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Estimation of fuel consumption and selection of the most carbon-efficient route for cold-chain logistics

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ABSTRACT

An eco-friendly supply chain (SC) is greatly determined by travel economy and fuel consumption rate. This research considered these two critical factors and explored the relationship between travel economy and vehicle loads, and developed mathematical models in cold-chain logistics (MMCCL) to determine fuel consumption and carbon footprint in cold-chain logistics. Longer routes are more prone to degrade food quality and endanger environmental safety by producing more carbon contents. Considering this fact, we aimed to reduce carbon emissions while maintaining food quality. First, an empirical SC was divided into three possible routes, namely, single-route transportation (SRT), and multiple-route transportation (MRT-I and MRT-II). Later, the proposed MMCCL model was deployed on each route to determine the most carbon-efficient route and found SRT as more fuel-efficient than MRT-I and MRT-II by a margin of 64.52% and 12.78%, respectively. This resulted in the reduction of carbon footprint by cutting the fuel consumption by a significant amount while making the SC eco-friendly and safe. The results were thoroughly justified and evaluated with an appropriate case study in the context of the west southern part of Bangladesh.

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Carbon footprint; cold-chain logistics; environmental safety; fuel consumption; vehicle-routing problems

1. Introduction

The transportation of temperature-sensitive products in an SC using thermal or refrigerated packaging methods is commonly known as cold-chain logistics. Such an SC requires systematic planning and monitoring to maintain the integrity of the packaged products while transporting them across geographically separated locations. Cold-chain goods such as fish, meat, fruit, and vegetables are becoming more popular as people's lifestyles change in response to global economic development. Many developing and developed countries across the world rely heavily on the perishable food sector to support their economies and societies (Gharehyakheh et al., 2020; Shukla & Jharkharia, 2013). Industries related to perishable foods contribute significantly to GDP throughout the world, especially in Asia, such as 12.6% in Bangladesh, 18.3% in India, and 7.7% in China. Similarly, it contributes to 38% of employment in Bangladesh, 43% in India, and about 25% in China (World Bank, n.d.). However, transportation of temperature-sensitive products involves a series of tasks such as preparation, storage, transportation and monitoring, where the cooling system, cold storage, cold transport, cold processing and distribution are the main elements of cold-chain logistics. Temperature control during transportation is the most important factor in a perishable product's life (Ali et al., 2018; Gharehyakheh et al., 2020). The following temperature: −28°C to −30°C for seafood, −16°C to −20°C for chilled items, meat, etc., 2–4°C for fruit, vegetables, pharmaceutical items, etc. and 2–8°C for medication and vaccines must not be exceeded during transportation (Weisbrod, 2011). We described logistics disruption as a failure in the flow of goods or information caused by major risk (Paul et al., 2020), which was supported by the definition of logistics as defined by the Council of Supply Chain Management Professionals (n.d.). Food waste occurs from logistical disruptions and incurs food shortages and financial losses (Ali et al., 2018; Mahtab et al., 2021). In addition, this wastage increases the risks associated with food transportation and preservation, which cannot be overlooked because they entail a significant cost at the end of the year. For example, the US economy

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Supplemental data for this article can be accessed here. https://doi.org/10.1080/23302674.2022.2075043 wastes \$218 billion each year due to food preservation failure, with an additional \$50 billion in societal costs due to foodborne illness (Gharehyakheh et al., 2020).

Holding and transportation system of a cold-chain discharge carbon dioxide(CO_2), methane(CH_4), nitrous oxide(N_2O), and ozone (O_3) those are Green House Gases (GHG) and affect the environment (Matthews et al., 2009; Solomon et al., 2009; Stott & Kettleborough, 2002). Considering this significant impact of GHG, this research entirely focused on the emission of CO_2 in cold-chain logistics. However, the rate of carbon emission is changing dynamically due to the variation of cargo load and transportation routes. Therefore, carbon emission and GHG growth rate depend on cargo load and transportation route. Apart from the adverse consequences of cold-chain logistics, rising living standards and economic progress are making us reliant on the usage of cold items (Li et al., 2019). Currently, the scenario is being more critical to reduce carbon emissions, maintain food quality, and improve environmental safety (Roy et al., 2020); researchers such as Lee et al. (2019) already applied Lamm's theory and Vehicle-Specific Power (VSP) methodology, Kazancoglu et al. (2021) used Grey prediction, Tirumalachetty et al. (2013) followed microsimulation model, Choi et al. (2014) and Eder et al. (2019) developed mathematical modelling to predict GHG emissions in transportation. Unlike the other methods, this research developed MMCCL to determine fuel consumption and carbon footprint in cold-chain logistics.

To bring advantages for the suppliers and environment, it is important to limit carbon footprints by optimising vehicle routes and minimising fuel consumption. In Bangladesh, the suppliers of cold-chain logistics such as *Igloo, Polar, Lovello*, *etc.* frequently follow alternative routes due to traffic jams, road fees, tolls and other factors. These alternatives require various amounts of fuel and produce various amounts of CO_2. Besides, travelling via non-optimised routes have an impact on redundant CO_2 in the environment. To restrict this redundant CO_2, this article added a new dimension in research developing MMCCL to reduce CO_2in cold-chain logistics. Along with the reduction of holding and transportation emissions, this article also reduces the emissions of in-field refrigeration. Splitting a route into multiple possible alternatives and developing mathematical models to determine CO_2 for those routes is the novel contribution of this research. The contribution also includes the development of a pair-wise relationship between travel economy and vehicle loads and the relationship between fuel consumption rate and truck size. Finally, this research found the most carbon-efficient route of transportation based on total emissions produced from associated transport routes, cold storage systems, and in-field refrigeration systems. To determine the most carbon-efficient route, the following two objectives were considered.

- Development of MMCCL to determine fuel consumption and carbon footprint for the routes of cold-chain logistics, and
- Finding out the most carbon-efficient route that produces the minimum amount of CO_2.

The rest of the paper is organised as follows: a thorough literature review is documented in Section 2; the problem statement and potential alternative routes are described in Section 3; Section 4 illustrates the methodology and problem formulation for different scenarios; results and outcomes are reported in Section 5 with necessary discussion and key findings; finally, the paper concludes with future research scopes and the practical and environmental implications in Section 6.

2. Literature review

The goal of this article is to develop mathematical models to estimate carbon footprint and to select the best transportation route which reduces carbon emissions and enhances environmental safety. To summarise the previous works, we reviewed them into two separate categories (1) factors of carbon emissions in cold-chain logistics and (2) methods to reduce carbon emissions

2.1. Factors of carbon emissions in cold-chain logistics

Low-carbon cold-chain logistics include less energy consumption, fewer carbon emissions, less pollution, and less environmental impact (Wong et al., 2018; Wong et al., 2020; Zhang et al., 2019). Hence, it has a significant influence on the logistics industry's energy usage and carbon emissions. In the logistics sector, cold-chain logistics is associated with significant energy consumption and greenhouse gas emissions, which runs counter to the ideals of a low-carbon economy. Furthermore, when compared to normal temperatures logistics, cold-chain logistics has been found to require more energy (Leng et al., 2020a; Leng et al., 2020b, 2020c; Zhang et al., 2019; Zhao et al., 2020). More energy is required and spent to keep the temperature low during the precooling, storing at cold storage, and cooling in refrigeration systems which results in more carbon emissions into the atmosphere (Wong et al., 2018; Zhang et al., 2019). Low-carbon logistics aims to reduce energy usage and greenhouse gas emissions, which runs counter to cold-chain logistics' fundamental characteristics. Low-temperature transportation is a critical component in the cold-chain logistics that leads to a low-carbon economy, yet it is notorious for its high energy consumption (Wang et al., 2018; Wong et al., 2018; Wong et al., 2020; Zhang et al., 2019). Lan et al. (2015) and Wang et al. (2018) improved routes in the logistics industry to support low-carbon growth. Cold-chain logistics is a type of systematic project that ensures product quality by maintaining a low temperature throughout the manufacturing, storage, transportation, and sales processes, as well as associated equipment within the logistics (Babagolzadeh et al., 2020; Dong et al., 2021; Wang et al., 2018; Zhao et al., 2018). However, Demir et al. (2011) were concerned about the planning activities and methods to measure and reduce CO_2emissions. Further research on the carbon footprint and fuel consumption by Demir et al. (2014) claimed vehicle, traffic, drivers, environment and operations as the responsible sources for the fluctuation of the total CO_2. Another study by Leng et al. (2019a, 2019b) found that the fleet composition, speed, payload, and vehicle-related factors were most responsible for carbon emissions and increased fuel consumption. Following that, researchers (Kouridis et al., 2010; ; Zhao et al., 2018) considered these factors to develop carbon-efficient models. However, in order to achieve a win-win scenario of economic and environmental sustainability, it is important to preserve energy and minimise carbon emissions in cold-chain logistics.

2.2. Methods to reduce carbon emissions

To store temperature-controlled products for a certain period at a non-ambient temperature, Bozorgi et al. (2014) developed a new inventory model considering both cost and emission functions. To improve the sustainability and low-carbon production of cold items, Xiao et al. (2018); Chen et al. (2009); Wang et al. (2018) proposed a profit maximisation strategy integrating the carbon footprint for supply chain logistics. Based on perishable products characteristics and considering their environmental protection, Wang et al. (2018); Wang et al. (2020a, 2020b) solved fresh food logistics distribution optimisation problems with the distribution network of cold-chain logistics. In order to solve the optimisation problem of cold-chain logistics considering carbon emissions, cost and customer satisfaction, Qin et al. (2019); Xiao et al. (2018); Gharehyakheh et al. (2020) proposed an optimisation model where minimum cost or sustainability was the objective function. The effectiveness of this model was verified by a numerical comparison experiment that enriched the optimisation research. To reduce the carbon emission of perishable foods in urban distributions, Lin et al. (2019) explored the impact of low carbon policy on the route planning for urban distribution using optimisation analysis. This analysis combined the Tabu search algorithm and genetic algorithm that reduced the distribution process of CO_2 and the total cost of an enterprise. Wang et al. (2020a, 2020b) optimised the distribution period and total cost for the logistics of cold-chain by the development of a bi-objective mathematical model establishing a network of economic, social and environmental benefits. They claimed better performance of their proposed model than the Non-dominated Sorting Genetic Algorithm II (NSGA-II). To maximise cold items' freshness and energy consumption reducing carbon emissions and transportation costs, Amorim and Almada-Lobo (2014); Gharehyakheh et al. (2020); Musavi and Bozorgi-Amiri (2017) proposed a novel multi-objective model and solved it using NSGA-II. Leng et al. (2020a; Leng et al., 2020b, 2020c); Leng et al. (2019a, 2019b) proposed an optimisation model of the low-carbon location-routing problem (LCLRP) for a comprehensive cold-chain to minimise total costs, vehicle waiting time and to increase cold items sustainable development. They solved this model by the adoption of two different algorithms: (1) multi-objective evolutionary algorithms (MOEAs) combining first (FI) and best-improvement (BI) search mechanisms, and (2) multi-objective hyper-heuristic (MOHH). The important features of the related articles described above are aggregated in Table 1 to find out our research scope.

Non-optimised routes in cold-chain logistics result in higher fuel usage, carbon emissions, and food wastage, therefore, we aimed to investigate commonly used optimised and non-optimised routes and to determine fuel consumption and carbon emissions from those routes. Finally, MMCCL were used to determine the most carbon-efficient route in cold-chain logistics.

3. Problems generalisation and finding out alternative routes

3.1. Problem statement

The empirical scenario was considered from the perspective of several major cold-chain providers in Bangladesh. Through a bi-direction discussion with respective providers, we identified the routing difficulties linked to supply chains to minimise food spoiling and fuel consumption. The research scope was determined as reported in Table 1 and the formulation of MMCCL was described in Section 4 based on the generalised problems. The generalised problems are:

- Bangladeshi cold-chain suppliers such as *Igloo, Polar, Lovello, Kwality, and Bellissimo ice-cream* supply cold

Table 1. A comparison of related researches.

Researcher(s)	Researchdomain	Emissions from: Transportation	Holding	In-field refrigeration	Method(s)	The outcome(s)
Bozorgi et al. (2014)	Cold items inventory modelling	√	√	×	Mathematical modelling	The proposition of cost and emission functions
Xiao et al. (2018)	Integration of carbon footprint	√	×	×	LCA & EOQ	Profit maximisation and carbon reduction
Wang et al. (2018)	Logistics problems	√	×	×	GA with heuristic rules	Optimisation of distribution systems
Lin et al. (2019)	Distribution routes optimisation	√	×	×	Mathematical modelling	Reduction of carbon emissions
Kazancoglu et al. (2021)	Sustainable road transportation	√	×	×	Grey prediction	Estimation of GHG emissions
Lee et al. (2019)	Various geometric designs of roads	√	×	×	Lamm's theory and VSP	
Wang et al. (2020a)	Location routing problems	√	×	×	Mathematical modelling	Optimisation of cost and distribution period
Gharehyakheh et al. (2020)	Vehicle routing problems	√	×	×	NSGA-II	Minimisation of cost and carbon emissions
Leng et al. (2020a)	Low-carbon location-routing problems	√	×	×	MOEAs	Minimisation of logistics cost
Leng et al. (2020b)		√	×	×	MOHH	
This work	Vehicle-routing problems	√	√	√	Mathematical modelling	Minimisation of fuel consumption and carbon footprint

products in various terminal demand points (TDPs) in different quantities. The west-southern part of Bangladesh shown in Figure 1 has a few TDPs where order quantity changes dynamically due to the regular changes of retailer demand. TDP-4 covers one of the divisional cities of Bangladesh and gets larger demand than the other TDPs. Hence TDP-4 places larger orders to the supply point (SP). Though TDP-3 covers the Jashore district, it is larger than TDP-1 and TDP-2 and hence it also places larger orders. In these situations, the suppliers have to use several transportation routes to deliver their orders, as shown in Figure 3.

- In Bangladesh, suppliers choose transportation routes considering cargo size, order quantity, traffic jams, road fees, tolls and other factors. From Figure 3, suppliers usually follow SRT since it allows them to fulfil the maximum TDPs in a single trip. However, suppliers also follow MRT-I or MRT-II in the case of fulfilling fewer TDPs that requires small or medium-sized refrigerated vehicles. MRT-I and MRT-II need multiple trips than SRT resulting in more toll fees and traffic jams.
- The routes in Figure 3 require different sized refrigerated trucks based on multiple cumulative order quantities that have different in-field refrigeration capacities. Lack of vehicle availability frequently makes it difficult for the suppliers to choose a certain route. Furthermore, TDPs' inventory replenishment periods have an impact on choosing vehicles and transportation routes. Failure to choose the proper vehicle and transportation route results in more fuel consumption and carbon emissions.

Travelling non-optimal routes increases carbon footprint and fuel consumption as stated in problem statements. However, considering the sources of emissions, such as in-field refrigeration, cold storage, and so on, we developed a research model as shown in Figure 2.

3.2. Finding out alternative routes

Figure 1 shows three alternative routes of transportation from the SP to TDPs and they are (a) single-route transportation (SRT) and (b) multiple-route transportation (MRT-I and MRT-II). SRT has a single delivery route and return route, while MRT has several alternatives. Besides, the MRT requires various-sized multiple vehicles. We used mathematical models (see Section 4) to

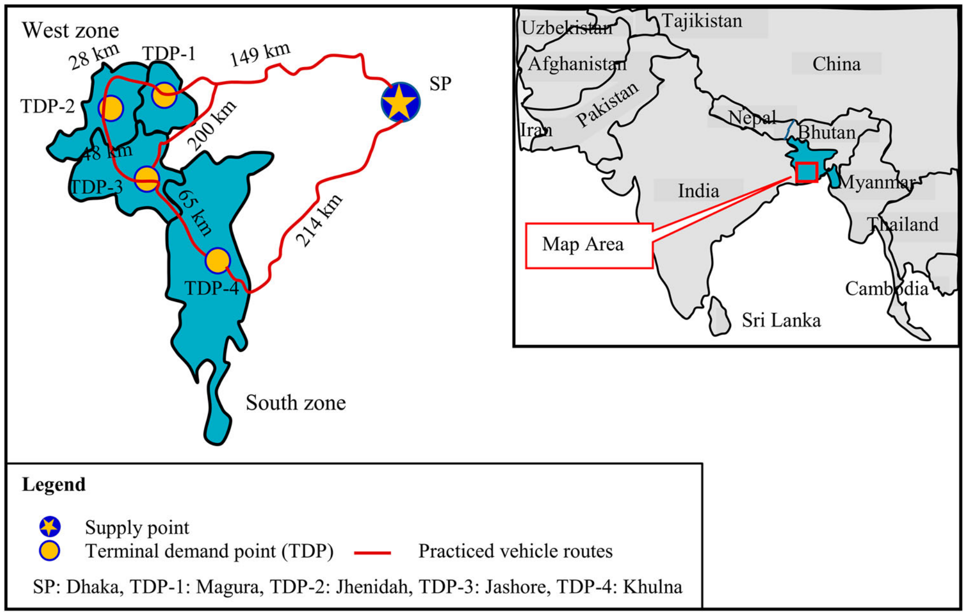


Figure 1. Transportation routes practiced by the suppliers of Bangladesh.

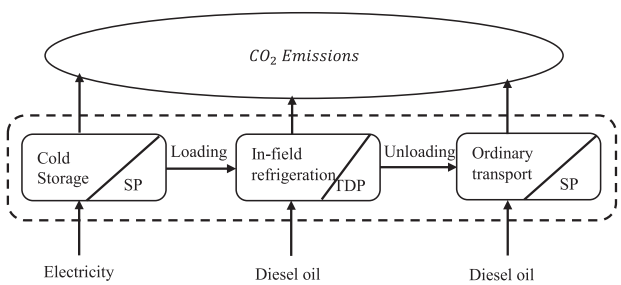


Figure 2. The research model.

determine and compare the carbon footprints for each transportation route shown in Figure 3.

4. Research methods

The study was carried out using the systematic research approach depicted in Figure 4, which is a step-by-step summary of the whole working process.

4.1. Development of mathematical models in cold-chain logistics (MMCCL)

Table 2 listed the parameters and variables with descriptions used in mathematical modelling. The variables that measure the amount of carbon emission, fuel consumption, and route distance are defined as decision variables.

4.1.1. MMCCL for SRT

Models of transportation emissions

The order quantity Q affects transportation emission as it determines the load and number of shipments. When Q increases, the load of cargo increases and KPL decreases due to the proportional fuel consumption. In other words, across a certain distance, a heavier cargo consumes more fuel than a lighter one (Ubeda et al., 2011). KPL and E of cargo for the quantity T_c and for the certain distance S can be determined by Equations (1) and (2) adopted from Bozorgi et al. (2014).

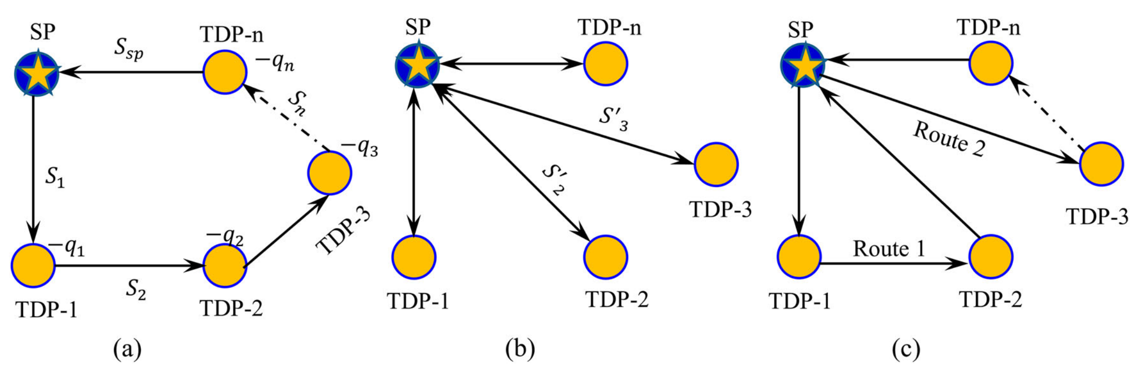


Figure 3. Transportation routes (a) SRT, (b) MRT-I and (c) MRT-II.

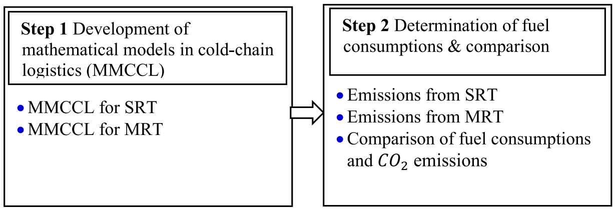


Figure 4. The research framework.

Table 2. Description of the symbols.

Symbols	Description
Decision variables	
Q	Order quantity
W_i	Weight of a unit
q_i	Delivery quantity
n	Number of TDP
N	Number of trucks
N'	Number of shipments/deliveries
D	Total demand quantity
T_c	Truck/cargo capacity
S_i	Distance from a SP/TDP to next TDP
b	Cold storage capacity
KPL	Travel economy (kmL^{-1}) for the loaded truck
KPL_o	Travel economy (kmL^{-1}) for the empty truck
Constant variables	
α	Weight coefficient of Q quantity
f_{rf}	Emission rate ($\mathrm{kgCO_2L}^{-1}$) for the in-field refrigeration system
l_{rf}	Consumption of fuel by cargo's refrigeration system (Lkm^{-1})
$CELF$	Constant emission from per litre fuel ($\mathrm{kgCO_2L}^{-1}$)
$TCFE$	Total carbon footprint from 1 kWh energy
Resultant variables	
E	Carbon emissions for a certain distance
$TETC$	Total emissions of transporting cold items
$TECF$	Total energy consumption by the cold storage freezers
$T_{HE(Q)}$	Total holding emission for Q quantity
$T_{HE(D)}$	Total holding emission for D quantity
TCE	Total carbon emission

$$KPL_{T_c} = KPL_{(GVW)} = KPL_{(W_{empty\ truck}+W_{(\alpha\times Q\times W_i)})} \quad (1)$$

$$E_S = CELF \times \frac{S}{KPL_{(GVW)}} \quad (2)$$

α is the weight coefficient of Q items that has an effect on KPL and E. Emissions in the whole returning route by the ordinary transport of an empty truck can also be determined by the developed Equation (3). The KPL and E of a cargo gradually increase and decrease respectively due to unloading q_i items at each TDP. Hence we revised Equations (1) and (2) and developed Equation (4) to calculate total emission.

Now, E for the distance from TDP-n to SP (ordinary transport by empty cargo/truck)

$$E_{S_{SP}} = CELF \times \frac{S_{sp}}{KPL_0} \quad (3)$$

The cargo returns from $TDP-n$ to SP at the speed of $KPLo$ because this is fully unloaded. However, $TETC$ to deliver T_c quantity by a truck/cargo for the route of SRT shown in Figure 3(a) can be determined by Equation (4). The proof of Equation (4) has been shown in the Appendix section.

Logistics route: $SP - TDP1 - TDP2 \ldots\ldots TDPn - SP$ (shown in Figure 3(a))

$$TETC_{T_c}= CELF \times \left[\sum_{i=1}^{n} S_i \frac{1}{KPL_i} + \frac{S_{sp}}{KPL_0}\right] + f_{rf} l_{rf} \sum_{i=1}^{n} S_i \quad (4)$$

If Q is much greater than $T_c(Q >> T_c), N(Q/T_c)$ trucks are required. This also increases the carbon emissions N times for the same path. However, Equation (4) can also be revised by Equation (5) for N trucks.

$$TETC_Q = TETC_{T_c} \times \frac{Q}{T_c} \quad (5)$$

Again in the case of D > > Q, $N'(D/Q)$ deliveries of N trucks are required to meet the demand, D. The carbon emissions for N' deliveries and N trucks can also be determined by revising Equation (5) which has been developed by Equation (6).

$$TETC_D = TETC_{T_c} \times \frac{Q}{T_c} \times \frac{D}{Q} \quad (6)$$

where

$$NN' = \frac{Q}{T_c} \times \frac{D}{Q}$$

Models of holding emissions

Cold items are stored in cold storage to maintain their original quality. Suppliers store T_c or D quantities for a certain period keeping T_c/b or D/b cold storage running. Cold storage consumes electricity and produces carbon footprints that can be determined by the developed Equations (7) and (8).

Emissions for the quantity, T_c : When suppliers store quantity, T_c equivalent to a particular order quantity for the time between two consecutive deliveries.

$$T_{HE(T_c)} = \left[\frac{T_c}{b}\right] \times TECF \times TCFE \quad (7)$$

Emissions for the demand quantity, D: When items equivalent to a demand quantity D ordered by n demand points are stored and delivered by T_c in each delivery/shipment, storage quantity decreases by the quantity of $T_{c1}, T_{c2}, \ldots\ldots, T_{cn}$ in each shipment. From the proof of holding emissions shown in the Appendix section, $T_{HE(D)}$ for the quantity, D can be determined by

Equation (8).

$$T_{HE(D)} = \frac{n}{b}\left[\left\{D - \frac{(n-1)}{2}T_c\right\}\right] \times TECF \times TCFE \tag{8}$$

Total emissions: Total emissions for the quantity, T_c or D can be determined by adding transportation emissions and holding emissions. Total CO_2 discharged in a complete trip (delivery and return) and to hold them in cold storage can be determined by the following equations.

Total carbon emission for T_c quantity – TCE_{T_c}

$$\begin{aligned} TCE_{T_c} &= TETC_{T_c} + T_{HE(T_c)} \\ &= TETC_{T_c} + \left[\left(\frac{T_c}{b}\right) \times TECF \times TCFE\right] \end{aligned} \tag{9}$$

Total carbon emission for Q quantity-TCE_Q (where $Q >> T_c$ and required N trucks)

$$TCE_Q = \left[TETC_{T_c} \times \frac{Q}{T_c}\right] + \left[\left(\frac{Q}{b}\right) \times TECF \times TCFE\right] \tag{10}$$

Total carbon emission for D quantity – TCE_D (required N trucks and N' deliveries)

$$\begin{aligned} TCE_D &= TETC_D + T_{HE(D)} \\ &= \left[TETC_{T_c} \times \frac{Q}{T_c} \times \frac{D}{Q}\right] + \frac{n}{b}\left[\left\{D - \frac{(n-1)}{2}T_c\right\}\right] \\ &\quad \times TECF \times TCFE \end{aligned} \tag{11}$$

4.1.2. MMCCL for MRT

The emissions of CO_2 to transport quantity T_c or D by one truck or Q/Tc trucks can be determined by Equations (12)–(17). The proof of Equations (12) and (14) have been shown in the Appendix section.

Models of transportation emissions

***MRT*−1**

Logistics route: $SP - TDP1 - SP, SP - TDP2 - SP$, *etc.* (shown in Figure 3(b))

TETC for the quantity, T_c

$$\begin{aligned} TETC_{T_c} &= CELF \\ &\quad \times \left[\left\{\sum_{i=1}^{n} S_{d(i)} \frac{1}{KPL_i}\right\} + \frac{1}{KPL_0}\sum_{i=1}^{n} S_{r(i)}\right] \\ &\quad + f_{rf} l_{rf} \sum_{i=1}^{n} S_{d(i)} \end{aligned} \tag{12}$$

Now, TETC for the quantity, D where Q/T_c trucks require D/Q shipments

$$TETC_D = TETC_{T_c} \times \frac{Q}{T_c} \times \frac{D}{Q} \tag{13}$$

***MRT*−2**

Logistics route: $SP - TDP1 - TDP2 - SP, SP - TDP3 - TDPn - SP$, *etc.* (shown in Figure 3(c))

TETC for the quantity, T_c in the first route ($SP - TDP1 - TDP2 - SP$)

$$\begin{aligned} TETC_{T_{cR1}} &= CELF \times \left[\sum_{i=1}^{2} S_i \frac{1}{KPL_i} + \left(\frac{S'_2}{KPL_0}\right)\right] \\ &\quad + f_{rf} l_{rf} \sum_{i=1}^{2} S_i \end{aligned} \tag{14}$$

TETC for the quantity, T_c in the second route ($SP - TDP3 \ldots\ldots - TDPn - SP$)

$$\begin{aligned} TETC_{T_{cR2}} &= CELF \times \left[\sum_{i=3}^{n} S_i \frac{1}{KPL_i} + \left(\frac{S_{S_{sp}}}{KPL_0}\right)\right] \\ &\quad + f_{rf} l_{rf} \sum_{i=3}^{n} S_i \end{aligned} \tag{15}$$

Now, TETC for the whole route,

$$\begin{aligned} TETC_{T_c} &= TETC_{T_{cR1}} + TETC_{T_{cR2}} \\ &= CELF \times \left[\left\{\sum_{i=1}^{2} S_i \frac{1}{KPL_i} + \left(\frac{S'_2}{KPL_0}\right)\right\}\right. \\ &\quad \left. + \left\{\sum_{i=3}^{n} S_i \frac{1}{KPL_i} + \left(\frac{S_{S_{sp}}}{KPL_0}\right)\right\}\right] \\ &\quad + f_{rf} l_{rf} \left(\sum_{i=1}^{2} S_i + \sum_{i=3}^{n} S_i\right) \end{aligned} \tag{16}$$

Now, TETC for the quantity, D where Q/Tc trucks require D/Q shipments

$$TETC_D = TETC_{T_c} \times \frac{Q}{T_c} \times \frac{D}{Q} \tag{17}$$

Models of total emissions

TCE for the quantity, T_c and D through the routes MRT-I or MRT-II can be determined by Equations (18) and (19), respectively.

MRT-I

TCE for the quantity, T_c

$$\begin{aligned} TCE_{T_c} &= TETC_{T_c} + T_{HE(T_c)} \\ &= \left[CELF \times \left[\left\{\sum_{i=1}^{n} S_{d(i)} \frac{1}{KPL_i}\right\}\right.\right. \\ &\quad \left.\left. + \frac{1}{KPL_0}\sum_{i=1}^{n} S_{r(i)}\right] + f_{rf} l_{rf} \sum_{i=1}^{n} S_{(d)i}\right] \\ &\quad + \left[\frac{T_c}{b}\right] \times TECF \times TCFE \end{aligned} \tag{18}$$

TCE for the quantity, *D*

$$TCE_D = TETC_D + T_{HE(D)} = \left[TETC_{T_c} \times \frac{Q}{T_c} \times \frac{D}{Q}\right] + \frac{n}{b}\left[\left\{D - \frac{(n-1)}{2}T_c\right\}\right] \times TECF \times TCFE \quad (19)$$

MRT-II

TCE for the quantity, T_c

$$TCE_{T_c} = TETC_{T_c} + T_{HE(T_c)} = \left[CELF \times \left[\left\{\sum_{i=1}^{2} S_i \frac{1}{KPL_i} + \left(\frac{S'_2}{KPL_0}\right)\right\} + \left\{\sum_{i=3}^{n} S_i \frac{1}{KPL_i} + \left(\frac{S_{S_{sp}}}{KPL_0}\right)\right\}\right] + f_{rf} l_{rf}\left(\sum_{i=1}^{2} S_i + \sum_{i=3}^{n} S_i\right)\right] + \left[\left(\frac{T_c}{b}\right) \times TECF \times TCFE\right] \quad (20)$$

TCE for the quantity, *D*

$$TCE_D = TETC_D + T_{HE(D)} = \left[TETC_{T_c} \times \frac{Q}{T_c} \times \frac{D}{Q}\right] + \frac{n}{b}\left[\left\{D - \frac{(n-1)}{2}T_c\right\}\right] \times TECF \times TCFE \quad (21)$$

4.2. Determination of fuel consumptions and comparison

Bellissimo ice cream, a product of the *Kazi Farms Group*, is distributed to the different demand points from the SP located in Savar, Dhaka. They follow various routes of transportation as shown in Figure 3 but fuel consumption and carbon emission from each transportation route are different.

To calculate transportation emissions, a relationship between gross vehicle weight (GVW) and travel economy (km/L) was adopted from Xiao et al. (2012), as shown in Figure 5(a). This relationship can be expressed by Equation (22).

$$y = 9.1141 - 0.278x \quad (22)$$

where y = travel economy (km/L), and x = gross vehicle weight (tonne).

Moreover, the fuel consumption rate (L/100 km) for the different sized (volume) refrigerators has been shown in Figure 5(b), which was adopted from Tassou et al. (2012) and Baartmans (2015). This research found this consumption rate for the −30°C temperature of the refrigerators and the 50 km/h average speed of the trucks. We divided the trucks into three categories based on the volume of their in-field refrigerator: (1) mini-type truck – 20 m^3 (2) middle-sized truck – 40 m^3 and (3) large-scale truck – 60 m^3. In this research, we have considered the average weight capacity per m^3 space is 167 kg, i.e. 1 m^3 = 167 kg, which was determined by reviewing the websites of (CLVEHICLES.COM, n.d.; DRX AUTO, n.d.).

4.3. A case study

Mathematical models in cold-chain logistics (MMCCL) had been developed to determine the fuel consumption and carbon footprint for cold-chain logistics. As shown in Figure 1, *Bellissimo ice cream* follows various routes SRT, MRT-I and MRT-II (see Figure 3), to deliver cold items to their demand points. In this section, consumption of fuel and emissions of carbon had been determined for each transportation route and identified the optimal route for *Bellissimo ice cream*.

4.3.1. Emissions from SRT

Route description: From the SRT route of Figure 3(a), the suppliers of *Bellissimo ice cream* use large-scale trucks (60 m^3) and unload 2 tonnes in TDP1, 2 tonnes in TDP2, 2.5 tonne TDP3, and 3.5 tonnes in TDP4. Finally, trucks return to SP from TDP4.

Truck Description: The average weight of the large-scale trucks is 14 tonnes and their in-field refrigeration capacity is 60 m^3 or 10 tonnes, i.e. the GVW of these trucks is 24 tonnes when fully loaded.

Now, from Equation (1), the weight coefficient, α depends on the weight of pallets, containers, belts, and cartons which are used to package and confine products during transportation. If those supplementary items carry 2% of total weight, the value of α used in Equation (1) can also be determined as follows:

$$\propto \times Q \times W_i = 10,000$$

$$\propto = \frac{10,000}{Q \times W_i} = 1.02$$

Emissions from transportation: From Equation (22), we can determine travel economy (KPL) for the corresponding truck GVW as shown in Table 3, such as y = 2.44 when x = 24 tonne (GVW for the loaded truck). y denotes the value of $KPL_{(24tonne)}$, i.e. $y = KPL_{(24tonne)} =$

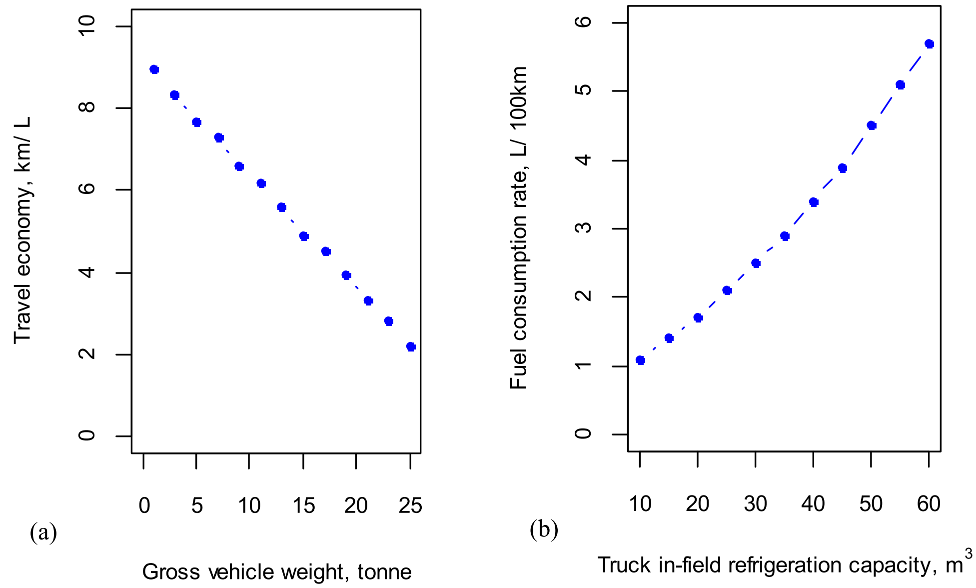


Figure 5. (a) Travel economy for various weighted trucks and (b) Fuel consumption rate for the various sized in-field refrigerators.

Table 3. Summarisation of fuel consumption and CO_2 emissions for the SRT transportation.

								Emission ($kgCO_2$) from		
		Destination	Distance, km	Unload, tonne	Truck GVW, tonne	Travel economy, KPL	Fuel consumption (L), distance/KPL	Transportation	In-field refrigeration	Cold storage
Transportation in SRT	Delivery	TDP1	149	2	24	2.44	61.07	160.00	38.75	167.86
		TDP2	28	2	22	2.99	9.36	24.52		
		TDP3	48	2.5	20	3.55	13.52	35.42		
		TDP4	65	3.5	17.5	4.25	15.29	40.05		
	Return	TDP4-SP	214	0	14	5.22	40.99	107.39		
	Total						140.24	367.40	38.75	167.86

2.44 km/L. This value can also be determined from Figure 5(a).

A sample calculation of $E_{(s)}$ has been shown in the Appendix entitled 'emissions from SRT'.

Similarly, the CO_2 emissions for the following destinations can be calculated as shown in Table 3. Equation (3) can also be used to calculate emissions for an empty truck.

Emissions from in-field refrigeration: From Figure 5(b), $l_{rf} = \frac{5.10\text{L}}{100\text{km}} = 0.051\ \text{Lkm}^{-1}$ for the $60m^3$ in-field refrigeration trucks. Again, $\sum_{i=1}^{n} S_i = (149 + 28 + 48 + 65) = 290$ km (total delivery path or total path of refrigerated transportation), and $f_{rf} = 2.62\ \text{kgCO}_2\text{L}^{-1}$. However, emissions from the in-field refrigeration have been shown in Table 3.

Emissions from cold storage: For $b = 10$ tonne, $T_c/b = \frac{10}{10} = 1$ cold storage is required to store $T_c = 10$-tonne items. The power of this cold storage is 15 kW. Lead time of 2 days = 48 hours. Then to store 10-tonne items for 2 days, emission from the cold storage can be determined from Equation (7).

$$T_{HE(T_c)} = \left[\frac{T_c}{b}\right] \times TECF \times TCFE$$
$$= 1 \times 15 \times 48 \times 0.23314\ \text{kWhkgCO}_2 kWh^{-1}$$
$$= 167.86\ \text{kgCO}_2$$

Total emission: Calculation of total carbon emissions, TCE_{T_c} has been shown in the Appendix section entitled 'emissions from SRT'.

Total emission from SRT was 574.01 $kgCO_2$ where emissions from transportation, in-field refrigeration, and cold storage were 367.40 $kgCO_2$, 38.75 $kgCO_2$, and 167.86 $kgCO_2$ respectively.

4.3.2. Emissions from MRT

For MRT-I

Route description: In the MRT-I route of Figure 3(b), the suppliers use mini-type and middle-sized trucks.

They unload 2 tonnes in TDP1 and return to SP. On the next trip, they unload 2 tonnes in TDP2 and return to SP. In this way, at last, they unload 3.5 tonnes in TDP4 and return to SP.

Truck Description: The average weight of the mini-type trucks is 4.5 tonnes and their in-field refrigeration capacity is 20 m^3 or 3.34 tonne (CLVEHICLES.COM, n.d.; DRX AUTO, n.d), which indicates the GVW of these trucks is 6.5 tonne when those are loaded by 2 tonnes.

Emissions from transportation: From Equation (22), $y = 7.31$ when $x = 6.5$ tonne (GVW for the loaded truck). y denotes the value of KPL, i.e. $y = KPL_{6.5tonne} = 7.31$ km/L. Now, we can determine the amount of emission for a certain distance for the fully loaded trucks from Equation (2).

Emissions $E_{(s)}$ for $S = 149$ km which is the distance from SP to TDP1

$$E_{(s)} = CELF \times \frac{S}{KPL_{6.5tonne}} = 2.62 \times \frac{149}{7.31}$$
$$= 2.62 \times 20.38 = 53.40 \text{ kg}CO_2$$

Similarly, the emission of CO_2 for the next destinations can be determined as summarised in Table 4.

Emissions from in-field refrigeration: From Figure 5(b), $l_{rf} = 0.018$ Lkm^{-1}& 0.0305 Lkm^{-1} for the 20m^3& 40m^3 in-field refrigeration trucks. Again, $\sum_{i=1}^{n} S_i$ = (149 + 177 + 200) = 526 km for the mini-type trucks and $\sum_{i=1}^{n} S_i = 265$ km for the middle-sized truck. However, emissions from the in-field refrigeration had been shown in Table 4.

Emission from cold storage: Emission from the cold storage was 167.86 kgCO_2 as determined in SRT.

Total emissions: Calculation of total carbon emissions, TCE_{T_c} has been shown in the Appendix section entitled 'emissions from MRT'.

Total emission from MRT-I was 818.30 kgCO_2 where emission from transportation, in-field refrigeration, and cold storage was 604.46 kgCO_2, 45.98 kgCO_2, and 167.86 kgCO_2 respectively.

For MRT-II

Route description: In the routes of Figure 3(c), the suppliers use middle-sized trucks. They unload 2 tonnes in TDP1, 2 tonnes in TDP2 and return to SP. On the next trip, they unload 2.5 tonnes in TDP3, 3.5 tonne TDP4 and return to SP.

Truck Description: The average weight of the middle-sized trucks is 10 tonnes and their in-field refrigeration capacity is 40 m^3 or 6.68 tonnes (CLVEHICLES.COM, n.d.; DRX AUTO, n.d) which indicates the GVW of these trucks is 14 tonnes and 16 tonnes when those are loaded by 4 tonnes and 6 tonnes, respectively.

Emissions from transportation: From Equation (22), $y = 4.67$ when $x = 16$ tonne (GVW for the loaded truck). y denotes the value of KPL, i.e. $y = KPL_{16tonne} = 4.67$ km/L. Now, we can determine the amount of emission for a certain distance for the fully loaded trucks from Equation (2).

Emissions $E_{(s)}$ for $S = 200$ km which is the distance from SP to TDP3

$$E_{(s)} = CELF \times \frac{S}{KPL_{16 \text{ tonne}}} = 2.62 \times \frac{200}{4.67}$$
$$= 2.62 \times 42.83 = 112.21 \text{ kg } CO_2$$

Similarly, the emission of CO_2 for the next destinations can be determined as summarised in Table 4.

Emissions from in-field refrigeration: From Figure 5(b), $l_{rf} = 0.0305$ Lkm^{-1} for the 40m^3 in-field refrigeration trucks. Again, $\sum_{i=1}^{n} S_i = (149 + 28) + (200 + 65) = 442$ km for the middle-sized truck. However, emissions from the in-field refrigeration had been shown in Table 4.

Emission from cold storage: Emission from the cold storage was 167.86 kgCO_2 as determined in SRT.

Total emissions: Calculation of total carbon emissions, TCE_{T_c} has been shown in the Appendix section entitled 'emissions from MRT'.

Total emission from MRT-II was 617.56 kgCO_2 where emission from transportation, in-field refrigeration, and cold storage was 414.38 kgCO_2, 35.32 kgCO_2, and 167.86 kgCO_2 respectively.

4.3.3. Comparison of fuel consumptions and CO_2 emissions

From Tables 3 and 4, we can find the most efficient and optimal route based on fuel consumption and CO_2 emissions from the transportation systems of *Bellissimo ice cream*. From Figure 6(a,b), SRT is optimal and the most economic since it consumes the lowest amount of fuel and produces the minimum amount of CO_2 574.01 kg. But from Figure 6(c), MRT-II is the most efficient in in-field refrigeration system because it produces a minimum amount of CO_2 35.32 kg.

5. Results and discussion

In this research, the consumption of fuel and the emission of carbon footprint for cold-chain logistics has been analyzed through mathematical modelling. This research focused on the existing practiced routes of the west-southern part of Bangladesh and identified the critical problems from those existing routes such as quality degradation, more fuel consumption and so on. To minimise these problems, we developed MMCCL to determine carbon footprint and select the optimal route that consumes minimal fuel. Besides, we developed the relationship between carbon footprint and truckload and the

Table 4. Summarisation of fuel consumption and CO_2 emissions for MRT-I and MRT-II.

				Truck GVW (tonne)		Travel economy, *KPL*		Fuel consumption (L), distance/KPL		Emission from		
Transportation	Destination	Distance, km	Unload, tonne	GVW_D	GVW_R	KPL_D	KPL_R	L_D	L_R	Transportation,	In-field refrigeration	Cold storage
MRT-I	TDP1	149	2	6.5	4.5	7.31	7.86	20.38	18.96	103.07	45.98	167.86
	TDP2	177	2	6.5	4.5	7.31	7.86	24.21	22.52	122.43		
	TDP3	200	2.5	7	4.5	7.17	7.86	27.89	25.45	139.75		
	TDP4	265	3.5	13.5	10	5.36	6.33	49.44	41.86	239.21		
Total								121.92	108.79	604.46	45.98	167.86
MRT-II	TDP1	149	2	14		5.22		28.54		74.77	35.32	167.86
	TDP2	28	2	12	10	5.78	6.33	4.84	27.96	85.94		
	TDP3	200	2.5	16		4.67		42.83		112.21		
	TDP4	65	3.5	13.5	10	5.36	6.33	12.13	41.86	141.45		
Total								88.34	69.82	414.37	35.32	167.86

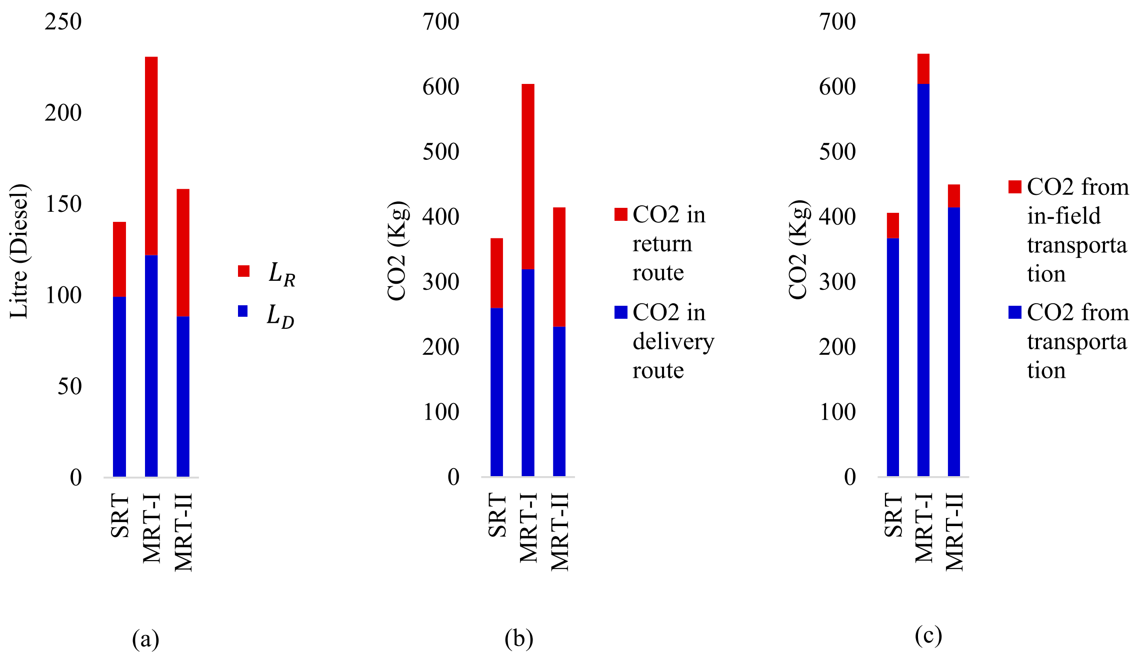
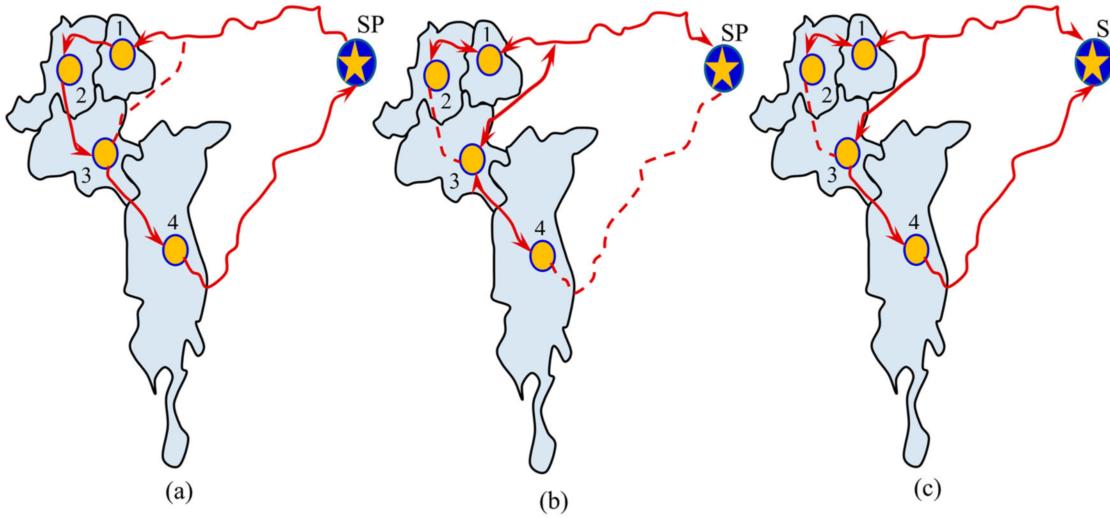


Figure 6. Comparison of (a) fuel consumption (b) CO_2 between delivery route and return route and (c) CO_2 between transportation and in-field refrigeration.

relationship between the rate of fuel consumption and truck size as shown in Figure 5. Moreover, a comparison among transportation routes also showed which route was optimal from the perspective of minimal fuel consumption and minimum carbon emission. For example, Figure 6(a,b) showed the transportation route SRT consumed the minimum fuel and produced the lowest CO_2 whereas Figure 6(c) showed the in-field refrigeration system of MRT-II produced the minimum CO_2. Clearly, SRT is the optimal transportation route since it emits the minimum CO_2 in transportation. Notice that the proposed mathematical models provide two major outcomes (1) minimise fuel consumption and (2) lower the carbon footprint.

5.1. Reduction of fuel consumption

Figure 7(a–c)demonstrated three transportation routes of west-southern Bangladesh, which are currently followed by the cold-chain suppliers. These routes cover all the paths that have different travelling distances. Hence the amount of fuel consumption and emission of CO_2 in each route is different. In a single trip of *Bellissimo ice cream*, transportation route SRT consumed 140.24 L diesel in travelling, which was 64.51% and 12.78% more efficient than MRT-I and MRT-II, respectively, because those consumed 230.71 L and 158.16 L, respectively. This transportation route consumed the amount of 38.75 L in its in-field refrigeration system which was closer to the optimal amount, 35.32 L. As a matter of fact, this research



Practiced/Followed Routes						
Delivery	(a)	SP-TDP1-....-TDP4-SP	(b)	SP-TDP1-SP etc.	(c)	SP-TDP1-TDP2-SP etc.
Return		TDP4-SP		TDP1-SP etc.		TDP2-SP etc.

Figure 7. Transportation modes in west-southern Bangladesh (a) SRT, (b) MRT-I and (c) MRT-II.

suggests the Bangladeshi cold-chain suppliers follow SRT in the west-southern zone of Bangladesh since this route is the most economical in fuel consumption and most efficient in reducing carbon footprint.

5.2. *Reduction of carbon footprint*

Figure 8 demonstrates the emission of CO_2 in each TDP for the transportation routes of *Bellissimo ice cream* as found in Tables 3 and 4. In SRT, the transportation truck produced the maximum CO_2 in its first TDP because this transportation route used the largest truck with full load capacity. But this produced the minimum CO_2 in the next TDPs. However, MRT-II produced a total of 414.37 kgCO_2 in transportation where 231.45 kgCO_2 was in delivery route and 182.93 kgCO_2 was in the return route. In MRT-I, the emission of CO_2 gradually increased from 103.07 kg to 239.21 kg, and this route produced the maximum of 604.46 kgCO_2 along with the maximum of 45.98 kgCO_2 emission in its in-field refrigeration system. The route SRT produced the minimum amount of 367.40 kgCO_2 in transportation which was 64.52% and 12.78% more efficient than MRT-I and MRT-II, respectively. In Figure 8, though the emission of TDP-1 of SRT was higher, the emission from the next TDPs was considerably low in transportation. Therefore, the SRT route in Figure 7(a) was optimal. Though there were differences among the transportation and in-field refrigeration emissions, the emission from the cold storage was the same on each transportation route with an amount of 167.86 kgCO_2.

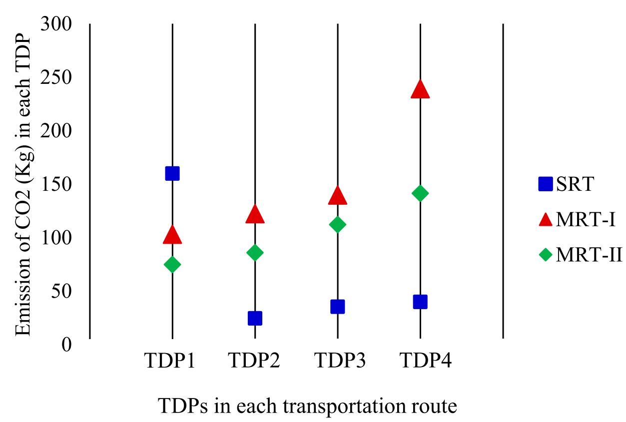


Figure 8. Comparison of CO_2 among the transportation routes.

6. Conclusions, implications and future research scope

This research aimed to enhance environmental safety and to determine the optimal usage of fuel by reducing unnecessary transportation and cutting off suppliers' extra fuel consumption. At first, we focused on the routing problems of transportation faced by the supplier. The problems were generalised based on the difficulties in the existing routing systems of the cold-chain logistics in Bangladesh. Later, we developed a mathematical model (MMCCL) to reduce the carbon footprint and cold-chain disruptions. Analysis of alternative routes by other researchers through the adoption of various analytical methods found solutions on carbon footprint, cost minimisation and environmental safety. However, our research undertook further analysis on existing problems and developed MMCCL to reduce carbon emissions and increase transportation flexibility. Carbon emission has an adverse effect on environmental safety, which increases proportionally to the increase of routing distance. Fuel consumption of MRT-I indicates a larger route increases the transportation cost along with more fuel consumption (see Table 4 and Figure 6(a)). The higher rate of CO_2 in longer routes provides evidence on increased fuel consumption as we observed the maximum emission in the longest route MRT-I, whereas the optimal SRT route generates minimum emission (see Figure 6(a,b)). Moreover, the suppliers may face some additional problems such as due time delivery failure, quality degradation, and schedule disorder due to the increase of the intermediate distance between SP and TDP. These, eventually, have an adverse effect on the overall SC performance and capability. In cold-chain logistics, perishable items should be treated with utmost priority due to their temperature sensitiveness. Lack of proper planning and longer routes may increase travel time and deteriorate the product quality or spoil in the worst scenario. However, the optimal transportation route is proven to reduce route distance, cutting off fuel consumption, and resulting in significant benefits as summarised below:

- Reduces carbon footprint
- Makes the routing system efficient and economic, and
- Enhances environmental safety and reduces food wastage

Moreover, this research provides some favourable aspects of managerial and environmental implications leading to supplier and environmental benefits.

Practical implications: To be economic and efficient in transportation and to determine the optimal transportation route, MMCCL plays the most significant role. Adopting MMCCL, the supplier can decide which one among SRT, MRT-I and MRT-II are the most efficient in transportation. The suppliers will also be benefited from enhanced SC performance through the adaptation of MMCCL. However, the optimal route shows the supplier the most economic and shortest route, which helps in time management, cost minimisation, and maintaining food quality. This route does not require any relocating among the TDPs. Therefore, benefits of the efficient route in cold-chain logistics can be gained by simply adopting MMCCL. Moreover, cost minimisation in fuel consumption and transportation helps the supplier in earning better profit.

Environmental implications: The optimal transportation route saves the environment by reducing carbon footprint, which ultimately reduces the amount of greenhouse gases. Global adoption of this optimal SRT route by cold-chain suppliers can play a significant role in reducing CO_2 emissions throughout the supply chain. In addition, saving food from spoiling following this optimum/efficient route also saves the environment.

Considering transportation emission, holding emission, and in-field refrigeration emission, well-known multi-objective evolutionary algorithms (MOEAs) can be applied to determine a more efficient transportation route. Besides, road temperature, road conditions, and speed variations can be taken into consideration.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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Appendix

The proof of Equation (4) (Figure 3(a))

$$\begin{aligned} TETC_{T_c} = {} & E_{refrigerated\ transportation} \\ & + E_{ordinary\ transportation} \\ & + E_{in-field\ refrigeration} \end{aligned}$$

$$= E_{Delivery} + E_{Return} + E_{in-field\ refrigeration}$$
$$= [E(S_1) + E(S_2) + \dots\dots\dots + E(S_n)] + [E_{TDPn-SP}] + [E(S_1) + E(S_2) + \dots\dots\dots + E(S_n)]$$
$$= CELF \times \left[\left\{\frac{S_1}{KPL_{GVW} - \propto \times Q \times W_i} + \frac{S_2}{KPL_{GVW} - \propto \times (Q - q_1) \times W_i} + \dots\dots + \frac{S_n}{KPL_{GVW} - \propto \times \{Q - (q_1 + q_2 + \dots\dots + q_{n-1}) \times W_i\}}\right\}\right] + \left[CELF \times \frac{S_{sp}}{KPL_0}\right] + [f_{rf}l_{rf}S_1 + f_{rf}l_{rf}S_2 + \dots\dots + f_{rf}l_{rf}S_n]$$
$$= CELF \times \left[\left\{\frac{S_1}{KPL_1} + \frac{S_2}{KPL_2} + \dots\dots\dots + \frac{S_n}{KPL_n}\right\} + \frac{S_{sp}}{KPL_0}\right] + [f_{rf}l_{rf}(S_1 + S_2 + \dots\dots + S_n)]$$

Where, $KPL_1 = KPL_{GVW} - \propto \times Q \times W_i$

$$= CELF \times \left[\sum_{i=1}^{n} S_i \frac{1}{KPL_i} + \frac{S_{sp}}{KPL_0}\right] + f_{rf}l_{rf}\sum_{i=1}^{n} S_i$$

The proof of Equation (8)

Emission from the quantity, D

$$T_{HE(D)} = \left[\frac{D}{b}\right] \times TECF \times TCFE \text{ where } D/b = \text{number of cold storage}$$

After the delivery of T_{c1}

$$T_{HE(D-T_{c1})} = \left[\frac{D - T_{c1}}{b}\right] \times TECF \times TCFE$$

After the delivery of $T_{c(n-1)}$

$$T_{HE[D-(T_{c1}+T_{c2}+\dots\dots\dots+T_{c(n-1)})]} = \left[\frac{D - (T_{c1} + T_{c2} + \dots\dots\dots + T_{c(n-1)})}{b}\right] \times TECF \times TCFE$$

Now, total carbon emissions until quantity, D is delivered

$$T_{HE(D)} = \left[\left\{\frac{D}{b} + \frac{D - T_{c1}}{b} + \dots\dots + \frac{D - (T_{c1} + T_{c2} + \dots\dots\dots + T_{c(n-1)})}{b}\right\}\right] \times TECF \times TCFE$$
$$= \left[\frac{nD - (n-1)T_{c1} - (n-2)T_{c2} - \dots\dots - T_{c(n-1)}}{b}\right] \times TECF \times TCFE$$
$$= \text{Let } T_{c1} = T_{c2} = \dots\dots = T_{c(n-1)} = T_c$$
$$= \left[\frac{nD - \{(n-1) + (n-2) + \dots\dots + 1\}T_c}{b}\right] \times TECF \times TCFE$$
$$= \left[\frac{nD - \left\{\frac{n(n-1)}{2}\right\}T_c}{b}\right] \times TECF \times TCFE$$
$$= \frac{n}{b}\left[\left\{D - \frac{(n-1)}{2}T_c\right\}\right] \times TECF \times TCFE$$

Proof of Equation (12) (Figure 3(b))

$$TETC_{T_c} = E_{refrigerated\ transportation} + E_{ordinary\ transportation} + E_{in-field\ refrigeration}$$
$$= E_{Delivery} + E_{Return} + E_{in-field\ refrigeration}$$
$$= [E(S_1) + E(S'_2) + \dots\dots + E(S_{sp})] + [E(S_1) + E(S'_2) + \dots\dots + E(S_{sp})] + [E(S_1) + E(S'_2) + \dots\dots + E(S_{sp})]$$
$$= CELF \times \left[\left\{\frac{S_1}{KPL_{GVW} - \propto \times q_1 \times W_i} + \frac{S'_2}{KPL_{GVW} - \propto \times q_2 \times W_i} + \dots\dots + \frac{S_{sp}}{KPL_{GVW} - \propto \times q_n \times W_i}\right\}\right] + \left[CELF \times \frac{1}{KPL_0}(S_1 + S'_2 + \dots\dots + S_{sp})\right] + [f_{rf}l_{rf}S_1 + f_{rf}l_{rf}S'_2 + \dots\dots + f_{rf}l_{rf}S_n]$$
$$= CELF \times \left[\left\{\frac{S_1}{KPL_1} + \frac{S'_2}{KPL'_2} + \dots\dots + \frac{S_{sp}}{KPL_{sp}}\right\} + \frac{1}{KPL_0}(S_1 + S'_2 + \dots\dots + S_{sp})\right] + [f_{rf}l_{rf}(S_1 + S'_2 + \dots\dots + S_n)]$$
$$= CELF \times \left[\left\{\sum_{i=1}^{n} S_{d(i)}\frac{1}{KPL_i}\right\} + \frac{1}{KPL_0}\sum_{i=1}^{n} S_{r(i)}\right] + f_{rf}l_{rf}\sum_{i=1}^{n} S_{(d)i}$$

where S_d = delivery routes and S_r = return routes

Proof of Equation (14) (Figure 3(c))

$$TETC_{T_c} = E_{refrigerated\ transportation} + E_{ordinary\ transportation} + E_{in-field\ refrigeration}$$
$$= E_{Delivery} + E_{Return} + E_{in-field\ refrigeration}$$
$$= CELF \times \left[\left\{\frac{S_1}{KPL_{GVW} - \propto \times Q \times W_i} + \frac{S_2}{KPL_{GVW} - \propto \times (Q - q_1) \times W_i}\right\}\right]$$

$$+\left[CELF \times \frac{S'_2}{KPL_0}\right]$$
$$+\left[f_{rf} l_{rf} S_1 + f_{rf} l_{rf} S_2\right]$$
$$= CELF \times \left[\left\{\frac{S_1}{KPL_1} + \frac{S_2}{KPL_2}\right\} + \frac{S'_2}{KPL_0}\right]$$
$$+\left[f_{rf} l_{rf}(S_1 + S_2)\right]$$
$$= CELF \times \left[\sum_{i=1}^{2} S_i \frac{1}{KPL_i} + \frac{S'_2}{KPL_0}\right] + f_{rf} l_{rf} \sum_{i=1}^{2} S_i$$

Emissions from SRT
Emissions from transportation

We can determine the amount of emission for a certain distance for the fully loaded trucks from Equation 2.

Emissions $E_{(s)}$ for $S = 149$ km which is the distance from SP to TDP1

$$E_{(s)} = CELF \times \frac{S}{KPL_{(28\ tonne)}} = 2.62 \times \frac{149}{1.33} = 293.52\ \mathrm{kg}CO_2$$

$$where\ CELF = 2.62\ \mathrm{kg}CO_2 L^{-1}$$

Again, Emissions $E_{(s)}$ for $S = 28$km which is the distance from TDP1 to TDP2

$$E_{(s)} = CELF \times \frac{S}{KPL_{(26\ tonne)}} = 2.62 \times \frac{28}{1.87} = 39.23\ \mathrm{kg}CO_2$$

$$where\ y = KPL_{GVW} - \propto \times (Q - q_1) \times W_i$$
$$= KPL_{(26\ tonne)} = 1.87$$

Total emissions: From Equation (9)

$$TCE_{T_c} = TETC_{T_c} + \left[\left(\frac{T_c}{b}\right) \times TECF \times TCFE\right]$$
$$= CELF \times \left[\sum_{i=1}^{n} S_i \frac{1}{KPL_i} + \frac{S_{sp}}{KPL_0}\right]$$
$$+ f_{rf} l_{rf} \sum_{i=1}^{n} S_i + \left[\left(\frac{T_c}{b}\right) \times TECF \times TCFE\right]$$
$$= 2.62 \times (112.03 + 14.97 + 19.67 + 20.70 + 52.07)$$
$$+ 2.62 \times (0.051 \times 290) + 39.17$$
$$= 574.94 + 38.75 + 167.86 = 781.55\ kgCO_2$$

Emissions from MRT
For MRT-I

From Equation (18),

$$TCE_{T_c} = \left[CELF \times \left[\left\{\sum_{i=1}^{n} S_{d(i)} \frac{1}{KPL_i}\right\} + \frac{1}{KPL_0} \sum_{i=1}^{n} S_{r(i)}\right]\right.$$
$$\left. + f_{rf} l_{rf} \sum_{i=1}^{n} S_{(d)i}\right]$$
$$+ \left[\frac{T_c}{b}\right] \times TECF \times TCFE$$
$$= 2.62 \times (121.92 + 108.79)$$
$$+ 2.62 \times (0.018 \times 526 + 0.0305 \times 265) + 39.17$$
$$= 604.46 + 45.98 + 167.86 = 818.30\ kgCO_2$$

For MRT-II

From Equation (20),

$$TCE_{T_c} = \left[CELF \times \left[\left\{\sum_{i=1}^{2} S_i \frac{1}{KPL_i} + \left(\frac{S'_2}{KPL_0}\right)\right\}\right.\right.$$
$$\left. + \left\{\sum_{i=3}^{n} S_i \frac{1}{KPL_i} + \left(\frac{S_{S_{sp}}}{KPL_0}\right)\right\}\right]$$
$$\left. + f_{rf} l_{rf} \left(\sum_{i=1}^{2} S_i + \sum_{i=3}^{n} S_i\right)\right]$$
$$+ \left[\left(\frac{T_c}{b}\right) \times TECF \times TCFE\right]$$
$$= 2.62 \times (88.34 + 69.82)$$
$$+ 2.62 \times (0.0305 \times 442) + 39.17$$
$$= 414.38 + 35.32 + 167.86 = 617.56\ kgCO_2$$