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Carbon emission modelling in container terminal operations planning using a system dynamics approach

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Abstract. This paper discusses the model development of carbon emission cost in container terminal operations planning using a system dynamics approach. Operational planning in a container terminal consists of planning a vessel at berth process, containers loading and unloading processes by quay cranes, containers transportation process by container trucks, containers loading and unloading processes by yard cranes, and containers receiving and delivery processes by container trailers. In each stage, the process will produce carbon gas emissions. A system dynamics simulation model was applied to determine the optimal allocation of the number of used material handling equipment based on the number of handled containers to minimize the total carbon emissions in a container terminal operations planning. The design of a system dynamics simulation model considers the uncertainty in the vessel arrival time and the number of containers that should be handled on each moored vessel at the berth. The system dynamics model had been applied to a numerical example for resulting the optimal solutions of planning decisions at container terminal operations.

1. Introduction

In recent years, container terminal industries have been under great pressure to meet economic and environmental standards. The level of energy consumption and resulting emissions in this industry significantly increases the energy consumption rate and costs. Nevertheless, few container terminal industries have implemented performance measurement and strategy of energy efficiency. Container terminal performance needs to be improved to create industries that are not only competitive and productive, but also need to be more sustainable. As a consequence, performance measurement efforts that must be beyond the measurement of traditional efficiency and productivity are emerging challenges. In terms of energy consumption, there is a strong relationship between sustainability, efficiency, competitiveness and port profitability. The relationship of sustainability with the efficiency of energy consumption and port performance has not been fully understood, nor has been analyzed in details [1].

Energy consumption level is one of the important factors in port operations and economic activities related to ports. Increased energy costs need to be responded by port authorities and container terminal operators by finding ways or strategies to reduce fuel expenditure. With the growth of global container trade and port infrastructure development, ports have become significant energy consumers.

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An analysis of energy consumption requires a detailed understanding of the portion of energy expenditure at container terminal operations expressed by different sizes and types of containers, so that it can determine what operating area consumes energy [2].

The remainder of this paper is structured in the following manner. Section 2 reviews the relevant literature with the main focus on energy consumptions and carbon emissions resulting from container terminal operations. A detailed description of the problem studied herein is described in Section 3. In Section 0, the model development using system dynamics approach is presented for minimizing the total carbon emissions in container terminal operations. Section 5 presents and discusses the results of simulation model and, finally, in the last section summarizes findings and outlines potential future research directions.

2. Literature review

Although the literature related to energy consumption in container terminal operations is quite limited, several research work on energy consumption in specific types of container handling equipment had been conducted by Yun et al. [3], Yang and Chang [4], Acciaro et al. [5] and Geerlings and Duin [6]. However, in general, there has been no systemic view research of the beyond impact of energy consumption on technological advancements in container terminals. Yun et al.'s work was one of findings reported on the impact of electric rubber-tired gantries on green port performance [3]. Yang and Chang's research indicates that bulbar-powered RTGs equipped with online braking can reduce energy consumption by up to 60% [4].

Sim has made energy activity clusters as follow: vertical operations (quay cranes), horizontal operations (e.g. reach-stacker (RS) cranes, rubber-tired gantry (RTG) cranes, rail-mounted gantry (RMG) cranes, etc.), lighting, buildings and cooling (reefers). Usage time is another important factor when it comes to measuring energy consumption and setting indicators for energy efficiency because of: (1) ship calling patterns, all which can trigger significant variations and peaks in energy consumption; (2) variations in the dwell time of different container types (e.g. import and export containers); and (3) the seasonality of certain types of traffic (e.g. reefers) [7]. Geerlings and Duin have classified the energy consumption per type of cargo handling equipment in terminals as shown in the following Table 1 [6].

Table 1. Energy consumption per type of equipment.

Energy	Type of equipment	Fixed consumption per container move	Variable consumption
Electric	Quay Crane [a]	6.00 kWh	
	Barge Crane [a]	4.00 kWh	
	Rail Crane [a]	5.00 kWh	
	Automated Stacking Crane [a]	5.00 kWh	
	Rail Mounted Stacking Crane [b]	7.25 kWh	
	Platform [b]	5.00 kWh	
Diesel	Automated Guided Vehicle [a]	1.10 liter	1.80 liter/km
	Straddle Carrier [a]	0.80 liter	3.50 liter/km
	Terminal Tractor [a]		4.00 liter/km
	Multi Trailer System [a]		4.20 liter/km
	Reach Stacker/Top Lifter [a]		5.00 liter/km

[a] Based on a TNO project by Oonk

[b] Based on a comparison with the ASC on the ECT Delta Terminal, in which the reach of the equipment (stack length) is taken into consideration

Carbon emissions at container terminals are produced by direct and indirect carbon emissions based on fuel consumption or electrical energy [3]. Equipment operated using fuel, such as container trucks and yard cranes, consumes fuel energy while operating such that it will produce direct carbon emissions. Equipment operated by using electricity, such as OPS, will produce indirect carbon emissions, which means that emissions are generated outside the seaport. Carbon emissions either directly or indirectly produced by each equipment (Figure 1.) can be calculated according to ISO 14064-1: 2006 standard [8] and IPCC 2006 [9], which are determined by the amount of energy consumption and the coefficient of emissions carbon from that energy, as given in Eq (1).

$$W = F.C_{energy} \quad (1)$$

where W represents the carbon emissions; F represents the energy consumption, which can be diesel (kg), LNG (kg), or electric (kWh); C_{energy} is the carbon emission coefficient of the energy, which can be obtained from IPCC 2006 [9] and the energy statistics department in corresponding region. The CO_2 emission coefficient of electricity for the port is 1073.65 lbs CO_2/MWh (1 lb =0.45359 kg), namely 0.7369 kg/kWh [10]. Therefore, once the energy consumptions are formulated, the carbon emissions can be obtained.

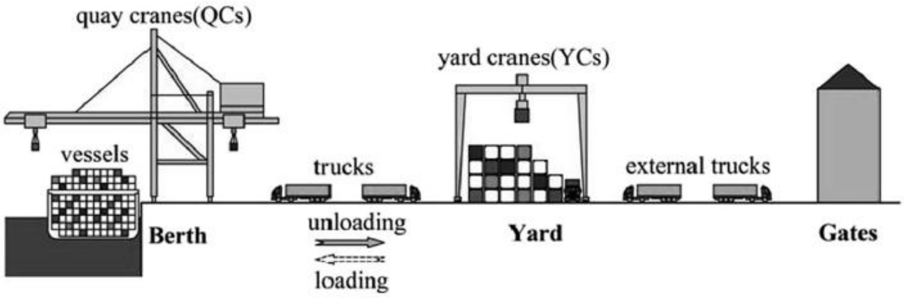

Figure 1. The equipment in container terminals [3].

The energy consumption level of ships can be divided into three components, namely: (1) energy consumption when the ship sails in the waterway, (2) energy consumption when the ship is waiting at the port, and (3) energy consumption when the ship is berthing at seaport. Based on Korean Environmental Industry and Technology Institute, 2016 in [7], this paper used emission density values published by a South Korean organization as a basis for estimating carbon emissions produced in South Korea (KLCI DB, 2016). The carbon density values of the major vessel and equipment activities are shown in Table 2.

Table 2. The carbon emission density of major vessel and equipment activities.

Activity	CO_2-e (kg/TEU)
Container ship maneuver	1.99000
Container ship at berth	0.02324
Quay crane	1.39000
Yard truck	0.04287
Yard crane	0.06873
Container trailer	0.38645

2.1. *CO_2 emission calculation for vessels*

The vessel emissions at the hoteling phase are calculated using the following equation from Hu et al. [11]

$$E_{vessel} = \sum_p PO.t_s.LF.EF_p.FCF_p.C_y \quad (2)$$

Where: E_{vessel} is the total vessel emission while hoteling in kg of CO_2;
PO is the rated power (kW) of the auxiliary engine of the vessel,
t_s is the makespan or completion time in which the engine is used (hours),
LF is the load factor of the engine while the vessel is moored;
EF_p is the emissions factor kg CO_2/kWh for each pollutant p considered,
FCF_p is the fuel correction factor for each emission factor, to replicate changes in the fuel properties over time
C_y is the number of cylinders of the auxiliary engines of the vessel.

2.2. CO_2 emission calculation for QCs
A QC is an electrical machine that does not emit CO_2 directly, but the electricity used, was previously generated through a process with CO_2 emissions. According to Geerlings and Van Duin [6] the QCs' energy consumption is considered fixed per handled container, with a fixed value of 6 kWh/container. Thus, the CO_2 emission during the crane operation can be calculated as:

$$E_{cranes} = \sum_k C_s . W_k . EFC_k \quad (3)$$

Where: $E_{\ cranes}$ is the total crane emission in kg of CO_2 during the loading/unloading process,
C_s is the fixed energy consumption for a QC, in kWh/container,
W_k is the amount of containers handled by each QC k,
EFC_k is the emission factor per electric QCs, in kg of CO_2/kWh;
k changes from 1 to n, which is the total number QCs used.

In this paper, the system dynamics simulation model is applied to help decision makers in solving the complex systems problem to minimize the total carbon emissions in container terminals in spatial and multi-temporal integration. The steps needed for system dynamics modeling and simulating of complex systems based on systems thinking are: (1). Identify the problem. (2). Develop a dynamic hypothesis explaining the cause of the problem. (3). Create a basic structure of a causal graph. (4). Augment the causal graph with more information. (5). Convert the augmented causal graph to a system dynamics flow graph. (6). Translate a system dynamics stock-flow graph into Powersim programs and equations [12].

3. Problem description
Based on real data at the port, the number of vessel calls can be 10 calls/week up to 60 calls/week. Quay cranes can process loading and unloading containers from and to vessels between 25 to 35 TEUs/h. The yard tractor moves at an average speed of 25 km/h and the handling capacity of each block is 25 TEUs/h. The number of loading containers may differ a lot between vessels of different sizes to simulate real conditions in container ports. The number of loading containers for one service call can reach 3600 TEUs and not less than 400 TEUs. For various types of loading tasks, mooring productivity may be different.

In this paper, the sets of parameter used in the system dynamics simulation model are as follow: the vessel arrival rate is Uniform Discrete distribution, UD [3,15] vessel calls/day at container terminals that have berth capacity of 20 vessels. The number of handled containers per vessel by Normal distribution with mean of 500 TEUs and standard deviation of 150 TEUs. Quay crane productivity rate Uniform Discrete distribution, UD [500,600] TEUs/day. While the amount of carbon emission density of vessel and equipment activities in kg/TEU is shown in Table 2, with the proportion of carbon emissions of the idle quay crane is about 3% of the carbon emission of quay crane in operating.

4. Model development
Total carbon emissions at container terminals are generated from the arrival of ships and the operation of all cargo handling equipment. In the process of arrival of ships at container terminals, carbon emissions are generated from the transport vessel and loading unloading vessel. Whereas carbon emissions from cargo handling equipment consist of quay crane processing, idle quay cranes, container truck transport and crane processing yards. Vessel arrival rate at berth is uncertain and is limited by berth capacity and the number of vessels still awaiting service on berth, while the vessel rate depends on the number of vessels in berth and container handling rate by quay cranes and the number of containers per vessel. The container handling rate by quay cranes is influenced by the number of containers that must be served and the number of quay cranes assigned to service each vessel. The number of quay cranes assigned to service each ship depends on the quay crane productivity rate and the number of quay cranes available at the container terminal. The number of containers in the storage container yard is affected by the capacity of container trucks and the capacity of yard cranes available. The relationship between variables in system dynamics in container terminals

is illustrated in the Causal Loop Diagram as shown in Figure 2 and Stock and Flow Diagram in Figure 3.

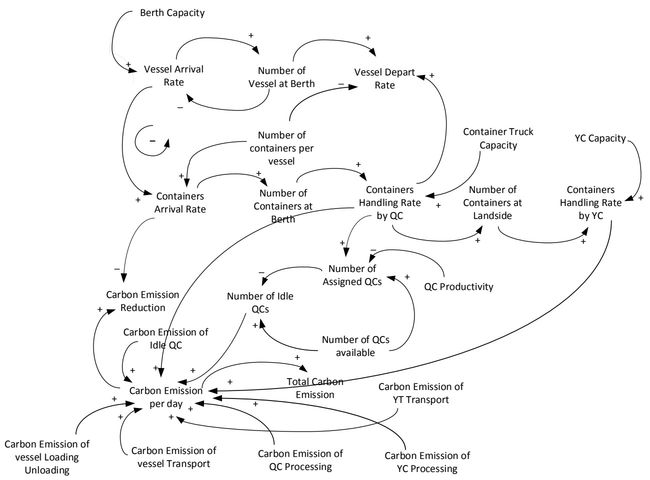

Figure 2. Causal Loop Diagram for system dynamics model of carbon emissions at container terminal.

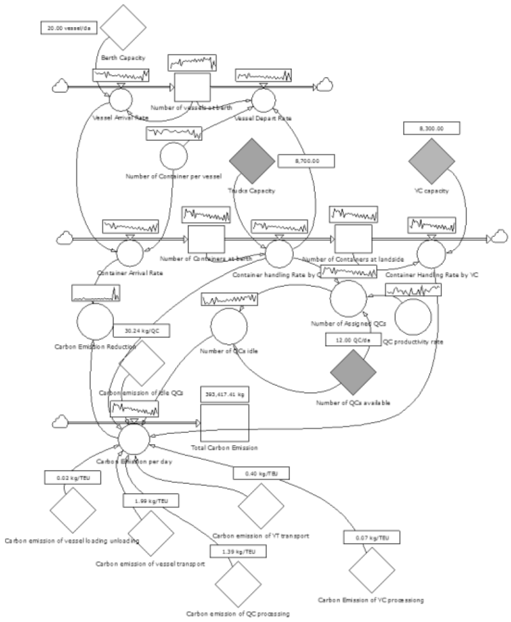

Figure 3. Stock and flow graph for system dynamics model of carbon emissions at container.

List of equations for each variable in the system dynamics model for minimizing the total carbon emissions is shown in Figure 4 below.

Name	Unit	Definition
Berth Capacity	vessel/da	20<<vessel/da>>
Carbon emission of idle QCs	kg/QC	30.24<<kg/QC>>
Carbon emission of QC processing	kg/TEU	1.39<<kg/TEU>>
Carbon emission of vessel loading unloading	kg/TEU	0.02324<<kg/TEU>>
Carbon emission of vessel transport	kg/TEU	1.99<<kg/TEU>>
Carbon Emission of YC processing	kg/TEU	0.06873<<kg/TEU>>
Carbon emission of YT transport	kg/TEU	0.39645<<kg/TEU>>
Carbon Emission per day	kg/da	('Carbon emission of vessel loading unloading'+'Carbon emission of vessel transport'+'Carbon emission of QC processing')*'Container handling Rate by QC'+('Carbon emission of YT transport'+'Carbon Emission of YC processiong')*'Container Handling Rate by YC'+'Carbon emission of idle QCs'*'Number of QCs idle'
Carbon Emission Reduction	kg/TEU	'Carbon Emission per day'/'Container Arrival Rate'
Container Arrival Rate	TEU/da	'Vessel Arrival Rate'*'Number of Container per vessel'
Container handling Rate by QC	TEU/da	MIN('Trucks Capacity','Number of Containers at berth'/TIMESTEP)
Container Handling Rate by YC	TEU/da	MIN('Number of Containers at landside'/TIMESTEP,'YC capacity')
Number of Assigned QCs	QC/da	CEIL(MIN('Container handling Rate by QC'/'QC productivity rate'/TIMESTEP,'Number of QCs available'),1<<QC/da>>,0<<QC/da>>)
Number of Container per vessel	TEU/vessel	ROUND(NORMAL(500<<TEU/vessel>>,150<<TEU/vessel>>,0.5),1<<TEU/vessel>>)
Number of Containers at berth	TEU	2000
Number of Containers at landside	TEU	3000<<TEU>>
Number of QCs available	QC/da	12<<QC/da>>
Number of QCs idle	QC/da	'Number of QCs available'-'Number of Assigned QCs'
Number of vessels at berth	vessel	3
QC productivity rate	TEU/(da*QC)	ROUND(RANDOM(500<<TEU/da/QC>>,600<<TEU/da/QC>>,0.5),1<<TEU/da/QC>>)
Total Carbon Emission	kg	0<<kg>>
Trucks Capacity	TEU/da	8700<<TEU/da>>
Vessel Arrival Rate	vessel/da	MIN('Berth Capacity'-'Number of vessels at berth'/TIMESTEP,ROUND(RANDOM(8<<vessel/da>>,15<<vessel/da>>,0.5),1<<vessel/da>>))
Vessel Depart Rate	vessel/da	FLOOR(MIN('Number of vessels at berth'/TIMESTEP,'Container handling Rate by QC'/'Number of Container per vessel'),1<<vessel/da>>,0<<vessel/da>>)

Figure 4. List of equations for system dynamics model of carbon emissions at container terminal.

5. Results and discussion

The system dynamics simulation model has run for 30 days to evaluate carbon emissions per day (Figure 5). Based on the available berth capacity, the minimum total carbon emission for 30 days is

393.42 tonnes that obtained by the optimal number of quay cranes is 12 QCs, capacity of container trucks is 8700 TEUs and yard cranes capacity of 8300 TEUs.

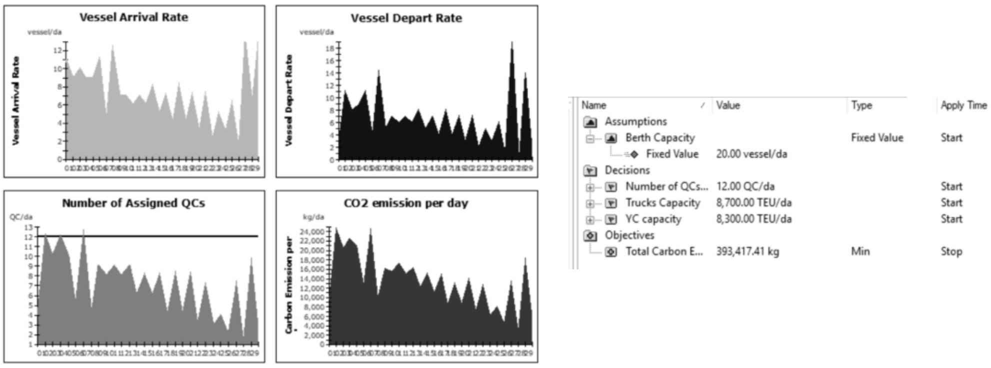

Figure 5. Simulation results of system dynamics model of carbon emissions at container terminal.

6. Conclusions

In this paper, an optimization model has been developed to minimize total carbon emissions in container terminal operations under the uncertainty environment by using a system dynamics simulation model approach. The minimum of total carbon emissions depends on the optimal number of assigned quay cranes for each vessel, the capacity of available container truck and yard cranes in the container terminal. For further research, a total carbon emission model can be developed with taking into account the technological advances in cargo handling equipment.

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References

[1] Wilmsmeier G and Spengler T 2016 Energy consumption and container terminal efficiency *Facilitation of Transport and Trade in Latin America and The Caribbean* **6** 1-10.

[2] Wilmsmeier G 2012 Energy consumption and efficiency : emerging challenges from reefer trade in South American container terminals *FAL Bull*. **329** 1–9.

[3] Yun P, Xiangda L, Wenyuan W, Ke L, and Chuan L 2018 A simulation-based research on carbon emission mitigation strategies for green container terminals *Ocean Eng.* **163** 288–98.

[4] Yang Y C and Lin C L 2013 Performance analysis of electric-rubber tired gantries from a green container terminal perspective *Transp. Res. D.* **23** 9–11.

[5] Acciaro M, Ghiara H, and Cusano M I. 2014 Energy management in seaports: a new role for port authorities *Energy Policy* **71** 4–12.

[6] Geerlings H and van Duin R 2011 A new method for assessing CO2-emissions from container terminals: a promising approach applied in Rotterdam *J. Cleaner Prod.* **19** 657–66.

[7] Sim J 2018 A carbon emission evaluation model for a container terminal *J. Cleaner Prod.* **186** 526–33.

[8] Group R 2006 Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals ISO 14064-1. 2006.

[9] Eggleston H S, Miwa K, Srivastava N, and Tanabe K 2006 IPCC Guidelines for National Greenhouse Gas Inventories – A primer *Intergov Panel Clim Chang (IPCC)* 1-20.

[10] Liu D and Ge Y 2017 Modeling assignment of quay cranes using queueing theory for minimizing CO 2 emission at a container terminal *Transp. Res. D.* 1–12.

[11] Hu Q, Hu Z, and Du Y 2014 Berth and quay-crane allocation problem considering fuel consumption and emissions from vessels *Comput. Ind. Eng.* **70** 1–10.

[12] Bala B K, Arshad F M, and Noh K M 2017 *System Dynamics: Modelling and Simulation* (Singapore: Springer Science Business Media Singapore).