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Optimising truckload operations in third-party logistics: a carbon footprint perspective in volatile supply chain

Abstract

With government and customers driving third-party logistics seeking opportunities to improve operation efficiencies and mitigating carbon emissions in the supply chain, third-party logistics firms have been striving to improve their truckload utilization and vehicle routing operations, especially in emission-regulated countries and volatile business environment. Traditional literature has focused on either truckload utilization or vehicle routing operations but seldom integrating carbon emission mitigation in their daily trucking operations. This paper delineates the operation review of three third-party logistics firms in Hong Kong and develops an organisation-based carbon emission measurement metrics for logistics operations. The truckload utilization and routing performance are reviewed, followed by a correlation analysis on the truckload utilization against truck capacity, loading volume, fuel consumption, truck size, travelling distances and number of destinations. An integrated carbon-driven multi-criteria model is developed achieving carbon emission reduction initiatives, time and distance cost penalty, minimizing number of trucks, and improving truck utilization. The integrated mathematical model has been developed into a simulation system which has been tested with evaluated results. The mathematical model is enhanced for the set of cargo items and vehicle fleet with additional factors of arrival time slots and weight. The model assists traffic planners to reduce cargo planning time and optimize the truckload operations. Further development will be focused on adding the dimensions of pallet loading operations and exception rules for customer loading requirements.

Keywords: Carbon emission, third-party logistics, sustainability, truckload utilisation

1. Introduction

Increasing pressure from customers and government for greenhouse gas (GHG) emission mitigation as well as motivation towards corporate social responsibility underpins a driving force in third-party logistics (3PL) firms. Not only do they aim at reducing operation costs but also quantifying and reducing carbon emission activities in warehouse and truck operations. Carbon emission reduction initiatives in logistics and transportation operations were discussed in the World Economic Forum in July 2013 (Le Quéré, 2014; Doherty et al., 2013). Government in the

United States issued an Executive Order in March 2015 to cut Federal Government's GHG emission 40 percent over the next decade and encourage Federal suppliers to set similar goals to bring GHG reduction commitment across the supply chain. The combined total GHG reduction commitment, together with the suppliers, including IBM, General Electric, Honeywell, ADS Inc., and Hewlett Packard, could be up to 5 million metric tons between 2008 and 2020 (The White House, 2015). In October 2014, the Singapore Stock Exchange (SGX) announced a sustainability-reporting mandate across all listed companies, including those in the logistics and transportation sector (Shah and Cheam, 2014). The Hong Kong Stock Exchange (HKEx) also announced that companies could voluntarily provide sustainability reports with best practice recommendations (HKEx, 2012).

Facing the global sustainability trend on carbon reduction initiatives carried out by leading logistics firms, other 3PL firms face fierce challenges in tackling the competition on pricing strategy, operations costs, corporate image and marketing, fuel price fluctuation, and operation efficiencies while exploring opportunities to mitigate carbon emissions in daily operations (Mohammed et al., 2017; Chanchaichujit et al., 2016; Konur, 2014; Ji et al., 2014; Pan et al., 2013). Hong Kong-based logistics corporations usually focus on profit margin and cost efficiency but find difficult to incorporate emission mitigation in their trucking operations, considering limited knowledge, resource and available tools. To meet the needs of improving operation efficiency and reducing carbon emission during the consolidation of thousands of boxes into trucks each week, 3PL firms require a systematic and intelligent system to plan for loading various boxes on different pallets and packed into the trucks for cargo delivery, with consideration of box size, arrival time, truck size, pallet size, and destinations (Levesque, 2011). This paper presents an analysis on the operation reviews of three global 3PL firms in Hong Kong and investigates the statistical relationship between dominant factors in carbon emission associated operations parameters. The performance measurement and sustainability reporting of 3PL firms are discussed. Upon the statistical analysis and sustainability performance measures, a carbon-driven bin packing model is developed, followed by simulations on three scenarios. A sensitivity analysis is carried out to evaluate the changes of time factors towards the carbon emission savings. Future development initiatives are recommended.

2. Truckload operations in third-party logistics

A new 3PL business model for logistics and physical distribution evolved in U.K. in the early 1990s (Kimura, 1998). The evolution of 3PL in simulating companies outsourcing logistics services to third-party operators in UK has been driven by factors in operation globalization, focusing of core business, and new business search by transport companies under deregulation and increased competition. Ackerman and Wise (1985) presented the early state of third-party warehousing in the Council of Logistics Annual Conference. Lieb (1992) described 3PL as the use of external companies to perform logistics functions that have traditionally been performed within an organization. The functions performed by the third-party can encompass the entire logistics process or selected activities within that process. In the early 2000s, 3PL is included in contract logistics and defined as multiple logistics services provided by a single vendor on a contractual basis (Lewis and Talalayevsky, 2000; Razzaque and Sheng, 1998). Aicha (2014) reviewed the outsourcing of logistics activities and the selection of 3PLs in the past two decades with the consideration of logistics services in transportation, distribution, warehousing, inventory management, packaging and reverse logistics. In recent years, globalization, offshoring, and complex supply chain network have incited the expansion of firms specializing in transport and logistics services (Williams, 2014; Selviaridis and Spring, 2007; Kholer, 2001). Companies tend to outsource logistics activities in order to focus on their core competencies, such as manufacturing, wholesaling and retailing. The role of 3PL is becoming more prominent in the 21st century as a professional logistician in providing services, including warehousing, cargo consolidation, distribution, customs, documentation, multi-modal transportation, and supply chain management (Jaafar and Rafiq, 2017; Mehmann and Teuteberg, 2016; Ajakaiye, 2012; Chin et al., 2010).

Whether a 3PL firm can fully utilize the spaces in trucks affects its operation costs and carbon emissions. Improving truckload utilization lowers operation cost, increases revenue, lessens the number of trucks used, and reduces congestion and pollution for the society (Centobelli et al., 2017; Abate, 2014; Van de Klundert and Otten, 2011; Min and Jong, 2006). Various analysis and modelling on truckload utilization have been carried out. Samuelsson and Tilanus (1999) developed a model to provide estimates on various measures for capacity utilization in regional less-than-truckload (LTL) distribution, considering the dimensions of time, distance, speed, and capacity. Hubbard (2001) described capacity utilization as high when trucks are hauled with a series of full loads with the support of computation tools and wireless networking applications. The utilization of each truckload is highly depended on the agglomeration of complementary demands into individual trucks. Tyan et al. (2003) evaluated the freight consolidation policies of global 3PL and developed a mathematical programming model to assist the evaluation of consolidation policies. Baykasoglu and Kaplanoglu (2011) proposed a multi-agent based load consolidation decision making approach for LTL orders to solve the complex interrelated factors including loading sequence, capacity limit, route selections, and cargo consolidation. Abate (2014) reviewed the capacity utilization in trucking considering the empty running and load factor. A joint econometric modelling framework is proposed for the truck utilization as a function of haul, carrier, and truck characteristics. Other truckload utilization literature includes Van de Klundert and Otten (2011), Baykasoglu et al. (2013), and Baykasoğlu and Kaplanoğlu (2015). Most of the literatures focused on modeling the truckload utilization based on time, distance, speed and capacity. A few of them successfully integrate truckload, utilization, departure and arrive time, and vehicle emission during the truckload planning and put them into real practices. There are lack of literature developing systematic and structured methodologies in carbon mapping and reporting in truckload operations of 3PL. These 3PL firms lack knowledge and skills in calculating and mitigating carbon emission in the warehouse and truck operations. This paper addresses these issues by building a framework and method in carbon reporting in logistics firms, analysing critical factors on truck load utilization, and developing novel optimisation model to improve truckload utilization and reduce the carbon emitted from truck operations.

3. Performance measurement in truckload utilization, carbon emission, and operation cost

Due to the extensive use of logistics services, there is a growing concern among customers and governments about greenhouse gases emitted from transportation and logistics services (EPA, 2013; EIA, 2012). This has pushed 3PLs in seeking ways to map out the carbon footprint and reduce carbon emission in their daily operations (Sathaye et al., 2010; Léonardi and Baumgartner, 2004). Thus, recent truckload utilization problems are linked, not only with operation efficiency, but also with the volume of carbon emission. Christie et al. (2006) presented the applications of vehicle logistics optimisation to minimise operation costs, save energy sources, and meet international protocol on greenhouse gas emission reduction targets. Sathaye et al. (2010) evaluated the cargo load consolidation and load factors together with freight truck trips, gross vehicle weight and pavement maintenance to mitigate road congestion and carbon emissions. Pishvaee et al. (2012) addressed the problem of supply chain network design under uncertain conditions by developing a bi-objective mathematical programming model with its objective functions on minimizing the total cost and maximizing the supply chain social responsibility. LINGO 9.0 optimization software is adopted to solve the proposed Robust possibilistic programming (RPP) model. Knour (2014) analysed an integrated inventory control and transportation model under the constraint of carbon cap, using truck costs and capacities as measurement. A heuristic search model was further proposed to solve the costs and emissions optimisation problem in inbound transportation. Other similar investigations in improving transportation operation and carbon emission with systematic measurement are Velázquez-Martínez et al. (2014), Carrano et al. (2015) and Nielsen et al. (2015).

The measurement of sustainable development and the management of environmental impact were among the issues raised in the World Economic Forum in January 2015 (World Economic Forum, 2015). Carbon emission is of high importance in sustainability reporting. The sources of carbon emission in logistics firms, including electricity consumption, warehouse operations, vehicle emissions, use of paper, carton boxes, and wooden pallets, are expected to be measured, analysed and reported regularly. Through performance measurements and sustainability reporting, carbon emission reduction initiatives could be further explored and executed. Integrating sustainability to performance measurements becomes crucial to logistics service providers when they are required to fulfill the requirements of customers and statutory regulations (Schaltegger and Burritt, 2014; Lee and Wu, 2014; Beske and Seuring, 2014; Colicchia et al., 2013; Green et al., 2012). Lieb and Lieb (2010) conducted an extensive survey with 40 large 3PL companies on their commitment to environmental sustainability goals and found that most of them have started to launch sustainability projects even under the global recession of 2008-2009. How to integrate data analytics in sustainability reports and improvement of operation efficiencies should be explored. Hallstedt et al. (2010) developed an approach to assess sustainability integration in a company's strategic decision system, based on established guidelines and a Bob Willard scale of sustainability integration. The performance of two companies was reviewed and it was found that there are potential ways to improve in sustainability integration. Bourlakis et al. (2014) examined the sustainability performance of a Greek dairy chain, with key performance factors related to efficiency, flexibility, responsiveness and product quality. Lee and Wu (2014) adopted a multi-methodology to integrate sustainability performance measurement into logistics and supply networks. The developed method supported the decision-making process on green practices of freight transport logistics. Ahi and Searcy (2015) proposed a mathematical model to assess sustainability in the supply chain after evaluating the dependent factors that impact sustainability performance. They carried out an extensive literature review on the identification and analysis of the metrics on green and sustainable supply chain management. McKinnon (2016) focused on developing transport decarbonisation frameworks, deriving various approaches in estimating fuel efficiency and carbon emission in freight transport, and analysing the impact of speed reduction towards carbon emission mitigation. Various studies on measuring and forecasting carbon footprint of road freight transport have also been carried out by McKinnon and Piecyk (McKinnon and Piecyk, 2009; McKinnon, 2007; Piecyk and McKinnon, 2010, McKinnon, 2014).

Other literature on 3PL services that seek to measure, and audit operation and energy efficiencies included Min and Jong (2006) and Mckinnon and Hr (2007). In practice, 3PLs encounter high fuel cost, continuously price cutting strategies and fluctuating economic changes in recent years, carbon emission initiatives are often limited to conceptual and theoretical stages instead of incorporating into daily operations. Banker et al. (2016) indicated that companies with their own fleets will be pushed by sustainability programs to reduce the emission from transportation far more quickly than companies employing carriers to move their goods. However, there are lack of methodologies in mapping out the overall carbon emissions in a 3PL firms for a designated duration. Most of the 3PLs have not devoted much resources in carbon reporting and mitigation, thus hindering the development of sustainability performance in logistics and transport industry. This paper illustrates the importance in filling the gap between the theories and practices in establishing the principles of quantifying direct and indirect carbon emissions in logistics firms and putting them into carbon emission mitigation practice in the warehouse and trucking operations of 3PLs.

4. Operations review and carbon reporting

Opportunities in process and system enhancement in logistics operations could be identified through reviewing the end-to-end process, from customer order to products arriving customer premises. Operations reviews and process mappings have been conducted with three 3PL firms. The first 3PL firm is headquartered in Hong Kong, providing transportation, relocation services, logistics and storage services with business covering over 60 countries with about 4600 employees. The operations review and carbon mapping here focus on the cosmetic products in the warehouses of Hong Kong. The second logistics firm is also a Hong Kong-based logistics company specializing hub distribution operations and value-added services for multinational and local brands, including household accessories and fast-moving consumer goods (FMCG). The analysis in this project focuses on the office, warehouse and trucks for the household accessories products, covering about 100 employees. The third firm has major operations in both U.S. and Asia, covering air and sea freight and serving electronics, healthcare and automotive industry, with about 50 employees in Hong Kong offices. The operation review focused on the entire process, starting from customer issuing orders with customer service; customer service officers preparing document forms; warehouse operators perform pick and pack procedures; warehouse workers carry out value-added services; traffic officers schedule delivery orders, consolidate cargos into boxes and pallets, and plan pallets into trucks; to drivers executing the product delivery from warehouse to customer premises.

Upon the operations review, the highlighted common issues encountered in 3PL operations are low truckload utilization and lack of scientific method in optimizing cargo consolidation into trucks. It showed that little attention has been put on planning the best route for truck delivery and no measurement has been taken on the volume of carbon emitted from trucks. In this paper, operations data are collected together with the factors affecting truckload utilization and carbon emissions. The amount of carbon emitted from the operations carried out in the firms are quantified and evaluated. A carbon report is produced with reference to the greenhouse gas reporting and accounting methodology of ISO14064 (Toffel and Van Sice, 2011; Pandey et al., 2011; Weng and Boehmer, 2006). The protocol of ISO14064 covers three major scopes. Scope 1 includes direct emissions from sources that are owned or controlled by the reporting entity and concerns both stationary and mobile combustion. Scope 2 refers to indirect emissions from the sources owned and controlled by another entity. Scope 3 comprises other indirect emissions associated with the activities of the company. A 24-month carbon emission related activity data in the warehouses, trucks, and offices are collected in the companies, including fuel and electricity consumption, paper usage, fire extinguisher quantities, are manipulated in the scoping framework as shown in Figure 1. Types of truck vehicle with different sizes, fuels and emission factors respectively are included in the manipulations. The vehicle fleet size of the three companies analysed ranges from 4 trucks to 15 vehicles including trucks and vans. The trucks range from 3.3 to 16 tonnes. Various sites with electricity supplied from different power stations are considered with respective to their respective emission factors.

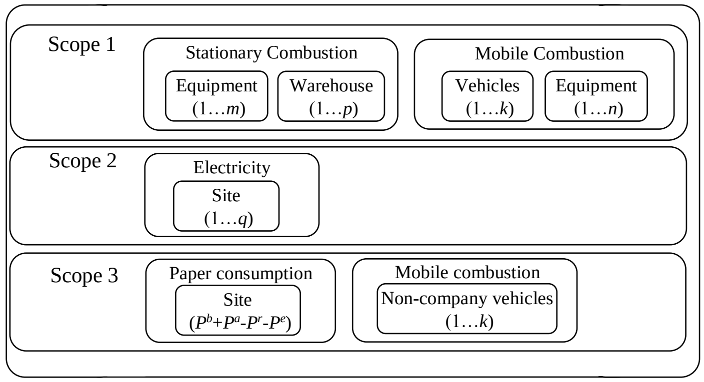

Figure 1. Carbon emission mapping in third-party logistics operations under ISO14064 protocol

The principles of quantifying carbon emission lie on activity data (*AD*), emission factor (*EF*) and global warming potential (*GWP*):

$$\text{Carbon emission } (E) = AD \times EF \times GWP \quad (1)$$

where *AD* refers to data on the magnitude of human activity resulting in emissions or removals taking place during a given period of time, *EF* represents a value relating the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant and *GWP* is a relative measure on how much heat a greenhouse gas is trapped and impacted the atmosphere. An activity-based approach is used for carbon emissions from trucks and fire extinguishers while an energy-based approach is adopted when quantifying electricity consumption. The stationary and mobile combustion in Scope 1 is calculated as follows:

$$Emission\left(E^{SM}\right) = \left[\sum_{i=1}^{m} AD_i^{se} \times EF^{se} + \sum_{i=1}^{p} AD_i^{sw} \times EF^{sw} + \sum_{i=1}^{k} AD_i^{mw} \times EF^{mw} + \sum_{i=1}^{n} AD_i^{me} \times EF^{me}\right] \times GWP \quad (2)$$

The electricity consumed in Scope 2 is expressed as

$$Emission\left(E^{e}\right) = \sum_{i=1}^{q} EC_i \times EF^{e} \quad (3)$$

where EC_i is the electricity consumption at site *i*.

The paper consumption, represented by emission from paper waste disposed at landfills, is derived by deducting paper collected for recycling (P_i^r) and paper inventory at the end of reporting period (P_i^e) from paper inventory at the beginning of reporting period (P_i^b) and paper added into inventory during reporting period (P_i^a).

$$Emission\ from\ paper\ waste\ disposed\ at\ landfills\ (E^p) = \sum_{i=1}^{q} \left(P_i^b + P_i^a - P_i^r - P_i^e\right) \times EF^p \tag{4}$$

The highlights of the results in a measured period on one of the companies are shown in Table 1, with considerations of data confidentiality. For many freight forwarding practitioners these results bring into question of whether there is a standard level of carbon emission in the industry. It could be seen that electricity and truck emissions contribute to the major emissions of the companies while the largest source of emission varies among different companies, depending on the focus of business, number of trucks owned and office environment. The carbon report of one of the pilot companies reveals that scope 1 contributes to the highest emission. The high emission volume in cargo loading trucks and forklift trucks reveals the need of using electrical forklift trucks and developing a truckload and vehicle routing optimisation model. The results of carbon reporting also reflect the need for showing density in performance indicators, e.g. emissions per pallet delivered, per truck, and per square feet of warehouse.

Table 1. Highlights of carbon reporting in the operations of a third-party logistics firm

Scope	Activity data type	Activity data details	Activity data		Emission factor		Global warming potential	Total carbon emission (ton CO_2-e)
			Value	Unit	Value	Unit		
Scope 1	Mobile combustion	Petrol and Diesel of medium goods vehicle light goods vehicle, motorcycle, and private vans.	37,373.4	Liter	2.404122-2.772372	kg CO_2-e/ Liter	CO_2: 1 CH_4: 21 N_2O: 310	102.98
Scope 2	Electricity	Electricity consumption on China Light and Power (CLP)	70,680.0	KWh	0.63	Kg CO_2-e / KWh	-	44.53
Scope 3	Paper	Paper consumption	3820.5	Kg	4.8	Kg CO_2-e / kg	-	18.34
Total carbon emissions								165.85

The result of total volume of carbon emission obtained in Table 1 provides managerial insights and implication on carbon emission mitigation with respect to emission volume, activity type, customer impact and supplier concerned. The figures and trends shown also support managerial decisions on truck usage and supplier selection. Based on the mitigation plan, statistical data analysis, factor correlation review, and truckload optimisation theoretical models could then be developed to achieve carbon emission mitigation targets.

5. Correlation and regression analysis

The relation between crucial factors impacting operation efficiencies and carbon emission in the first company described in Section 4 is analyzed. The factors reviewed include Utilization (*U*), Carbon emission (*E*), Cargo loaded volume (*V*), Fuel consumption (*F*), Number of destinations (*N*), Capacity (*C*), Unused space (*S*), and Truck type (*T*) of each truck. With reference to the mean, standard deviation, and the estimates on the coefficient of correlation among these variables being collected and analysed, all the pairwise correlation coefficients are statistically significant as shown in Table 2. The truckload utilization is highly correlated with loading volume, fuel consumption, number of destinations, truck capacity and truck type. The carbon emission is positively correlated with the unused space. A regression analysis is further conducted on the truckload utilisation and carbon emission against the other six factors. All factors are found significant in estimating truckload utilisation and truck carbon emission individually. Table 3 shows a further analysis with all factors being examined simultaneously. Besides, capacity and volume are found significant in the truckload utilisation and large R^2 being determined. Fuel consumption and unused space are revealed to be critical to carbon emission in the truckload planning and operations. Leonardi and Baumgartner (2004) intended to identify the most important factors influencing CO_2 efficiency. Using survey instead of data collection in a company, the results from the correlation analysis were different, with vehicle load weight and vehicle class as factors found critical to the emission mitigation in road freight transportation. Diaz-Ramirez et al. (2017) conducted related studies recently and found in freight fleet data that drivers' experience, driving errors, average speed and weight-capacity ratio are highly relevant to fuel consumption and sustainability.

Table 2. Estimates of Pearson correlation coefficients

	U	*E*	*V*	*F*	*N*	*C*	*S*	*T*
U	1	-0.6632	0.9023	0.6361	0.7072	0.5204	-0.8601	0.5675
		(<.0001)	(<.0001)	(<.0001)	(<.0001)	(<.0001)	(<.0001)	(<.0001)
E		1	-0.6551	-0.4486	-0.6556	-0.5066	0.7391	-0.5389
			(<.0001)	(<.0001)	(<.0001)	(<.0001)	(<.0001)	(<.0001)
V			1	0.815	0.8421	0.8129	-0.8734	0.8210
				(<.0001)	(<.0001)	(<.0001)	(<.0001)	(<.0001)
F				1	0.8328	0.8142	-0.7886	0.8774
					(<.0001)	(<.0001)	(<.0001)	(<.0001)
N					1	0.7758	-0.8295	0.8451
						(<.0001)	(<.0001)	(<.0001)
C						1	-0.6887	0.9289
							(<.0001)	(<.0001)
S							1	0.7830
								(<.0001)
T								1

Table 3. Estimates of regression analysis on independent variables

Response	Predictors	Coefficients	Standard error	R^2	Adjusted R^2	*F* Value	*p*-value
Utilization	Intercept	0.8681*	0.050	96.88%	96.62%	373.17	<0.0001
	V	0.0590*	0.003				
	F	-0.0016	0.002				
	N	-0.0015	0.002				
	C	-0.0342*	0.005				
	S	-0.3874*	0.058				
	T	-0.0137*	0.005				
Emission	Intercept	0.0320	0.061	65.49%	62.62%	22.78	<0.0001
	V	-0.0010	0.003				
	F	0.0089*	0.002				
	N	-0.0074*	0.003				
	C	-0.0047	0.006				
	S	0.3414*	0.070				
	T	-0.0004	0.007				

Note: * Significance at 5%.

Having the correlation among carbon emission, fuel consumption, number of destinations and utilization being analyzed, the important factors associating and impacting truckload utilization and carbon emission are identified. To further evaluate the relationship between fuel consumption and distance, a regression analysis is carried out on the two factors using 52 trucks on their fuel consumption and travelled distance per day. The relationship is shown in equation (5) with α_k and β_k equals to 3.4664 and 0.1240, and the p value is 3.93×10^{-8}, which less than 0.05.

$$\text{Fuel consumption } F \text{ of truck } k = \beta_k \times D_k + \alpha_k \tag{5}$$

6. Carbon-driven multi-criteria truckload utilization optimization model

To improve the truckload utilization and reduce the volume of carbon emitted from trucks, a carbon-driven multi-criteria truckload utilization model is developed. The proposed model aims to optimize the loading of consolidated cargos from multiple customers with different sizes, weight, and destinations into a fleet of trucks with minimum distance and fuel consumption. This improves the operation efficiencies and minimizes the carbon emitted from trucks.

Assumptions

The fundamental assumptions used in this literature is that all cargos are measured in cubic-meter (*cbm*), which is widely used in the third-party logistics as one of the fundamental measures.

Assumption 1. There is no service disruption, for example, truck engine breakdown, traffic accident, strike, typhoon and severe weather environment. The cargo distribution and truckload planning are optimized in a normal regular fashion. Contingency recovery plan is required beyond the truckload optimization plan.

Assumption 2. The pallets sizes and capacity are not affecting the loading of cargo items and the utilization of the truck.

Assumption 3. The total number of trucks operating for the logistics service has no change, with size of trucks and pallets used are remaining unchanged.

The model includes the notation, decision variables, derived variables, and objective function to allow representation on defined number of trucks, available capacity, cargo loaded volume, cargo destinations and cargo weight. Time and distance penalties are considered to ensure the departure time and arrival time meet the required timeslots.

Notations

The logistics operations are modelled with the notations described as follows. The cargo item and truck are represented by subscripts while the departure and arrival time are shown in the superscripts.

E	the total carbon emission in the third-party logistics operations,
U	the utilization of truck *k* departed warehouse,
P	the penalty cost of a cargo item with departure delay and additional distance travelled,
N	the total transportation cost of trucks per day.

The followings are the input data for the model

K	the set of trucks available per day,

For each $k \in K$, let

E_k	the emission of truck *k* per day,
C_k	the capacity of truck *k* in *cbm,*
L_k	the maximum loading of truck *k* in kg,
D_k	the distance of planned route for truck *k*,
t_k^D	the actual departure time of truck *k*,
t_k^A	the actual arrival time of truck *k*,
h_k	the destination of truck *k*,
c_k	the cost of truck *k*,
α_k	the intercept of relationship between fuel consumption and distance travelled,
β_k	the slope of relationship between fuel consumption and distance travelled,
z_k	the multiplied factor between emission factor and global warming potential of the greenhouse gases emitted by truck *k*,

I	the set of items to be delivered
	For each $i \in I$, let

$\hat{\tau}_i^D$	the planned departure time of item *i* from warehouse,
$\hat{\tau}_i^A$	the planned arrive time of item *i* at destination,
g_i	the destination of item *i*,
v_i	the volume of item *i* in *cbm*,
w_i	the weight of item *i* in kg,
p_i^{ED}	the penalty for early departure of item *i* per unit time,
p_i^{LD}	the penalty for late departure of item *i* per unit time,
p_i^{EA}	the penalty for early arrival of item *i* per unit time,
p_i^{LA}	the penalty for late arrival of item *i* per unit time,
R	the number of destinations,
$A(r_1,r_2)$	penalty cost when the destination of an item is r_1 and it is on a truck with destination r_2,
M	a big number.

The derived variables are

τ_i^D	the actual departure time of item *i* from warehouse,
τ_i^A	the actual arrive time of item *i* at destination.

The traffic planning manager is to decide which item to be loaded to which truck. The decision variables are

X_k	= 1 if truck *k* is in use; = 0 otherwise.
Y_{ik}	= 1 if item *i* is loaded to truck *k*; = 0 otherwise.

Define two auxiliary variables by

S_i^D	= 1 if item *i* departs early; = 0 otherwise.
S_i^A	= 1 if item *i* arrives early; = 0 otherwise.

Objective function

To implement the optimal truckload plan with consideration of truckload utilisation, transportation cost, carbon emission, arrival time and departure time, a multi-objective objective function is derived. The fuel consumption is revealed to be critical to carbon emissions as shown in the earlier section. Define Z by the utility of the operator which is given by $Z = \gamma_1 E + \gamma_2 P + \gamma_3 N - \gamma_4 U$. The formulation of the carbon-driven multi-criteria model is given by

$$min\, Z = \gamma_1 E + \gamma_2 P + \gamma_3 N - \gamma_4 U \quad (6)$$

where γ_1, γ_2, $\gamma_{3,}$ and γ_4 are the weighting factors.

(1) Total carbon emission:

$$E = \sum_{k} E_k \tag{7}$$

Fuel consumption *F* of truck *k*: $\beta_k \times D_k + \alpha \quad _k$

$$E_k = z \times (\beta_k \times D_k + \alpha_k) \times X_k \tag{8}$$

(2) Penalty cost: The penalty cost consists of

$$P = \sum_{i} P_i \tag{9}$$

The actual departure and arrival time of an item depend respectively on those of the truck it is loaded to:

$$\tau_i^D = \sum_{k} t_k^D Y_{ik} \tag{10}$$

$$\tau_i^A = \sum_{k} t_k^A Y_{ik} \tag{11}$$

for all *i*.

When an item is on the truck with destination other than its original destination, a penalty cost is incurred as an emergency transshipment is needed. We refer this case as "wrong destination". The total penalty cost consists of the penalty cost for wrong destination, penalty costs for early departure, late departure, early arrival and late arrival for each item.

The penalty cost for wrong destination is given by

$$\sum_{i} \sum_{k} Y_{ik} \times A(g_i, h_k) \tag{12}$$

The penalty cost for early departure for item *i* is given by

$$P_i^{ED} \times \left(\hat{\tau}_i^D - \tau_i^D\right) \times 1\left(\hat{\tau}_i^D - \tau_i^D > 0\right), \tag{13}$$

where 1(·) is an indicator function such that 1(·) = 1 when · is true and 1(·) = 0 when · is false. We then express (13) in terms of the binary variable S_t^D:

$$P_i^{ED} \times \left(\hat{\tau}_i^D - \tau_i^D\right) \times S_i^D \tag{14}$$

subject to an additional constraint

$$\hat{\tau}_i^D - \tau_i^D \leq M \times S_i^D, \tag{15}$$

which is equivalent to

$$\hat{\tau}_i^D - \sum_k t_k^D Y_{ik} \leq M \times S_i^D \tag{16}$$

We remark that (14) is not linear. Hence, for each $i \in I$, $k \in K$, introduce a binary variable b_{ik}^D by

$$b_{ik}^D = Y_{ik} S_i^D,$$

then (14) can be expressed as

$$P_i^{ED} \times \left(\hat{\tau}_i^D \times S_i^D - \sum_k t_k^D b_{ik}^D \right) \tag{17}$$

subject to additional constraints

$$b_{ik}^D \leq \frac{1}{2} Y_{ik} + \frac{1}{2} S_i^D,$$

$$b_{ik}^D \geq Y_{ik} + S_i^D - 1,\ i \in I, k \in K. \tag{18}$$

The penalty cost for late departure is given by

$$P_i^{LD} \times \left(\tau_i^D - \hat{\tau}_i^D \right) \times 1\left(\tau_i^D - \hat{\tau}_i^D \geq 0 \right), \tag{19}$$

which can be expressed in terms of S_i^D:

$$P_i^{LD} \times \left(\tau_i^D - \hat{\tau}_i^D \right) \times \left(1 - S_i^D \right), \tag{20}$$

subject to additional constraint

$$\tau_i^D - \hat{\tau}_i^D \leq M \times \left(1 - S_i^D \right), \tag{21}$$

which is equivalent to

$$\sum_k t_k^D Y_{ik} - \hat{\tau}_i^D \leq M \times \left(1 - S_i^D \right). \tag{22}$$

Since (20) is not linear, we then rewrite (20) as

$$P_i^{LD} \times \left(\sum_k t_k^D Y_{ik} - \sum_k t_k^D b_{ik}^D - \hat{\tau}_i^D \times \left(1 - S_i^D \right) \right). \tag{23}$$

By similar arguments in developing (14) and (20), we may write the penalty costs for early and late arrivals as

$$P_i^{EA} \times \left(\hat{\tau}_i^A \times S_i^A - \sum_k t_k^A b_{ik}^A \right), \tag{24}$$

and

$$P_i^{LA} \times \left(\sum_k t_k^A Y_{ik} - \sum_k t_k^A b_{ik}^A - \hat{\tau}_i^A \times \left(1 - S_i^A\right) \right), \tag{25}$$

with constraints

$$\begin{aligned} &\hat{\tau}_i^A - \sum_k t_k^A Y_{ik} \le M \times S_i^A, \\ &\sum_k t_k^A Y_{ik} - \hat{\tau}_i^A \le M \times \left(1 - S_i^A\right), \\ &b_{ik}^A \le \tfrac{1}{2} Y_{ik} + \tfrac{1}{2} S_i^A, \\ &b_{ik}^A \ge Y_{ik} + S_i^A - 1,\ i \in I, k \in K, \end{aligned} \tag{26}$$

where $b_{ik}^A = Y_{ik} S_i^A$.

The total penalty cost for item *i* is then given by

$$\begin{aligned} P_i = &\sum_k Y_{ik} \times A(g_i, h_k) + p_i^{ED} \times \left(\hat{\tau}_i^D \times s_i^D - \sum_k t_k^D b_{ik}^D \right) \\ &+ p_i^{LD} \times \left(\sum_k t_k^D Y_{ik} - \sum_k t_k^D b_{ik}^D - \hat{\tau}_i^D \times \left(1 - S_i^D\right) \right) \\ &+ p_i^{EA} \times \left(\hat{\tau}_i^A \times s_i^A - \sum_k t_k^A b_{ik}^A \right) \\ &+ p_i^{LA} \times \left(\sum_k t_k^A Y_{ik} - \sum_k t_k^A b_{ik}^A - \hat{\tau}_i^A \times \left(1 - S_i^A\right) \right), \end{aligned} \tag{27}$$

subject to constraints (16), (18), (22), and (26).

(3) Transportation cost:

$$N = \sum_k c_i X_k \tag{28}$$

(4) Utilization:

$$U = \sum_k U_k \tag{29}$$

$$U_k = \frac{Total\ CBM\ of\ cargo\ items\ on\ truck\ k}{CBM\ of\ truck\ k} = \frac{\sum_i v_i Y_{ik}}{C_k} \tag{30}$$

Constraints

The optimisation function is bounded by the constraints described as follows.

Constraint 1. Each cargo item *i* must be carried by one truck *k*

$$\sum_{k} Y_{ik} = 1 \tag{31}$$

for all *i*.

Constraint 2. Only serving trucks can carry items

$$Y_{ik} \leq X_k \tag{32}$$

for all *i*, *k*.

Constraint 3. The total volume of items in a truck *k* cannot be larger than the capacity of the truck

$$\sum_{i} v_i Y_{ik} \leq C_k \tag{33}$$

for all *k*.

Constraint 4. The total weight of items in a truck *k* cannot be larger than the maximum loading of the truck

$$\sum_{k} w_i Y_{ik} \leq L_k \tag{34}$$

for all *k*.

7. Simulation analysis

A carbon-driven multi-criteria model focusing on improving truckload utilization is firstly developed with the use of Excel Solver and Visual Basic Application (VBA) programming tools. The model has considered fuel consumption, carbon emission, cargo volume, cargo item leaving time, truck leaving time, cargo destinations, truck capacity, and truck destinations. The objectives and constraints are developed in the Solver optimisation engine model to determine the recommended allocation of cargo into truck by minimizing emissions of trucks per day, unused space of the truck per day, total penalty on time and distance, and number of trucks being used per day. The allocations of twenty cargo items of various sizes and destinations to six trucks of various capacities, destinations, and departure time slots are simulated with the data collected from the first 3PL firm described in Section 4. The total carbon emission is derived from the fuel consumption of trucks and the factor determined by $EF \times GWP$ as described in equation (1) and (5) respectively. With reference to the size and fuel type of trucks, the *z* in equation (8) is determined as 0.002799. The results of first scenario with the cargos assigned to respective trucks are shown in Table 4 and Table 5. A daily order control form is then generated automatically with the scheduling results obtained from the simulation, enhancing the current manual planning and data inputting practice. The average carbon emission per *cbm* has been reduced to 3.8284 $kgCO_2e$/*cbm*, with an improvement of 9.83%. The total number of trucks used has been reduced from the manual planning of 4 trucks to simulated solution of 3 trucks. The truckload utilisation model, identified and developed from the results of carbon reporting in Section 4 and correlation analysis in Section 5, integrates utilisation, transportation cost, arrival and departure schedule and carbon emission mitigation objectives as a carbon-driven multi-criteria truckload utilisation optimisation model.

Table 4. Results of simulated truckloading plan

Cargo item	Customer code	Cargo size	Cargo weight	Cargo leaving time	Cargo destination	Truck code	Truck leaving time	Truck destination	Departure accuracy
1	FC	2.304	12	0830	STN	6560	0830	STN	On time
2	NO	2.376	12.5	0730	CWB	6401	0900	CWB	Late
3	NO	2.419	13	0730	CWB	6401	0900	CWB	Late
4	FC	2.361	12.5	0830	TST	1589	0930	TST	Late
5	VS	2.448	11	1000	STN	6560	0830	STN	On time
6	VS	2.491	11.5	0730	CWB	6401	0900	CWB	Late
7	FC	2.462	12	0900	CWB	6401	0900	CWB	On time
8	ND	2.189	10.5	0830	TST	1589	0930	TST	Late
9	FC	2.232	11	0800	TST	1589	0930	TST	Late
10	FC	2.261	11	0930	STN	6560	0830	STN	On time
11	FC	2.102	11	0900	STN	6560	0830	STN	On time
12	VS	1.886	10	0800	CWB	6401	0900	CWB	Late
13	FC	1.728	10	1000	CWB	5660	0730	CWB	On time
14	NO	1.700	10	0930	TST	1589	0930	TST	On time
15	NO	2.131	11.5	0730	CWB	5660	0730	CWB	On time
16	FC	1.728	10	0830	CWB	5660	0730	CWB	On time
17	VS	1.700	9.5	0800	TST	1589	0930	TST	Late
18	VS	2.131	11	0930	CWB	5660	0730	CWB	On time
19	ND	2.304	12.5	1000	TST	1589	0930	TST	On time
20	FC	2.203	12	1000	TST	1589	0930	TST	On time

Table 5. Total carbon emissions of all trucks per day

Truck code	Truck destination	Utilization (%)	Travelled distance (km)	Fuel consumption (Liter)
5660	CWB	44	71.0	12.041
6560	STN	97	82.6	14.008
6401	CWB	63	71.0	12.041
1589	TST	98	58.2	9.870
Total travelled distance (km) / Fuel consumption (Liter)			282.8	47.96
Total carbon emission (kg-CO_2e)				165.217

Considering a second scenario with recovery planning under sudden operations issues, the engine of a truck with truck code 6401 is found not working and required repair. The set of cargos and available combinations of vehicles in the second scenario are input. The simulated results show the twenty cargo items are consolidated into three trucks. The truck 6401 with destination as CWB is not available due to repair issues. Item 13 and 16, with destination as CWB and volume as 1.44 and 2.16 *cbm* respectively, are allocated to truck 1599. Instead of placing the item 13 and 16 to truck 6401, they are allocated to 1599. The emission intensity, in average carbon emission per *cbm*, have been reduced 9.27% when compared to immediate manual recovery planning. The optimisation tool assists the traffic planner in recovery planning operations. It also maximizes the usage of trucks and reduce the travelling distance, thus mitigating the carbon emissions from the trucks.

Table 6. Results of simulated truckloading plan in the second scenario

Cargo item	Customer code	Cargo size	Cargo weight	Cargo leaving time	Cargo destination	Truck code	Truck leaving time
1	FC	1.536		0830	STN	6560	0830
2	NO	1.98		0730	CWB	5660	0730
3	NO	1.68		0730	CWB	5660	0730
4	FC	1.5744		0830	TST	1589	0930
5	VS	2.04		1000	STN	6560	0830
6	VS	2.076		0730	CWB	5660	0730
7	FC	2.052		0900	CWB	5660	0730
8	ND	1.824		0830	TST	1599	0830
9	FC	1.488		0800	TST	1599	0800
10	FC	4.072		0930	STN	6560	0830
11	FC	1.752		0900	STN	6560	0830
12	VS	1.2576		0800	CWB	5660	0730
13	FC	1.44		1000	CWB	1599	1000
14	NO	1.416		0930	TST	1599	0930
15	NO	1.4208		0730	CWB	5660	0730
16	FC	2.16		0830	CWB	1599	0830
17	VS	1.4688		0800	TST	1599	0800
18	VS	1.548		0930	CWB	5660	0730
19	ND	1.716		1000	TST	1894	1000
20	FC	1.704		1000	TST	1894	1000

Table 7. Total carbon emissions of all trucks per day in second scenario

Truck code	Truck destination	Utilization (%)	Travelled distance (km)	Fuel consumption (Liter)
5660	CWB	98.6	138.0	23.041
6560	STN	98	84.2	14.152
1599	TST	93	48.2	8.174
Total travelled distance (km) / Fuel consumption (Liter)			270.4	45.367
Total carbon emission (kg-CO_2e)				156.284

The truckload model is further developed not only with a set of cargo items and vehicle fleet but also additional factors of arrival time slots and weight. With more factors and variables involved, the model is enhanced and developed with the use of MATLAB mixed integer linear programming as the simulation engine. Let $p_i^{ED}, p_i^{LD}, p_i^{EA}, p_i^{LA} = 1$ for all i, $A(r_1,r_2) = 10$ for all $i \neq j$ and $\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = 0.25$. Consider four trucks and ten items with given cargo volume, truck capacity, cargo destinations, cargo weight and arrival time. The results show that the optimal $X = (X_1, X_2, X_3, X_4) = (1,1,1,0)$ and $Y = (Y_{ik})$ which is given by

$$Y = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}.$$

The corresponding optimal function value is $Z^* = 14.8994$. Details about the trucks are shown in Table 8.

Table 8. Total carbon emissions of all trucks per day

Truck code	Truck destination	Utilization (%)	Travelled distance (km)	Fuel consumption (Liter)
5660	CWB	81	33	7.558
1894	TST	57	28	6.938
6560	STN	58	27	6.814
6401	CWB	-	-	-
Total travelled distance (km) / Fuel consumption (Liter)			88	21.31
Total carbon emission (kg-CO_2e)				59.6

The developed system also provided a function of manipulating the total *cbm* of each cargo item automatically after user input. The system replaced traffic daily order control sheets from manual input to direct capturing the simulated results into daily order control sheets. The decision support and planning system assists traffic team to reduce the cargo load planning time and optimise the cargo loading operations to the truck by considering more factors including carbon emission, utilisation, warehouse departure time, destination arrival time, cargo volume, truck capacity and cargo destination.

8. Conclusion

Severe competition, customer demand, and government policies have pushed 3PL to seek effective ways in improving operations and reducing carbon emissions in daily operations. This paper aims to reduce carbon emissions emitted in warehouses, trucking, and offices by quantifying carbon emissions in daily operations and developing models to improve the efficiencies of truckload operations. It reveals the latest literature on truckload utilisation problems in 3PL operations. With reference to the literature, most of them focused on modelling the truckload utilization based on time, distance, speed and capacity. Lack of successful implementation cases are on carbon reporting and model development integrating truckload, utilisation, departure and arrive time, and vehicle emission during truckload optimisation planning. Systematic and structured methodologies in carbon mapping and reporting in 3PL truckload operations are needed for sustainability development and truckload planning. The operation processes of three 3PL companies in Hong Kong are mapped and reviewed. Reports on direct and indirect carbon emission on the office, warehouse, and trucking environments with reference to the ISO14064 standard for the three firms are conducted to quantify carbon emissions in the companies as a base-year establishment and identify key performance indicators related to truckload operations. It could be seen that electricity and truck emissions contribute the major emissions of the companies. Correlation and regression analysis are carried out to investigate the relationship among the key variables in truckload operations. The truckload utilization against truck capacity, loading volume, fuel consumption, truck size, travelling distances and number of destinations are reviewed. An integrated carbon-driven multi-criteria model is developed in achieving carbon emission reduction initiatives, time and distance cost penalty, minimizing number of trucks, and improving truck utilisation. This integrated mathematical model has been developed into a simulation system and enhanced for the vehicle fleet, with additional factors of arrival time slots and weights. The developed model assists traffic personnel to reduce the time in cargo loading plan with reference to complex dimensions, including cargo size, loading sequences, truck capacity and cargo destinations. It also supports them in optimising truckload operations with reference to the factors identified in the paper, including utilisation, carbon emission, warehouse departure time, destination arrival time, cargo volume, truck capacity and cargo destination. Further development can focus on adding the dimensions of pallet loading operations and exception rules in customer loading requirements.

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