy exploitation. The Port Authority of Genoa has developed a Port Energy Environmental Plan to improve the use of renewable energy and boost the efficiency of energy in port areas, allowing to one save around 197,000t of CO_2 by 2020 based on an estimation of CO_2 reduction for the year 2011 (Acciaro et al., 2014). The largest terminal operator Hamburger Hafen und Logistik AG, operates a fleet of electric cars and uses heat generated by burning biogas produced in the neighboring sewage handling plant in Köhlbr and höft, which accounts for a reduction of 1000t of CO_2 per year. The company aims to decrease the emission by 30% before the year of 2030 compared with that in 2008, and by 2012 had already achieved a reduction of 24% (Pietsch, 2013).

Besides, studies have been focused on green port policies related to mitigation strategies, which are currently adopted in advanced ports worldwide, such as using on-shore power, transitioning to alternative fuels, replacement of older diesel equipment and switching to renewable energy. For example, Hong Kong Port has introduced the Fair Winds Charter program for the use of low-sulfur oil in ships since 2011, and has implemented ERTG Replacement Project, reducing 70% fuel cost and 80% maintenance cost (Kim and Kim, 2014). The Port of Long Beach Clean Trucks Program implemented a progressive ban on older heavy polluting diesel drayage trucks. When the Program was fully implemented in 2012, emissions from trucks were cut down by over 90 percentages.

Another challenge in quantifying the impact of mitigation strategies on carbon emissions is how to estimate the emissions emitted inside the container terminal. Based on an activity-based methodology, Meyer et al. (2008) estimated the atmospheric emissions from four Belgian seaports, which accounted a total of 1880 kton of CO_2 from the port for the period 2003–2004. Besides, Jiang et al. (2012) calculated the carbon emissions from three types of multimodal transport in ports of China, based on the calculation model provided by IPCC. Villalba and Gemechu (2011) monitored emission prevention measures according to the carbon emission indicators obtained from practical engineering. Based on a dedicated investigation, Zamboni et al. (2015) estimated emissions and fuel consumption of heavy vehicles in urban and port areas. Liao et al. (2010) used the activity-based emission model to calculate carbon emissions after investigating the real emission data from the port of Taipei.

The above-mentioned emissions are all calculated based on real operation data obtained from port companies. However, a container terminal operation system is very complicated and stochastic, including many sub-systems, such as ships arriving & leaving through waterway subsystem, ships berthing at berth and being handled subsystem, containers assignment and being carried & transported subsystem, and the subsystem of containers being handled by yard cranes or other equipment etc. at yard or gate. The components of the container terminal operation system are queuing systems that are interconnected. It's very hard to formulate how each subsystem interact with each other, not to mention how carbon emission mitigation strategies influence the emissions from a container terminal operation system. As to deal with

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