Optimizing sustainable multimodal distribution networks in the context of carbon pricing, with a case study in the Thai sugar industry

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Abstract

Transportation is a major cause of energy consumption and emissions which can be reduced by optimizing routings and using alternative modes of transport. This paper relates to the strategic design of multimodal transportation networks. It presents a general model of green vehicle routing problems that supports strategic decision-making by identifying optimal solutions and provides data on costs and emissions. Three general linear programming models were developed that optimize multimodal distribution networks that could be applied in many industries. Model I evaluates carbon emissions; model II assesses carbon emissions and capacity constraints; and model III establishes total costs including transportation, handling, storage, fuel and carbon costs.

Thailand is the third largest world sugar exporter in the world and is piloting carbon pricing, which will affect energy intensive industries, including the sugar industry. The models are applied using data obtained from a collaborating company. The research contributed to practice by informing managerial decisions relating to the export of sugar from the factory. This included evaluating the possible use of a dry port with rail connections, which could reduce transportation and carbon costs by 54.3% and facilitate the building of another factory to increase exports.

Keywords: Linear Programming; green logistics; multimodal transportation; distribution networks; sugar industry; carbon pricing.

1 Introduction

Transportation is a major source of carbon emissions, which contributes to climate change. Many countries are introducing carbon pricing to incentivise reductions in emissions. Green logistics seeks to design and operate logistics systems to maximize energy efficiency and minimize emissions (Leggieri & Haouari, 2017). The use of multimodal transport can reduce greenhouse gases by shifting journeys to modes with less environmental impact (Bauer et al., 2010). Previous research has used linear programming to optimize inbound and outbound logistics networks based on cost and sustainability objectives.

This research was motivated by the widespread requirement to reduce emissions and minimize costs under a carbon pricing regime through adopting and optimizing multimodal networks, which is particularly important for industries such as agriculture and mining that produce bulk products. The objective of this paper was to develop three novel generic linear programming models that evaluate emissions and costs to inform strategic decisions relating to network design. The models optimize distribution networks with multiple modes of transportation and dry ports. The first model assumes sufficient warehousing capacity and minimizes carbon emissions. The second model additionally considers warehousing capacity constraints. The third model considers total costs including transportation, handling, storage, fuel and carbon costs.

To illustrate the approach, a case study was conducted in collaboration with a Thai sugar company. Thailand is the third largest exporter of sugarcane (Workman, 2020) and in 2021 produced more than 66m tonnes of sugarcane (Office of The Cane and Sugar Board, 2021), at low cost (around 13.6 US cents/lb), second only to Brazil (11.2 cents/lb). Thailand's production is in a different season to Brazil which decreases competition in export markets (Manivong & Bourgois, 2017). Bagasse, a by-product of sugar milling is used for heat and power generation (Alves et al., 2015). Molasses-based ethanol is an important source of bioenergy (Gheewala et al., 2019). Thailand promotes the use of blended E10/E20 petrol (Silalertruksa & Gheewala, 2009), with reduced taxes on gasohol and B5 fuel (Wianwiwat & Asafu-Adjaye, 2011). Thailand's sustainable development goals emphasize sustainable agriculture as a main priority (DIO, 2021). Power generation from biomass residuals is an attractive option for satisfying the increasing demand for power in the Association of South East Asian Nations (ASEAN) in a cost effective and sustainable manner (Stich et al., 2017).

Mashoko et al. (2010) conducted a life cycle assessment (LCA) of the South African sugar industry and found that road transportation was the highest contributor to fossil energy use and concluded that significant savings could be achieved through optimizing delivery routes. Thailand's National Transport Master Plan is focused on sustainability and encourages multimodal transportation, emphasizing modes of transportation that minimize energy consumption, particularly rail, water and pipelines (Jaensirisak et al., 2016).

The first model, which considered CO_2 emissions, was used to evaluate the existing distribution network with road and river transportation and the proposed introduction of a dry port to include rail transportation. The second model evaluated CO_2 emissions with capacity constraints and was used to consider the possibility of doubling exports. The final model was used to evaluate the existing and proposed distribution networks in terms of total costs.

Section 2 presents a comprehensive literature review and identifies gaps in the academic literature. Section 3 describes sugar supply chains in Thailand. Section 4 describes the problem and the modelling assumptions. Section 5 describes the Linear Programming models. Section 6 presents the case study conducted in collaboration with a large sugar factory in the Lower Northern Region of Thailand. This is followed by the computational results, discussions and conclusions.

2 Literature Review

This section reviews the literature relating to sustainability, carbon pricing and multimodal network design using multi-objective linear programming.

2.1 Sustainability and the move towards carbon pricing

NASA defined climate change as "(t)he increase in Earth's average surface temperature due to rising levels of greenhouse gases" and "a long-term change in the Earth's climate or of a region on Earth" (NASA, 2008). Climate change is leading to adverse weather events including storms, droughts, heat waves and increased sea levels due to the polar ice caps melting (IPCC, 2014). In common with many countries, Thailand is vulnerable to climate change which causes floods, tropical storms and droughts. The monsoon season in 2011 caused severe flooding in 65 of 75 provinces, leading to 815 deaths and an estimated economic loss of $46.5bn. Rainfall in normal seasons has decreased over the last 50 years. In 2020, Thailand had a severe drought (Boonpanya & Masui, 2021b).

The main cause of climate change is an increase in atmospheric greenhouse gases caused by human activities (IPCC, 2014; Zhou & Lee, 2017) that cannot be naturally decomposed (IPCC, 2014). Global warming is caused by greenhouse gases in the earth's atmosphere trapping infrared radiation near the earth's surface (Waltho et al., 2019).

The Kyoto Protocol set binding targets for countries to reduce or limit greenhouse gas emissions (GHGEs) during the period 2008-2012. It also created a framework for national climate policies including the creation of carbon markets (UNFCCC, 2008). The protocol was extended until 2020 by the Doha Amendment (UNCC, 2012). This was followed by the Paris Agreement (UNFCCC, 2015) which agreed a collective goal to limit global warming to 1.5ºC with countries establishing 'nationally determined contributions'. The Glasgow Climate Pact (UNFCCC, 2021) agreed to 'phase down' the use of coal; and to provide climate finance to developing countries.

Global GHGEs are mainly attributed to five sectors: energy systems; industry; buildings; transport; and agriculture, forestry and other land uses (AFOLU). In 2018 the breakdown was: energy systems (34%), industry (24%), AFOLU (21%), transport (14%) and buildings (6%) (Lamb et al., 2021). In Thailand, the breakdown of CO_2 was: energy systems (36.2%), industry (31.3%), transport (26.1%) and other sectors (6.4%) (EPPO, 2018). Thus, transport in Thailand makes a greater contribution to total emissions than the global average. Freight is the third largest sector of the Thai economy. Road transport accounted for 87.32% of total domestic transport in 2012, with rail contributing only 1.4% (Boonpanya & Masui, 2021a). In 2015, Thailand had 467,221km of roads and a total of 4,043km of rail, of which 80% was single track, leading to a reliance on road transport (Boonpanya & Masui, 2021a).

Carbon pricing incentivizes low-carbon activities by internalizing the cost of greenhouse gas emissions back to the polluter and improves the competitiveness of low carbon activities and generates government revenue, which can support additional investment (World Bank, 2021). However, carbon taxes may have a negative impact on economic growth (Solaymani et al., 2015) with adverse effects being greater for low-income regions than high-income countries (Wesseh et al., 2017).

In 2019, Singapore was the first Asian country to introduce carbon taxes. China implemented a national emission trading system (ETS) in February 2021, the largest carbon market in the World. Vietnam passed a law in November 2020 to develop a carbon market and Thailand plans to pilot an ETS in the Eastern Economic Corridor, a special economic zone in three eastern provinces (World Bank, 2021). In Thailand, monitoring, reporting and verification and sector specific guidelines have been developed for the beverage, sugar, textile and flat glass industries (World Bank, 2021). Carbon pricing will have significant implications for the sugar industry that uses heavy duty trucks with high CO_2 emissions (Nilrit et al., 2017).

Recent research has applied Linear Programming to minimize carbon emissions in the supply chains for perishable products that require controlled temperature including fresh food transported by road and air (Wangsa et al., 2023) and fresh fish transported by road (Purnomo et al., 2022). Ardliana et al. (2022) considered general products that do not require controlled temperature transported by road and rail. Hence this previous research has addressed only one or two modes of transportation.

2.2 Multimodal networks

Multimodal transportation involves the transportation of products with two or more modes of transportation (Steadieseifi et al., 2014), which can reduce greenhouse gases by shifting to modes with less environmental impact (Bauer et al., 2010). Multimodal transportation may be considered in terms of three decision levels: the strategic level addresses long term planning decisions including the selection of transportation modes or the design of networks; tactical decisions relate to the optimization of existing infrastructure; and operational planning considers dynamic, real-time requirements (Steadieseifi et al., 2014).

Woxenius (2007) proposed a framework that included six transportation network designs: *direct link*, where goods are transported directly from the origin to destination; *corridor*, comprising an artery with high flow with short capillaries linking other nodes to the corridor; *hub-and-spoke*, where there is a hub node and all transportation routes go through the hub; *connected hubs*, where local hubs collecting local flows are connected to hubs in other regions; *static routes*, where a number of links are used regularly with transfer occurring at several notes; and *dynamic routes*, where links are determined by demand and may be changed during transportation. The utilization of multimodal networks can be maximized by using consolidation systems that combine low volume demand. These are mainly configured as hubs within hub-and-spoke networks that provide consolidation and freight handling facilities (Steadieseifi et al., 2014).

Multimodal transportation systems may include freight terminals that perform four functions: transferring cargo between two transportation modes; assembling freight in preparation for transfer; storing inventory prior to pick up or delivery; and the management of logistical flows (Slack, 1999). A dry port uses rail to connect an inland intermodal terminal with a seaport (Roso et al., 2009). Dry ports help reduce congestion and can reduce GHGEs, as 35 trucks can be replaced by a single train (Roso, 2007). Dry ports may provide customs clearance, consolidation, storage of empty containers and goods and maintaining and repairing containers (Roso et al., 2009). There are various types of seaport ranging from a small quay to a large centre with many terminals with multimodal/intermodal interfaces, logistics/distribution facilities, industrial development areas, free zones and trading hubs (Bichou & Gray, 2005). The number of modes of transportion at seaports may vary.

2.3 Optimising Network Design Problems using Linear Programming with multiple objectives

The Scopus database was used to search for articles and reviews with the terms “linear programming” AND “network design” AND (“multiobjective” OR multi-objective”) in the title, abstract and keywords, which identified 188 outputs. This was followed by a second search for the terms “linear programming” AND “multimodal” AND (“multiobjective” OR multi-objective”), which found a further 33 outputs, giving a total of 217 outputs that were considered for the review. The search was then limited to the last ten years, which removed 20 outputs. Full texts were obtained for the 188 articles that were available from Newcastle University Library or from internet sources. The nine papers that could not be obtained were discounted on the basis of the abstract. The remaining outputs were screened for relevance and the full texts were assessed for eligibility.

The literature review focused on the most relevant outputs which are summarized in Table 1. The problem characteristics include: logistics (inbound/outbound); the data used; the product considered, whether the product is perishable, the inclusion of recycling and finally the decision level (strategic, tactical or operational). This is followed by the mode of transportation (air, road, water, rail / dry port) and then the criteria considered by the objective function in terms of costs (operational costs, transportation costs, greenhouse gas emission charges, fuel cost, warehousing/stocking costs) and green criteria (fuel consumption, greenhouse gas emissions and environmental impact).

Saffar et al. (2014) proposed a multi-objective fuzzy mathematical programming model for optimizing green networks. It aimed to integrate forward and reverse supply chains and optimize traditional cost and environmental objectives in the design of a logistics network. The work considered the environmental impact of road transport for multiple products and periods and integrated strategic, tactical and operational decisions. The data for the modelling was obtained from the literature (Pishvaee & Hamed, 2009; Pishvaee & Torabi, 2010).

Bortolini et al. (2016) used linear programming to optimize the tactical planning of outbound multimodal distribution networks supplying fresh food by air, road and rail. The objectives were to minimize cost, carbon footprint and deliver time. Data were obtained from an Italian case study. Heidari-Fathian and Pasandideh (2018) developed a mixed integer linear programming model to minimize the total cost and environmental impact of an outbound blood supply chain network with transportation by road. Yadollahinia et al. (2018) used mixed integer linear programming to model forward and reverse logistics in tire supply networks with road transportation. The objectives were to maximize total profit, customer satisfaction and to minimize the total distance travelled. The model was applied at the operational level with data obtained from an Iranian manufacturing plant and two distribution centers supplying eight cities.

Martins et al. (2019) proposed a multi-objective mixed integer linear programming model that optimized a food bank supply chain network with road transportation with inward and outward logistics at the operational level using objective functions that took into account economic, environmental and social aspects of sustainability. Data were obtained from the Portuguese Federation of Food Banks, which coordinates a network of 21 food banks. Rohmer et al. (2019) used a linear programming model to address sustainability issues in a food system network design problem with inbound and outbound logistics that utilized multiple modes of transportation at the operational level. The objectives considered included cost, CO_2 emissions, water and land use, fossil fuel usage and dietary health. The data was obtained from a case study conducted in the Netherlands.

Vafaei et al. (2020) proposed a mixed integer programming model for optimizing a sustainable distribution network design with inbound and outbound logistics and road transportation at the operational level. The objectives included were costs associated with transportation, purchasing vehicles, building warehouses, CO_2 emissions and the number of job opportunities was also considered. The data was obtained from Digikala, an online retailer. Yakavenka et al. (2020) developed a mixed integer linear programming model optimizing sustainable supply networks for fruit transported by trucks with outbound logistics at the strategic level. The objectives included transportation cost and emissions generated. The data was obtained from a fruit importer located in North-East Europe.

Orjuela-Castro et al. (2021) used mixed integer linear programming to optimize a seasonal perishable food supply chain logistics network with outbound logistics at the operational level. The objectives included minimizing transportation costs and the loss of perishable food due to transportation by non-refrigerated trucks. The data was obtained from surveys conducted in Columbia. Ardliana et al. (2022) developed a mixed integer linear programming model to optimize production and multimodal transportation decisions at the operational level. The model aimed to minimize total costs which included costs associated with operations, transport, CO_2 emissions and warehousing. The model evaluated two modes of transportation: road and rail for a hypothetical example.

Purnomo et al. (2022) used mixed integer linear programming to optimize a sustainable and traceable closed-loop fish supply chain network including sea farms, fishponds, warehouses, plants distribution centers, fish recycling centers, livestock markets and distribution to multiple customers over multiple periods at the operational level. The objectives included costs associated with transportation, operations, warehousing and CO_2 emissions. The model considered only truck transportation. The data was obtained from an Indonesian case study. Bortolini et al. (2022) used linear programming to optimize a supply chain network with outbound logistics at the tactical level for construction materials transported by road. The objectives included operational cost, warehouse cost, and CO_2 emissions. The data was based from a European case study.

Kharrat et al. (2022) proposed mixed integer linear programming to optimize the outbound distribution of cereal products via road transportation from suppliers to customers located in urban areas at the strategic, tactical and operational levels. The objectives considered economic, environmental, social sustainability. The economic indicators included costs (fuel, wages, vehicle maintenance, vehicles, warehouse opening, storage and handling) and vehicle fill rate. The environmental indicators included CO_2 due to transport, vehicle depreciation, construction of facilities and facility operations. The social indicators included the reduction of accident risk rate due to reduced travelling, noise level and job opportunities. The institutional constraints included limits to travelling time and routes. The data were obtained from a case study in the Tunisian agri-food industry distribution network.

Orjuela-Castro et al. (2022) presented a mixed integer linear programming for agri-food logistics networks design with outbound logistics. It established the location of distribution centers, transformation nodes and stores, markets and hypermarkets. The objectives include minimizing operational costs and the loss of perishable food. The model considered only truck transportation. The data was obtained from a case study in Columbia. Fathi et al. (2023) presented mixed integer linear programming to optimize the design of an agri-food supply chain network with inbound and outbound logistics at the strategic level. The objectives included: economic sustainability (minimizing operational and transportation costs): environmental sustainability (minimizing CO_2 and NO_2 emissions and water consumption) and social sustainability (maximizing the number of jobs). A further objective was to minimize the product delivery time. The model considered only truck transportation. The data was obtained from a case study conducted by Kadbanoo company.

Moreno-Camacho et al. (2023) proposed mixed integer linear programming to determined optimal location and capacity of processing and distribution facilities for a dairy supply chain with inbound and outbound logistics. The objectives included economic criteria (total network costs); an environmental dimension (CO_2 emissions) and social criteria (work conditions and societal development). The model considered only road transportation. The data was based from a case study of supply chain of dairy products in Columbia. Wangsa et al. (2023) presented mixed integer linear programming model to optimize total costs of logistics activities including purchasing, inspection, food waste, packing, cold storage, transportation and carbon emission. The model considered air and road transportation. The data was based on a case study of a network supplying fresh fruits to a single processing and packaging centre in Malang city and two distribution centres in Surabaya City in Indonesia.

2.4 Research Gap and Research Contribution

Table 1 summarizes relevant literature. The research gaps are as follows:

- There is a lack of research that has considered exports and dry ports;
- Some papers have considered several modes of transport, but none have simultaneously considered road, water, rail and dry ports.

The main contributions of the paper are as follows:

- The development of general linear programming models that optimize outbound distribution networks to minimize carbon emissions and costs;
- Modelling multimodal distribution networks including road, water, rail and dry ports;
- Contributing to practice by supporting managerial decisions relating to carbon pricing, distribution network design and the possible expansion of exports.

Table 1 Literature Summary

Authors (year)	Problem Characteristics						Transportation Mode					Objective Function based on							
	Logistics	Data used	Product	Perishable	Recycling	Decision level	Air	Road	Water	Rail	Dry port	Operational cost	Transport cost	GHG emission charges	Fuel cost	Warehouse/stock cost	Fuel consumption	GHG emissions	Environment impact
Saffar et al. (2014)	IO	Literature	Product		✓	STO		✓					✓					✓	✓
Bortolini et al. (2016)	O	Case	Food	✓		T	✓	✓		✓		✓						✓	
Heidari-Fathian and Pasandideh (2018)	O	Synthetic	Blood	✓	✓	O		✓				✓	✓			✓		✓	
Yadollahinia et al. (2018)	IO	Case	Tires		✓	O		✓				✓	✓					✓	
Martins et al. (2019)	IO	Case	Food	✓		O		✓				✓	✓	✓		✓			✓
Rohmer et al. (2019)	IO	Case	Food	✓		O	✓	✓	✓	✓		✓	✓						✓
Vafaei et al. (2020)	IO	Case	Online retailer			O		✓				✓	✓			✓			✓
Yakavenka et al. (2020)	O	Case	Fruit	✓		S		✓				✓							✓
Orjuela-Castro et al. (2021)	O	Survey	Fruit	✓		O		✓					✓						
Ardliana et al. (2022)	IO	Synthetic	Product			O		✓		✓		✓	✓	✓		✓			✓
Purnomo et al. (2022)	IO	Case	Fresh fish	✓	✓	O		✓				✓	✓	✓		✓			✓
Bortolini et al. (2022)	O	Case	Civil materials			T		✓				✓				✓		✓	
Kharrat et al. (2022)	O	Case	Cereal			STO		✓					✓					✓	
Orjuela-Castro et al. (2022)	O	Case	Agri-food	✓		S		✓				✓							
Fathi et al. (2023)	IO	Case	Agri-food	✓		S		✓				✓	✓					✓	
Moreno-Camacho et al. (2023)	IO	Case	Dairy	✓		S		✓				✓						✓	
Wangsa et al. (2023)	IO	Case	Fresh food	✓		O	✓	✓				✓	✓	✓		✓			
This work	O	Case	Sugar			S		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

Abbreviation: Logistic case: Inbound (I) and Outbound (O); Decision level: Strategic (S), Tactical (T), and Operational (O).

3 Sugar supply chains in Thailand

Thailand's agriculture sector employs 49% of the population and contributes 10% of GDP (Supratid & Aribarg, 2022). Agricultural land covers 29.3m hectares, approximately 46% of the nation's surface area. The primary agricultural exports are rice, rubber, sugar, cassava, and oil palm. In 2021, Thailand exported approximately 3.9 million tons of sugar, generating $1,737m (Office of The Cane and Sugar Board, 2022). In 2020, the sugarcane plantation area in Thailand was 1.73m hectares, covering 47 provinces (Office of The Cane and Sugar Board, 2021) (Sowcharoensuk, 2021).

In 2022, there were 58 sugarcane factories in Thailand (Office of The Cane and Sugar Board, 2022). The destination of sugar was: (i) domestic consumption, including direct consumption and indirect consumption by other industries; (ii) exports of raw, white and refined sugar; and (iii) stockpiling (Sriroth et al., 2016). Figure 1 illustrates the sugar supply chain in Thailand.

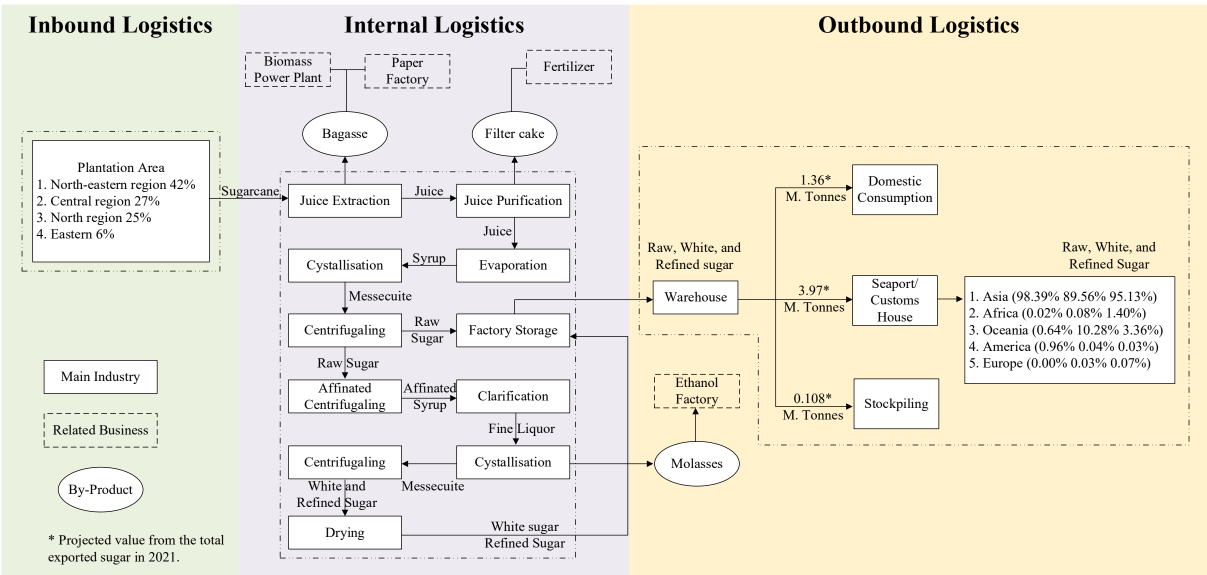

Figure 1 Sugar supply chain in Thailand

The Sugars and Derivatives Analytical Laboratory (2019) described the sugar industry supply chain as follows. First, farmers plant, grow and harvest sugarcane. Inbound logistics then transports the sugarcane to a local factory. Sugar production starts with sugarcane juice extraction using a crushing machine. Next, a heating and filtering purification process sterilizes and cleans the juice that is fed to a boiler to evaporate the water to concentrate the sugarcane juice into a syrup, which then goes through a vacuum pan which evaporates water until the syrup is at its saturation point, when sugar crystals are formed. The sugar crystals and cane syrup (molasses) are called Messecuite. Sugar crystals are separated from the molasses by centrifuging the Messecuite to produce raw sugar.

The production of white and refined sugar process starts with raw sugar going through the affinated centrifuging process. Raw sugar is dissolved in water to produce affinated syrup which then goes through a clarification process to remove impurities to produce a fine liquor that goes through a vacuum pan to evaporate until it reaches its saturation point to produce Messecuite, which is centrifuged to separate the refined sugar and white sugar crystals from the molasses. White and refined sugar goes through an oven to remove the moisture (Sugars and Derivatives Analytical Laboratory, 2019).

Sugar is transported by outbound logistics to a warehouse for storage prior to distribution or stockpiling. In 2021, domestic consumption was approximately 1.36m tonnes, exports 3.97m tonnes and stockpiling 0.108m tonnes (Office of The Cane and Sugar Board, 2022). Three by-products can be processed to create added value: bagasse can be processed into paper or biomass energy production; filter cake can be used to make fertilizer and molasses can be used to produce ethanol (Sowcharoensuk, 2021).

4 Problem description and assumptions

The distribution network for sugar exports may include road, rail and water, together with warehouses and/or dry ports. Road transportation is dominant but results in high emissions and costs. The proposed linear programming models allow the design of distribution networks with multiple modes of transportation with/without dry ports and warehouse facilities to be optimized in terms of carbon emissions and total transportation costs including carbon pricing. The research considered ‘minor seaports’ with two modes of transportation (road and water), or ‘major seaports’ with three modes (road, rail and water). Dry ports require a seaport with rail access. The mathematical models considered three scenarios: (i) the routes and modes of transportation to minimize CO_2 emissions; (ii) the routes and modes of transportation to minimize CO_2 emissions with warehouse capacity constraints; and (iii) the routes and modes of transportation to minimize total costs (including CO_2 emission costs).

4.1 Assumptions

The model adopted the following assumptions:

- The amount of sugar is always sufficient to satisfy demand;
- There is sufficient vehicle capacity to meet demand;
- No sugar is lost in transportation or warehousing.

4.2 Indices

i index of factories $i = 1,2...NF,$ where NF = total number of factories

j index of warehouses $j = 1,2 ..NW,$ where NW = total number of warehouses

k index of minor seaports $k = 1,2 .. NP, NP$ = number of seaports with road access only

l index of major seaports $l = 1,2 .. NL, NL$ = number of seaports with road and rail access

m index of dry ports (DP) $m = 1,2.. ND,$ where ND = number of dry ports

v index of types vehicles $v = 1,2...NV,$ where NV = total number of types vehicles

4.3 Parameters

S amount of sugar (tonnes)

CAP_v capacity of the vehicle (tonnes)

EF_v emission factor of vehicle ($kgCO_2$/tonnes*km)

a_{ikv} transportation distance between factory i to minor seaport k by vehicle v (km)

b_{ijv} transportation distance between factory i to minor seaport j by vehicle v (km)

c_{jkv} transportation distance between factory j to minor seaport k by vehicle v (km)

d_{imv} transportation distance between factory i to dry port m by vehicle v (km)

e_{mlv} transportation distance between dry port m to major seaport l by vehicle v (km)

$CAPWH$ capacity of warehouse (tonnes)

TFU_v transfer cost for loading the sugar onto the vehicle type v (Baht/tonne)

TFD_v transfer cost for unloading the sugar out of the vehicle type v (Baht/tonne)

TFB_j transfer cost of sugar from warehouse j to barge (Baht/tonne)

TFB_k transport cost of sugar by barge to minor seaport k (Baht/tonne)

TFM_{kv} transfer cost for loading sugar onto the liner at seaport k from vehicle v (Baht/tonne)

WHC_k storage cost at minor seaport k (Baht/tonne)

WHC_m storage cost at major seaport m (Baht/tonne)

WHC_j storage cost at warehouse j (Baht/tonne)

FC fuel cost (Baht/litre)

VHC vehicles hire coefficient

$CAPC$ capacity of container (tonne)

TFI cost of loading sugar into container (Baht/container)

Fr freight rate of train (Baht/container)

CTN number of containers for transporting sugar

R_v number of times sugar transported by vehicle v

TPC transport cost by train from dry port to seaport (Baht/container)

CEX CO_2emission cost (Baht/tonne)

M large positive number

TC_{ikv} total cost for transporting sugar from factory *i* to minor seaport *k* by vehicle *v* (Baht)

TC_{ijv} total cost for transporting sugar from factory *i* to warehouse *j* by vehicle *v* (Baht)

TC_{jkv} total cost for transporting sugar from warehouse *j* to minor seaport *k* by vehicle *v* (Baht)

TC_{imv} total cost for transporting sugar from factory *i* to dry port *m* by vehicle *v* (Baht)

TC_{mlv} total cost for transporting sugar from dry port *m* to major seaport *l* by vehicle *v* (Baht)

4.4 Decision variables

ε_{ikv} a binary variable (1 if sugar is transported from factory *i* to seaport *k* by vehicle *v*; 0, otherwise).

μ_{ijv} a binary variable (1 if sugar is transported from factory *i* to warehouse *j* by vehicle *v*; 0, otherwise).

ρ_{jkv} a binary variable (1 if sugar is transported from warehouse *j* to seaport *k* by vehicle *v*; 0, otherwise).

σ_{imv} a binary variable (1 if sugar is transported from factory *i* to dry port *m* by vehicle *v*; 0, otherwise).

ω_{mlv} a binary variable (1 if sugar is transported from dry port *m* to seaport *l* by vehicle *v*; 0, otherwise).

Q_{ikv} the amount of sugar transported from factory *i* to seaport *k* by vehicle *v* (tonne)

R_{ijv} the amount of sugar transported from factory *i* to warehouse *j* by vehicle *v* (tonne)

S_{jkv} the amount of the sugar transported from warehouse *j* to seaport *k* by vehicle *v* (tonne)

T_{imv} the amount of sugar transported from factory *i* to dry port *m* by vehicle *v* (tonne)

U_{mlv} the amount of the sugar transported from dry port *m* to seaport *l* by vehicle *v* (tonne)

4.5 Model I: Carbon dioxide emission

Model I minimizes the carbon emissions associated with the routes and the modes of transportation (road, rail and water):

$$MinZ = \sum_{i}^{NF}\sum_{k}^{NP}\sum_{v}^{NV}(CAP_v \times a_{ikv} \times EF_v \times R_v)\varepsilon_{ikv}$$
$$+ \sum_{i}^{NF}\sum_{j}^{NW}\sum_{v}^{NV}\left(CAP_v \times b_{ijv} \times EF_v \times R_v\right)\mu_{ijv}$$
$$+ \sum_{j}^{NW}\sum_{k}^{NP}\sum_{v}^{NV}\left(CAP_v \times c_{jkv} \times EF_v \times R_v\right)\rho_{jkv}$$
$$+ \sum_{i}^{NF}\sum_{m}^{ND}\sum_{v}^{NV}(CAP_v \times d_{imv} \times EF_v \times R_v)\sigma_{imv}$$
$$+ \sum_{m}^{ND}\sum_{l}^{NL}\sum_{v}^{NV}(CAP_v \times e_{mlv} \times EF_v \times R_v)\omega_{mlv} \quad (1)$$

Subject to:

$$\sum_{i}^{NF}\sum_{k}^{NP}\sum_{v}^{NV}\varepsilon_{ikv} + \sum_{i}^{NF}\sum_{j}^{NW}\sum_{v}^{NV}\mu_{ijv} + \sum_{i}^{NF}\sum_{m}^{ND}\sum_{v}^{NV}\sigma_{imv} = 1 \ (2)$$
$$\sum_{i}^{NF}\sum_{v}^{NV}\mu_{ijv} = \sum_{k}^{NP}\sum_{v}^{NV}\rho_{jkv} \ ; \ \forall j \quad (3)$$
$$\sum_{i}^{NF}\sum_{v}^{NV}\sigma_{imv} = \sum_{l}^{NL}\sum_{v}^{NV}\omega_{mlv} \ ; \ \forall m \ (4)$$
$$\varepsilon_{ikv}, \mu_{ijv}, \rho_{jkv}, \sigma_{imv}, \omega_{mlv} \in \{0,1\} \ ; \ \forall \ i, j, k, m, l, v \ (5)$$

Constraint (2) includes: 1) the transportation of sugar from the factory to a major seaport; (2) the transportation of sugar to a warehouse and then to a major seaport; and (3) transport from the factory to a major seaport by railway via a dry port. Constraint (3) ensures that sugar can only be released from the selected warehouse. Constraint (4) ensures that sugar can only be released from a dry port when it is selected. Constraint (5) specifies that the decision variables are binary.

4.6 Model II: Carbon dioxide emission with warehouse capacity constraints

Model II optimizes the routes and modes of transportation (road, rail, water) for sugar exports to minimize carbon dioxide emissions with warehouse capacity constraints:

$$
\begin{aligned}
MinZ = & \sum_{i}^{NF}\sum_{k}^{NP}\sum_{v}^{NV}(Q_{ikv}\times\ a_{ikv}\ \times EF_v) \\
& + \sum_{i}^{NF}\sum_{j}^{NW}\sum_{v}^{NV}\left(R_{ijv}\times\ b_{ijv}\ \times EF_v\right) \\
& + \sum_{j}^{NW}\sum_{k}^{NP}\sum_{v}^{NV}\left(S_{jkv}\times\ c_{jkv}\ \times EF_v\right) \\
& + \sum_{i}^{NF}\sum_{m}^{ND}\sum_{v}^{NV}(T_{imv}\times\ d_{imv}\ \times EF_v) + \sum_{m}^{ND}\sum_{l}^{NL}\sum_{v}^{NV}(U_{mlv}\times\ e_{mlv}\ \times EF_v) \quad (6)
\end{aligned}
$$

Subject to:

$$Q_{ikv} + R_{ijv} + T_{imv} = S\ ; \forall i, \forall j, \forall k, \forall m, \forall v \ (7)$$

$$R_{ijv} =\ S_{jkv}\ ; \forall i, \forall j, \forall k, \forall v \ (8)$$

$$T_{imv} =\ U_{mlv}\ ; \forall i, \forall m, \forall l, \forall v \ (9)$$

$$R_{ijv}\ \leq CAPWH\ ; \forall i, \forall j, \forall v \ (10)$$

$$Q_{ikv}, R_{ijv}, S_{jkv}, T_{imv}, U_{mlv} \geq 0\ ; \forall i, \forall j, \forall k, \forall m, \forall v \ (11)$$

The objective function, Equation (6), evaluates the total carbon emissions for all modes of transport. Constraint (7) ensures that the sum of sugar transported by all modes of transport is equal to the amount exported from the factory. Constraint (8) ensures that the quantities transferred to and from each warehouse are equal. Constraint (9) ensures that the quantities transferred to and from each dry port are equal. Constraint (10) ensures that the warehouse capacity is not exceeded. Constraint (11) specifies that the decision variables are real numbers greater than zero.

4.7 Model III: Total cost including transportation and carbon dioxide emission costs

Model III minimizes the total cost including transportation and carbon emission costs for all modes of transport (equation 12):

$$MinZ = \sum_{i}^{NF}\sum_{k}^{NP}\sum_{v}^{NV} TC_{ikv}\varepsilon_{ikv} + \sum_{i}^{NF}\sum_{j}^{NW}\sum_{v}^{NV} TC_{ijv}\mu_{ijv} + \sum_{j}^{NW}\sum_{k}^{NP}\sum_{v}^{NV} TC_{jkv}\rho_{jkv} + \sum_{i}^{NF}\sum_{m}^{ND}\sum_{v}^{NV} TC_{imv}\sigma_{imv} + \sum_{m}^{ND}\sum_{l}^{NL}\sum_{v}^{NV} TC_{mlv}\omega_{mlv} \quad (12)$$

The total cost of transporting sugar from a factory to a minor seaport via a warehouse (TC_{ikv}) was calculated using Equation (13):

$$TC_{ikv} = (TFU_v \times S) + (TFD_v \times S) + (TFM_{kv} \times S) + \left[R_v \times \left(\frac{a_{ikv}\times 2}{2.2}\right) \times FC \times VHC\right] + (WHC_k \times S) + \left[\left(\frac{R_v \times CAP_v \times a_{ikv} \times EF_v}{1000}\right) \times CEX\right] \ (13)$$

The total cost of transporting sugar from factories to warehouses (TC_{ijv})was calculated using Equation (14):

$$TC_{ijv} = (TFU_v \times S) + (TFD_v \times S) + \left[R_v \times \left(\frac{b_{ijv}\times 2}{2.2}\right) \times FC \times VHC\right] + \left(WHC_j \times S\right) + \left[\left(\frac{R_v \times CAP_v \times b_{ijv} \times EF_v}{1000}\right) \times CEX\right] \ (14)$$

The total cost of transporting sugar from warehouses to seaports (TC_{jkv}) by road ($v \leq 9$) was calculated using Equation (15):

$$TC_{jkv} = (TFU_v \times S) + (TFM_{kv} \times S) + \left[R_v \times \left(\frac{c_{jkv}\times 2}{2.2}\right) \times FC \times VHC\right] + \left[\left(\frac{R_v \times CAP_v \times c_{jkv} \times EF_v}{1000}\right) \times CEX\right] \ ; \ v \ \leq 9 \ (15)$$

The total cost of transporting sugar from warehouses to seaports (TC_{jkv}) by rail (v = 10) was calculated using equation 16:

$$TC_{jkv} = \left(CTN \times (TFI + Fr)\right) + \left[\left(\frac{R_v \times CAP_v \times d_{jkv} \times EF_v}{1000}\right) \times CEX\right] \ ; \ (v \ = \ 10) \ (16)$$

The total cost of transporting sugar from warehouses to seaports (TC_{jkv}) by water (v =11) was calculated using equation 17:

$$TC_{jkv} = \left(S \times \left(TFB_j + TPB_k + TFM_{kv}\right)\right) + \left[\left(\frac{R_v \times CAP_v \times c_{jkv} \times EF_v}{1000}\right) \times CEX\right] \ ; \ (v = 11) \ (17)$$

The total cost of transporting sugar from a factory to a dry port (TC_{jkv}) by road ($v \leq 9$) was calculated using equation 18:

$$TC_{imv} = (TFU_v \times S) + (TFD_v \times S) + (WHC_m \times S) + \left[R_v \times \left(\frac{d_{imv} \times 2}{2.2}\right) \times FC \times VHC\right] + \\ + \left[\left(\frac{R_v \times CAP_v \times d_{imv} \times EF_v}{1000}\right) \times CEX\right] \; ; \; v \; \leq 9 \; (18)$$

The total cost of transporting sugar from a factory to a dry port by rail (v = 10) was calculated using equation 19:

$$TC_{imv} = \left(CTN \times (TFI + Fr)\right) + \left[\left(\frac{R_v \times CAP_v \times d_{imv} \times EF_v}{1000}\right) \times CEX\right] \; ; \; (v \; = \; 10) \; (19)$$

The total cost of transporting sugar from a dry port to a major seaport by rail (v = 10) was calculated using equation 20:

$$TC_{mlv} = (CTN \times TPC) + \left[\left(\frac{R_v \times CAP_v \times e_{mlv} \times EF_v}{1000}\right) \times CEX\right] \; ; \; (v \; = \; 10) \; (20)$$

Subject to:

Eq. (2) – Eq. (5)

5 Case study

The mathematical models were used by sugar factory managers to select transportation modes, identify appropriate networks and to evaluate the possible use of a dry port. The sugar factory plantation area covers seven provinces in the Lower Northern Region of Thailand. The Factory's current and proposed outbound logistics network is shown in Figure 2. This included several network types: a direct link, corridor and a variant of connected hubs (Woxenius, 2007). The network had a direct road link between the factory and the seaport and a connected hub including four warehouses and three minor seaports with road links. Another major seaport with road and rail access connects to a dry port to provide a corridor for sugar exports. Introducing multimodal transport or solely using rail with a dry port could reduce the emissions and costs. In 2018, sugar exports were 141,152.5 tonnes/year (considered by models I and III) and warehousing capacity was sufficient. The Company wished to evaluate the possibility of building another identical factory to double export capacity, which was considered in model II, which included a capacity constraint.

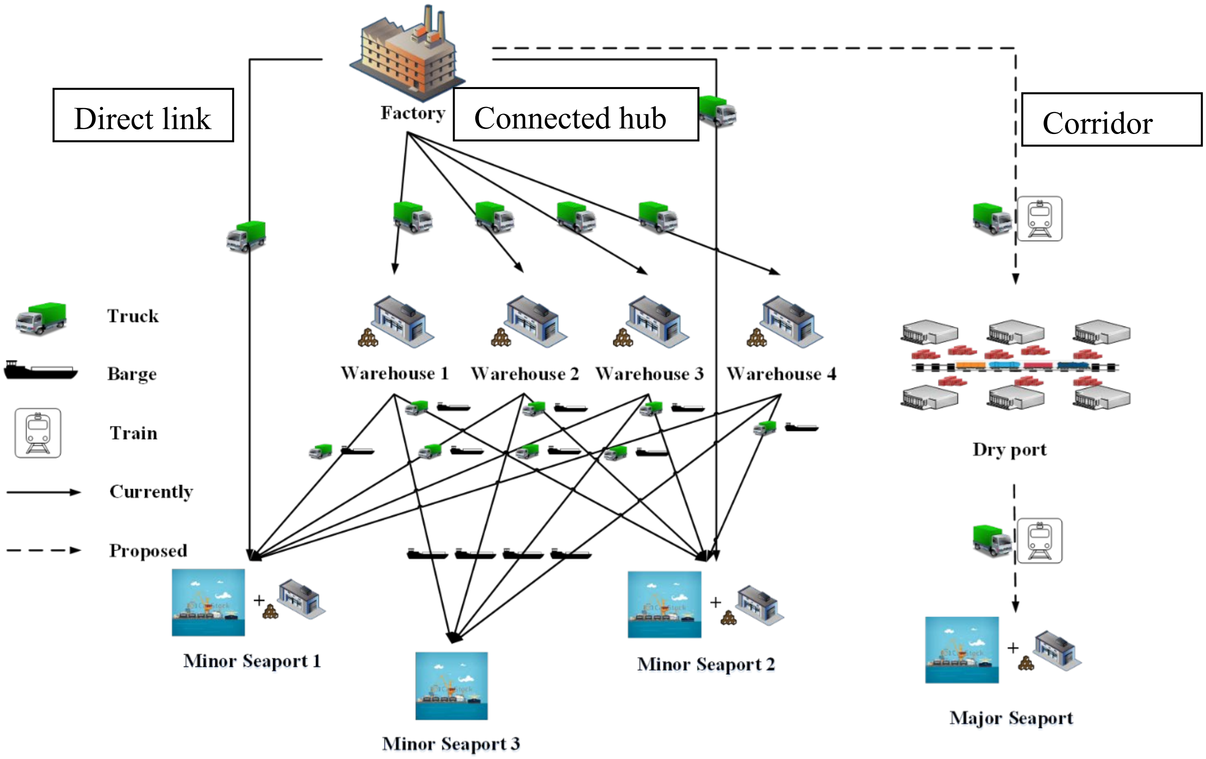

Figure 2 Case study distribution network for sugar exports

5.1 Case study data

The sugar factory provided the data summarized in Table 2 - Table 11 in 2018. Light and heavy trucks, barges and trains were considered. The distances were obtained from Google Maps.

Table 2 Case study model parameters

Parameters	Notation	Case study
Number of factories	*NF*	1
Number of warehouses	*NW*	4
Number of minor seaports	*NP*	3
Number of major seaports	*NL*	1
Number of dry ports	*ND*	1
Number of vehicle types	*NV*	11
Amount of sugar (tonnes)	*S* (model I and III) *S* (model II)	141,152.5 tonnes; 282,305 tonnes.
Capacity of vehicle (tonnes)	CAP_v	See Table 3

Emission factor of vehicle ($kgCO_2$/tonnes*km)	EF_v	See Table 3
Transportation distance: factory i to seaport k by vehicle v (km)	a_{ikv}	See Table 4
Transportation distance: factory i to warehouse j by vehicle v (km)	b_{ijv}	See Table 5
Transportation distance: warehouse j to minor seaport k by vehicle v (km)	c_{jkv}	See Table 6
Transportation distance: factory i to dry port m by vehicle v (km)	d_{imv}	See Table 7
Transportation distance: dry port m to major seaport by vehicle v (km)	e_{mlv}	See Table 7
Capacity of warehouse (tonnes)	$CAPWH$	200,000 tonnes
Transfer cost for loading the sugar onto the vehicle type v	TFU_v	See Table 8
Transfer cost for unloading the sugar out of the vehicle type v (Baht/tonne)	TFD_v	See Table 8
Transfer cost of sugar from warehouse j to barge	TFB_j	See Table 9
Transport cost of sugar by barge to minor seaport k (Baht/tonne)	TFB_k	See Table 10
Transfer cost for loading the sugar onto the ocean liner at seaport k from vehicle v (Baht/tonne)	TFM_{kv}	See Table 9
Storage cost at minor seaport k (Baht/tonne)	WHC_k	$k = 1$; 55 Baht/tonne $k = 2$; 24 Baht/tonne
Storage cost at major seaport m (Baht/tonne)	WHC_m	15 Baht/tonne
Storage cost at warehouse j (Baht/tonne)	WHC_j	See Table 9
Fuel cost (Baht/litre)	FC	23.5 Baht/litre
Vehicles hire coefficient	VHC	1.4
Capacity of container (tonne)	$CAPC$	21.7 tonnes
Cost of loading sugar into container (Baht/container)	TFI	477.4 Baht/tonne
Freight rate of train (Baht/container)	Fr	5,130 Baht/container
Number of containers for transporting sugar	CTN	6,516
Number of times sugar transported by vehicle v	R_v	S / CAP_v

Transport cost by train from dry port to major seaport (Baht/container)	*TPC*	1,850 Baht/container
Carbon dioxide emission cost (Baht/tonne)	*CEX*	115.75 Baht/tonne
Large positive number	*M*	*M*

Table 3 The capacity and emission factors of vehicles.

Type of Vehicle (Mode)	Capacity of vehicle (tonne)	Emission Factor ($kgCO_2$/tonne.km)
1 (Road)	7.00	0.15190
2 (Road)	8.50	0.07140
3 (Road)	11.00	0.06740
4 (Road)	16.00	0.05860
5 (Road)	32.00	0.04885
6 (Road)	32.00	0.04595
7 (Road)	32.00	0.04975
8 (Road)	32.00	0.04995
9 (Road)	32.00	0.05130
10 (Rail)	782.00	0.03700
11 (Water)	2,900.00	0.04460

Table 4 Distance from factory to seaport by vehicles (km)

Type of Vehicle (Mode)	Seaport			
	Minor seaport 1	Minor seaport 2	Minor seaport 3	Major seaport
1-9 (Road)	472.00	388.00	-	492
10 (Rail)	-	-	-	-
11 (Water)	-	-	-	-

*There is no data for seaport 3 since it cannot be accessed directly from the factory

Table 5 Distance from factory to warehouse by vehicles (km)

Type of Vehicle (Mode)	Warehouse			
	Warehouse 1	Warehouse 2	Warehouse 3	Warehouse 4
1-9 (Road)	259.00	302.00	305.00	308.00
10 (Rail)	-	-	-	-
11 (Water)	-	-	-	-

Table 6 Distance from warehouse to seaports by vehicles (km)

Type of Vehicle (Mode)	Warehouse	Seaport			
		Minor seaport 1	Minor seaport 2	Minor seaport 3	Major seaport
1-9 (Road)	Warehouse 1	214.00	127.00	-	-
	Warehouse 2	179.00	86.00	-	-

	Warehouse 3	181.00	88.00	-	-
	Warehouse 4	184.00	91.00	-	-
10 (Rail)	Warehouse 1	-	-	-	-
	Warehouse 2	-	-	-	-
	Warehouse 3	-	-	-	-
	Warehouse 4	-	-	-	-
11 (Water)	Warehouse 1	262.76	176.17	265.87	-
	Warehouse 2	192.76	106.00	195.87	-
	Warehouse 3	194.76	108.00	197.87	-
	Warehouse 4	197.76	111.00	200.87	-

Table 7 Distance from factory to the dry port by vehicles

Type of Vehicle (Mode)	Distance from factory to the dry port (km)	Distance from the dry port to major seaport (km)
1-9 (Road)	378.00	-
10 (Rail)	369.00	100.00
11 (Water)	-	-

Table 8 Transfer cost for road transportation

Transfer cost	Cost (Baht)
Loading sugar in vehicle (1-9)	22.00
Unloading sugar in vehicle (1-9)	36.00

Table 9 Warehousing costs

Warehouse	Transfer cost from warehouse to barge (Baht/tonne)	Warehousing storage costs (Baht / tonne)
Warehouse 1	185.00	24.00
Warehouse 2	180.00	19.00
Warehouse 3	180.00	19.20
Warehouse 4	180.00	19.40

Table 10 Transport cost by barge to minor seaports

Seaport	Cost (Baht)
Seaport 1	66.00
Seaport 2	66.00
Seaport 3	80.00

Table 11 Transfer cost from each vehicle types to ocean liners (Baht/tonne)

Type of Vehicle (Mode)	Seaport 1	Seaport 2	Seaport 3
1-9 (Road)	205.00	190.00	-
10 (Rail)	-	-	-
11 (Water)	34.00	29.00	29.00

6 Computational results and discussion

The Gurobi solver software (http://gurobi.com/), was used for implementing the models using a Core I7, 2.00 GHz CPU and 4 GB RAM personal computer.

6.1 Optimizing the transportation of sugar to minimize carbon dioxide emissions

Model I optimized the carbon emissions associated with the routes and modes of transportation for sugar exports. The results are shown in Table 12. The configuration with the lowest carbon dioxide emission rates was a corridor to transport sugar products from the factory to the dry port by train which would produce emissions of 1,932.47 tCO_2/year and then onwards to the major seaport by train producing emissions of 523.7 tCO_2/year, giving total carbon dioxide emissions of 2,456.2 tCO_2/year. The carbon emissions due to road transport were 2,452 tCO_2/year to the dry port and 3,191.8 tCO_2/year from the factory to the seaport directly (with custom's clearance at the seaport). The use of rail only would reduce total carbon dioxide emissions by 23.05% compared to the use of only road. Transporting sugar to the dry port by rail and then to the seaport by road would reduce carbon emissions by 2.85% compared to the sole use of road. Compared to the current modes of transport, shifting to rail can reduce carbon emissions by approximately 22.78%. The small benefit was because the dry port much closer to the major seaport than the factory. Figure 3 provides a sensitivity analysis that investigates how changes in the distance travelled would impact total carbon emissions. Rail (only) results in the lowest emissions, followed by road and rail in all cases, showing that the choice of mode is insensitive to changes in the distance.

Table 12 Model I results

Type	From	To	Vehicle Type	Number of trips	The amount of sugar delivered (tonnes)	Total carbon emissions (tCO_2/year)		% saving *
Current configuration	Factory	Warehouse 2	Road	4,412	141,152.50	1,959.20	3,180.85	
	Warehouse 2	Minor seaport 1	Water	49	141,152.50	1,221.65		
Best solution	Factory	Dry port	Rail	181	141,152.50	1,932.47	2,456.17	22.78
	Dry port	Major seaport	Rail	181	141,152.50	523.70		
Alternative solution 1	Factory	Dry port	Road	4,412	141,152.50	2,452.24	2,975.94	6.44
	Dry port	Major seaport	Rail	181	141,152.50	523.70		
Alternative solution 2	Factory	Major seaport	Road	4,412	141,152.50	3,191.80	3,191.80	-0.34

*% saving compared to the current configuration

6.2 Optimizing the transportation of sugar to minimize carbon dioxide emissions with capacity constraints

Model II optimized routings and the modes of transportation for sugar exports to minimize CO_2 emission rates with doubled export capacity and warehouse capacity constraints. The models confirmed this was feasible. The results are shown in Table 13. The lowest carbon emissions were achieved by a corridor using rail from the factory to the dry port (3,854.31 tCO_2/year) and then to the seaport (1,044.53 tCO_2/year) giving a total of 4,898.84 tCO_2/year. The total carbon emissions for directly going from the factory to the seaport would be 6,382.18 tCO_2/year. Thus, the rail only option would reduce carbon emissions by 23.24% compared to the sole use of road. The combination of using road to the dry port and then rail to the seaport would reduce emissions by 6.80%. Compared to the current modes of transport, shifting to rail could reduce carbon emissions by approximately 23.40%. Figure 4 shows a sensitivity analysis that considers changes in the distances travelled. The choice of mode is insensitive to changes in the distance.

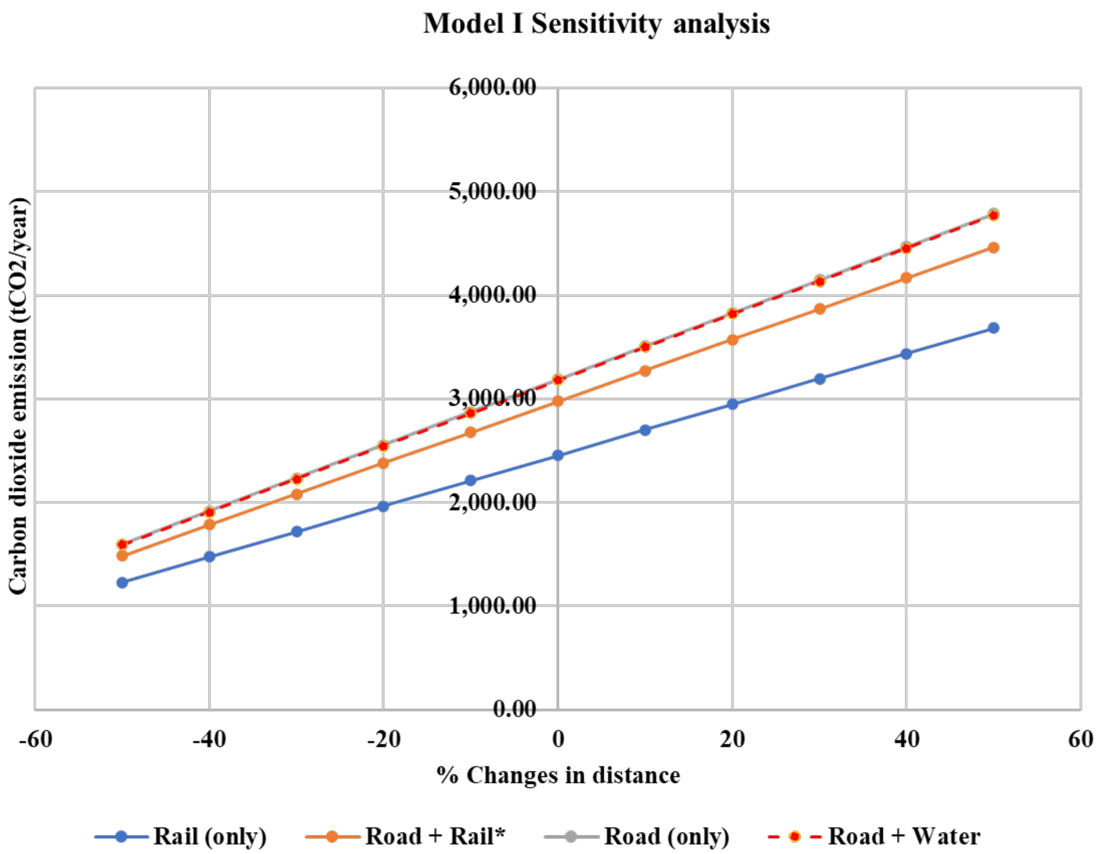

Figure 3 Model I Sensitivity Analysis

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Table 13 Model II Results

Type	From	To	Vehicle Type	Number of trips	The amount of sugar delivered (tonnes)	Total carbon emissions (tCO_2/year)		% saving*
Current configuration	Factory	Warehouse 2	Road	6,250	200,000	2,775.38	6,395.27	
	Factory	Warehouse 3	Road	2,572	82,305	1,153.48		
	Warehouse 2	Minor Seaport 1	Water	69	200,000	1,719.42		
	Warehouse 3	Minor Seaport 1	Water	28	82,305	746.99		
Best solution	Factory	Dry port	Rail	361	282,305	3,854.31	4,898.84	23.40
	Dry port	Major seaport	Rail	361	282,305	1,044.53		
Alternative solution 1	Factory	Dry port	Road	8,822	282,305	4,903.38	5,947.91	7.00
	Dry port	Major seaport	Rail	361	282,305	1,044.53		
Alternative solution 2	Factory	Major seaport	Road	8,822	282,305	6,382.18	6,382.18	0.20

*% saving compared to the current configuration

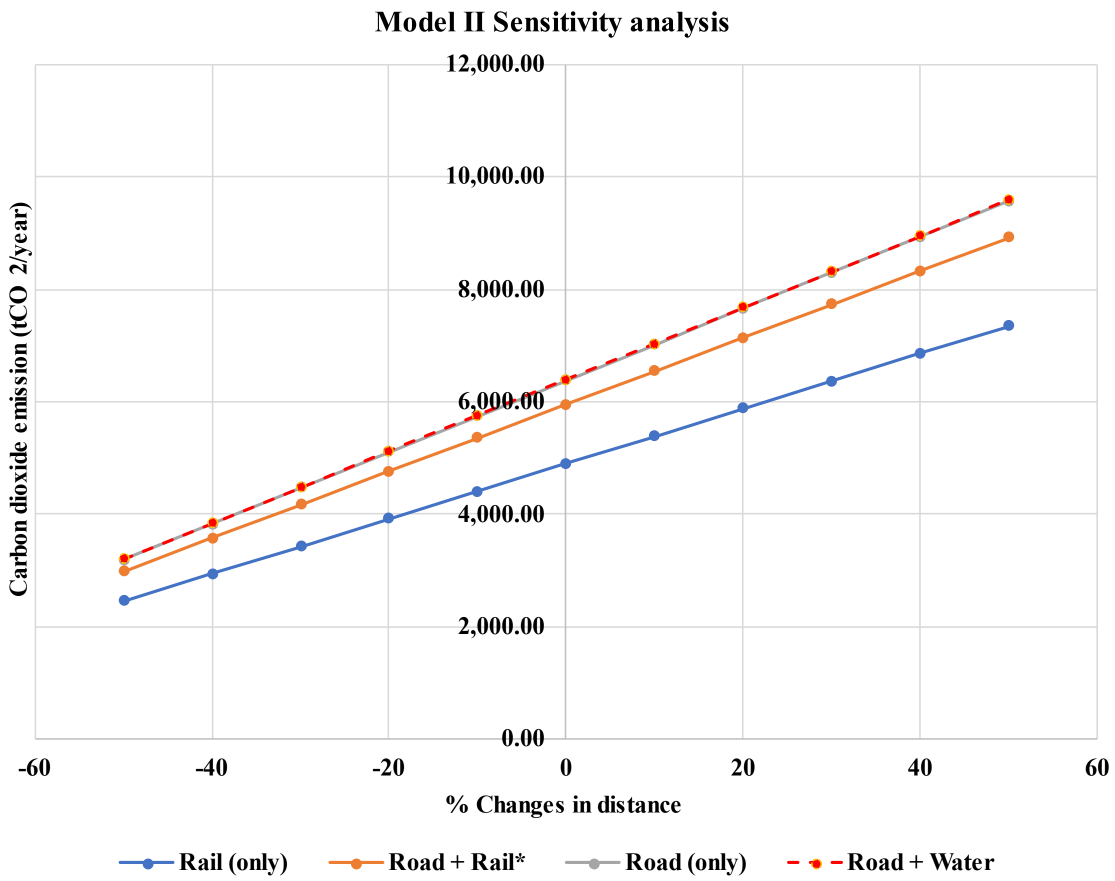

Figure 4 Model II Sensitivity Analysis

6.3 Optimizing the transportation of sugar to minimize the combination of transportation and emission costs.

Model III minimized total costs including transportation and carbon emission costs for all modes of transport. The results are shown in Table 14. The lowest total cost was achieved by transporting sugar from the factory to the dry port by rail (36.76m Baht/year), followed by rail from the dry port to the seaport (12.12m Baht/year) giving a total cost of 48.88m Baht/year. The corresponding cost of using road only was 89.89m Baht/year meaning a saving of 41m Baht/year (54.3%). Compared to the current modes of transport, shifting onto rail could reduce total cost by approximately 46.47%. The sensitivity analysis showing the impact of changes in distances travelled is shown in Figure 5. The choice of mode is insensitive to changes in the distance.

Table 14 Model III Results

Type	From	To	Vehicle Type	Number of trips	The amount of sugar delivered (tonnes)	Total cost (Million Baht/year)		% saving*
Currently	Factory	Warehouse 2	Road	4,412	141,152.50	51.65	91.32	
	Warehouse 2	Minor seaport 1	Water	49	141,152.50	39.66		
Best solution	Factory	Dry port	Rail	181	141,152.50	36.76	48.88	46.47
	Dry port	Major seaport	Rail	181	141,152.50	12.12		
Alternative solution 1	Factory	Dry port	Road	4,412	141,152.50	60.47	72.58	20.52
	Dry port	Major seaport	Rail	181	141,152.50	12.12		
Alternative solution 2	Factory	Major seaport	Road	4,412	141,152.50	89.88	89.88	1.57

*% saving compared to the current configuration

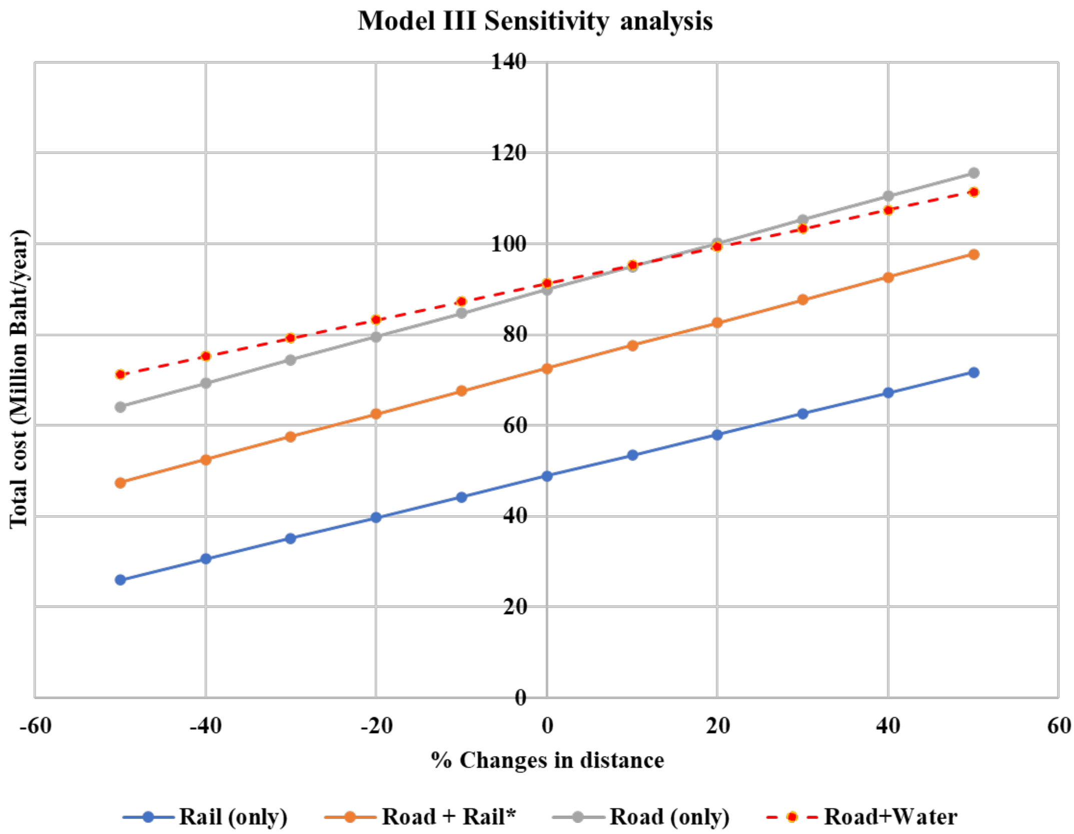

Figure 5 Model III Sensitivity Analysis

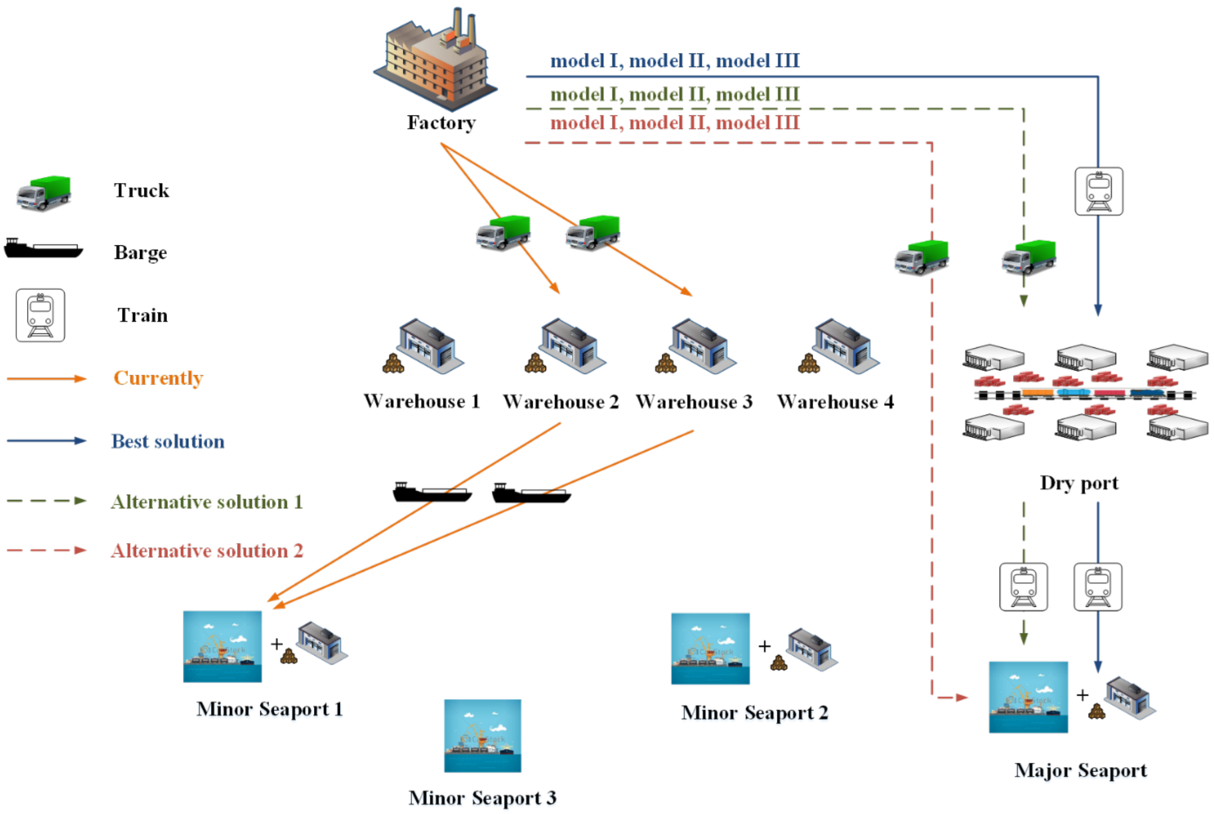

Figure 6 Graphical representation of results

7 Managerial insight

The introduction of carbon pricing will have significant impact on carbon intensive industries. To remain competitive companies will need to optimize their operations and logistics to reduce emissions and costs. Many industries are currently reliant on road transportation which is relatively inefficient and produces high emissions. This research has demonstrated that emissions could be reduced significantly by adopting multimodal transportation with a greater use of rail, but this requires redesign of the distribution network to connect facilities to the rail system. Dry ports can link modes of transport and reduce the volume of activities that need to be undertaken at the seaport. In the case, it was demonstrated that it is possible accommodate additional warehousing to support a significant increase in the volume of exports.

8 Conclusions and future research

Companies in many industrial sectors are evaluating possible responses to carbon pricing. This research has contributed to theory by developing three models that optimize distribution networks with road, water, rail and dry ports to minimize carbon emissions and total costs including transportation, handling, storage, fuel and carbon costs. Model II additionally included capacity constraints, which allows possible increases in export volumes to be evaluated.

This research was conducted in collaboration with a sugar company, which provided data and used the models to make strategic decisions. The models evaluated alternative network designs and modes of transport to identify an optimum configuration. A corridor using rail and a dry port minimized carbon dioxide emissions and total costs. The possible building an additional factory to double export sugar production was also evaluated, which included warehousing capacity constraints in the model. It was identified that this was feasible and that the use of rail connections with the use of a dry port was the best approach to reduce carbon emissions and transport costs. The use of rail and a dry port would save 23.05% compared to the use of road to take sugar directly to the seaport and would reduce total transportation and carbon costs by 41m Baht/year (54.3%). Thus, in addition to identifying the optimum configuration the research also provided data on costs and emissions that could be used in capital budgeting decisions.

The research focused on outbound logistics. Further research could use metaheuristics to solve integrated inbound/outbound logistics and consider stochastic factors.

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CRediT authorship contribution statement

Thanatporn Somasi: Conceptualization, Investigation, Methodology, Writing–original draft. **Pupong Pongcharoen:** Conceptualization, Investigation, Methodology, Writing–original draft; Review & editing, Project administration, Supervision. **Christian Hicks**: Literature Review, Writing, Reviewing & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data is available within the manuscript.

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