A mixed-integer linear programming model for multiechelon and multimodal supply chain system considering carbon emission

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Abstract: Considering carbon emissions when making supply chain decisions has been an essential contributor for keeping this world more sustainable. This paper presents a mixed-integer linear programming (MILP) model to optimize production and transportation decision where the transportation activities involve a multimodal combination. The proposed mathematical model was aimed at minimizing the total costs incurred from supply chain activities as well as the emissions generated. Carbon cap is used to ensure that the emissions produced in the whole activities do not exceed the allowable limit. In this research, we address a multi-product, multi-plant, multi-departure, and arrival stations where multiple customers are to be served for multiple periods. The numerical tests show that the demand, carbon tax, and distance significantly affected the total emissions and the total costs. Interestingly, we observed that the decisions are much more affected by the logistical costs rather than the emission costs. The model presented in this paper can assist the decision makers to make production, delivery, and inventory decisions when multi-modal transportation is involved.

1. Introduction
In the last decades, much research on environmental issues has emerged in various countries. One of the issues has been greenhouse gases (GHGs) emissions. There are different types of emissions, including carbon dioxide (CO2), which has the most influence on air
quality. This type of pollutant is a greenhouse gas that contributes to global warming and climate change. Global warming as an indicator of climate change occurs as a result of increased GHGs. As a result of global warming, there is clear evidence of natural damage and disasters in various parts of the world, including degradation, storm, floods, earthquakes, and tsunamis.

Based on the data from the WRI Climate Action Initiative (CAIT), from 1990 to 2017, global emissions showed that eight countries contributed the most pollutants. The eight countries are China (26.1%), United States (12.67%), European Union 28 (7.52%), India (7.08%), Russia (5.36%), Japan (2.5%), Brazil (2.19%), and Indonesia (2.03%; WRI, 2017). Therefore, the association of countries in Europe and in other part of the world initiated a policy to control carbon emissions (Huo et al., 2011). The three policies having the most influence in anticipating the global climate are the UNFCC, the Kyoto Protocol, and the Paris Agreement (Ardliana, Pu jawan, Siswanto et al., 2018). The United Nations Framework Convention on Climate Change (UNFCC), approved in 1992, implements strategies to tackle climate change through adaptation and mitigation. Then, the Kyoto Protocol policy, signed in 1997, brings efforts to reduce world carbon emissions. It includes three mechanisms that member countries can carry out to reduce carbon emission: the carbon market, clean development, and joint implementation. Paris Agreement, signed in 2016, was aimed to achieve net-zero emissions in the second half of the century and the signing parties agreed to take actions for long-term goals (Ramudhin et al., 2010; Mohammed et al., 2017).

In the context of supply chain, all activities in logistics operations such as production, storage, material handling, and transportation impact carbon emissions. However, transportation activities have the most visible carbon effect because they produce the most emissions (Dekker et al., 2012). The transportation aspect has contributed 14% of the GHG emissions generated by the business sector (Pachauri et al., 2014). Fortunately, there are various innovations in the transportation sector that could somehow reduce the emissions from transportation activities. Automotive companies have developed electric vehicle or apply high compression engines so that they are becoming more efficient and emit less carbon dioxide (Al-Arkawazi & A, 2019).

The two largest sectors contributed almost half of the world’s emissions are transportation (29%) and electricity (25%). The largest sources of transportation-related greenhouse gas emissions are passenger cars, medium- and heavy-duty trucks, and light-duty trucks, including sport utility vehicles, pickup trucks, and minivans (EPA, 2019). Trucks that carry cargo dominate GHG emissions compared to other means of transporting goods, such as trains, airplanes, and ships (Konur & Schaefer, 2014). There are two strategies to manage carbon emissions: reducing the company’s carbon footprint in various ways or capping carbon emission to the companies. All of these efforts are to gain the company’s reputation towards zero-emission or low carbon.

Recent studies have developed optimization modeling for operational management to minimize total supply chain costs while reducing carbon emissions (Benjaafar et al., 2012; Daryanto et al., 2019; Elhedhi & Merrick, 2012; Hua et al., 2011; Sarkar et al., 2021; Wahab et al., 2011; Wangsa, 2017). These methods include companies adopting or investing in energy-efficient equipment (and causing lower emissions), facilities, and transport vehicles (Hua et al., 2011; Chen et al., 2013). On the other hand, companies can also optimize their operational decisions on production, transportation, and inventory (Hua et al., 2011). This approach makes it possible to reduce carbon emissions with minimum or no cost compared to adopting or replacing technologies that consume lower energy (Benjaafar et al., 2012).
Long distance transportation of goods often involves more than one mode. This is especially true in archipelagic countries like Indonesia where land and sea transportation or other combinations are often used. Likewise, when the distance travelled is very long, combining truck and train is also desirable for cost and environmental reasons. In this paper, we address an integrated production and transportation decisions where the transportation is carried out in a multi-modal system. While this is an important area, we have not seen much of this problem explored in the previous studies, especially when we concern costs and emissions both at production, storage, material handling, and transportation activities. There have been several studies that presented the integration between inventory and transportation decisions, but most of them only apply or implicitly assume a single transportation mode (Konur, 2014; Konur & Schaefer, 2014; Palak et al., 2014;; Ardliana, Pujawan, Siswanto et al., 2018;; Goodarzian et al., 2021).

More specifically, we model a system that includes production in manufacturing plants, transfer of these products to departure stations, long haul transportation from this departure station to arrival stations, and then final transfer from arrival stations to customers. These include production, storage, and transportation activities, where all incur costs and generate emissions. Two carbon emission control mechanisms were considered in this study, namely, carbon cap and carbon tax. Carbon cap is a regulation limiting the amount of carbon emissions allowed. Meanwhile, carbon tax is the tax levied or the penalties imposed by the government on the amount of emissions emitted for producing goods or services. The use of these carbon emission control mechanisms was motivated by previous research conducted by Benjaafar et al. (2012), Palak et al. (2014), and Mohammed et al. (2017).

This paper is organized into six sections. Following the introduction section, we present the literature review that describes the related works and the research gap. This is followed by a section on model development that consists of the problem description, system configuration, and formulation mathematical model. The fourth section provides a numerical test of the model. The fifth section provides the sensitivity analysis. The sixth section presents the managerial insight that is finally followed by the conclusion section.

2. Literature review
There have been a continuing discussion on how supply chain decisions need to consider not only costs but also their impacts on environmental sustainability. This is an important area because supply chain decisions such as sourcing, production, storage, and transportation heavily incur costs and emits carbon emissions to the environment. There are a number of recent studies that address this issue, including for example, Benjaafar et al., 2012; Hua et al., 2011; and Hammami et al., 2015. More specifically, some researchers have addressed selecting transportation modes with carbon emissions (Hoen et al., 2014; Pan et al., 2013; Jin et al., 2014;; Mohammed et al., 2017). More recently, there have been some attempts to coordinate inventory decisions with the choice of transportation modes taking into account carbon emissions as in addition to costs (Konur, 2014; Konur & Schaefer, 2014; Palak et al., 2014; and Schaefer & Konur, 2015). Further, some researchers, including Kim et al. (2009), examined the choice of intermodal transportation that produces less CO2 emissions. However, their research does not integrate his modeling with inventory problems but only describes the effect of modal selection on emissions.

Benjaafar et al. (2012) present another work that forms the basis of this research, namely the effect of carbon emission regulation on the total supply chain costs. The carbon emission factor becomes the limit and objective function under the established regulations. Benjaafar et al. (2012) generally contribute to optimizing emissions and system costs without showing
the link between inventory and transportation due to carbon emission considerations. Some studies have considered the role of energy savings and emissions (Bazan et al., 2015a), the reversed logistics and emission reduction consider manufacturing, remanufacturing, and transportation activities (Bazan et al., 2015b), as well as include emissions from deteriorated items (Tiwari et al., 2018). Wangsa (2017) developed an integrated inventory model that considers emissions between transportation and production. Daryanto et al. (2019) proposed the integration of three-echelon supply chain considering emissions and deterioration. This model involves 3PL service as an outside party that regulates the selection and delivery of suppliers to buyers. Daryanto et al. (2019) succeeded in optimizing the number of shipments and integrating transportation and warehousing. Sarkar et al. (2021) modeled a sustainable multi-echelon inventory consisting of a single supplier, a single manufacturer, and a multi-retailer by considering carbon emissions and waste. Their research aims to minimize the total cost and optimized decision variables, for example, the cycle time, cost of setup, number of shipments for raw material, and number of shipments for work-in-process items.

In the last few years, several studies have applied mixed-integer linear programming (MILP) models to solve supply chain problems by considering carbon emissions. Mohammed et al. (2017) developed a model for design and planning of a closed-loop supply chain considering carbon footprint. Cheng et al. (2017) applied a relaxed mixed-integer linear programming to model one type of inventory routing problem called green routing. Qiu et al. (2019) use MILP to solve the multi-product green supply chain network with the constraints of carbon price uncertainty.

Hoen et al., 2014) developed various types of transportation mode selection on carbon emission regulation. However, Hoen only calculated the effect of each type of mode from terminal to terminal leaving the connectivity in the first mile to the terminal and from terminal to the final destination. In addition, Hoen et al., 2014 do not show the relationship between inventory and transportation in various considerations of carbon emission regulation. As we can see, from Table 1, most of works that address emissions in the area of transportation assume that transportation is done by a single mode only. Very few of them consider a multi-modal combination. Among these are the works of Kim et al. (2009) and Hoen et al., 2014. Both, however, did not attempt to integrate the model to include wider supply chain activities from manufacturing to final shipment to the customers. Our work is different from most of the earlier publication in that: (1) We model the integrated processes of production, storage, material handling, and transportation from plants to customers, (2) We include multimodal transportation with two exchanges, first is the transfer from truck to train and then later from train to truck. Emission and costs are the results of all those interconnected activities and considered in this study.

3. Model development

3.1. Problem description
In this study, we model a system that integrate the production, inventory, and transportation decisions simultaneously. The transportation involves a combination of different modes. Transportation from the manufacturing plant to the departure station is carried out by truck in a TL (truckload) mode. The next stage of transportation is using train, moving goods from departure station to the arrival station. Finally, goods are transported from arrival station to the customer location by truck in an LTL (less than truckload) mode. The TL mode refers to the case where the shipper has a large volume of cargos and each truck will pick the cargo in
| Researcher(s) | Multi-echelon | Multi-product | Multi-period | Decision variables | Logistics | Carbon emission sources | Objective function | Method |
|--------------|---------------|---------------|--------------|--------------------|-----------|------------------------|-------------------|--------|
| Kim et al. (2009) | * | * | * | * | PS OS I DR SF MS | Intermodal (truck, rail, short sea transport) | Freight emission | Multiobjective of freight cost and carbon emission | Pareto optimal solution |
| Hoen et al., 2014 | * | * | * | * | Intermodal (truck, rail, short sea transport) | Transport | Minimize total cost | NTM |
| Hua et al. (2011) | * | * | * | * | Unimodal | Transport, inventory | Minimize total cost | Classical optimization |
| Benjaafar et al. (2012) | * | * | * | * | Unimodal | Freight emission | Minimize total cost | MILP |
| Konur and Schaefer (2014) | * | * | * | * | Unimodal | Freight emission | Minimize total cost | Classical optimization |
| Sokar et al. (2016) | * | * | * | * | Unimodal | Transport | Minimize total cost | Classical optimization |
| Hamann et al. (2015) | * | * | * | * | Unimodal | Transport, inventory, production | Minimize total cost | MILP |
| Cheng et al. (2017) | * | * | * | * | Unimodal | Transport | Minimize total cost | MILP, Branch-and-cut algorithm |
| Mohammed et al. (2017) | * | * | * | * | Unimodal | Transport, disposal, inventory, production | Minimize total cost | MILP |
| Tiwari et al., 2018 | * | * | * | * | Unimodal | Transport, disposal, inventory | Minimize total cost | Classical optimization |

(Continued)
| Researcher(s) | Multi-echelon | Multi-product | Multi-period | Decision variables | Logistics | Carbon emission sources | Objective function | Method |
|---------------|---------------|---------------|--------------|-------------------|-----------|------------------------|-------------------|--------|
| Daryanto et al. (2019) | • | | | | Unimodal | Transport, disposal, inventory | Minimize total cost | Classical optimization |
| Sarkar et al. (2021) | • | • | | | Unimodal | Transport | Minimize total cost | MIP and classical optimization |
| This research | • | • | • | | Multimodal (truck, rail, truck) | Inventory, material handling, transport, and production | Minimize total cost | MILP |

Note. PS = production size, OS = order size, I = inventory, DR = distribution route, SF = shipment frequency, MS = mode selection
full truck capacity from one location. The LTL is different in that each shipper has a smaller volume of cargos and thus consolidating loads of different shippers is needed to increase the truck capacity utilization. In this paper, we do not intend to model the consolidation process in the LTL mode, but instead, just limit the capacity to a significantly lower level than the TL. The train is transporting goods in a much longer distance compared to that performed by truck in the first and last stage. As illustrated by Figure 1, there are multiple manufacturing plants and multiple customer locations. In the middle, there are also multiple train departure and arrival stations.

The demands in each customer location, the cost parameters, the distances, and the storage and manufacturing capacities are known. In addition, the rate of emissions in the production, storage and transportation activities are also known. The objective of the model is to find the best production, storage, and transportation quantity that minimize the total costs. These three activities incur logistical costs and emissions. In this model, we also convert the emission quantity into cost and is considered an element of total cost in the objective function. It is also assumed that the total emission produced along the supply chain cannot exceed a certain limit, which is called carbon cap, normally determined by the government.

Logistical activities in this supply chain include production, storage, material handling, and transportation. Each of these activities will produce carbon emissions and incur costs. Inventory at plant $p$ in period $t$ ($I_{pt}$) generates emissions at plant $p$ at time $t$ ($e_{pt}$). Then, product $m$ produced in plant $p$ is transported to the departure station $v$. This delivery uses a truck that causes emissions from plant $p$ to station $v$ at time $t$ ($e_{pvt}$). The quantity of product delivered from $p$ to $v$ ($q_{pvt}$) affects emissions and costs. At the departure station, the products are pre-collected from the shipments coming from all plants. Therefore, at this station $v$, there are inventory being held ($I_{vt}$) and carbon emission created ($e_{vt}$). The long-haul transportation is using train, moving goods from the departure station $v$ to the arrival station $w$. This long-haul transports ($Q_{vwt}$) amount of goods and also produces emissions ($e_{vwt}$). At the arrival station, the product will be pre-stored and therefore there are inventories ($I_{wt}$) that will produce emissions ($e_{wt}$). The product will then be distributed from the arrival station $v$ to each customer location $j$. This shipment uses truck mode, delivering products with the amount of ($q_{wj}$), and generates truck emissions ($e_{wj}$). The configuration of the supply chain system studied can be seen in Figure 1.

### 3.2. Assumptions

Following are the assumptions used in this study:

1. The initial inventory at each plant and each station is zero.

2. The demand rate, production rate, and the cost parameters are deterministic.

3. Inventory cost applies if it passes one period in the planning horizon.

4. The average vehicle speed is constant and the same for each type of mode.
### 3.3. Notations

**Indices and set**

| Index | Description | Notes |
|-------|-------------|-------|
| $p$   | Set of plants | $p = 1, 2, \ldots, P$ |
| $m$   | Type of product | $m = 1, 2, \ldots, M$ |
| $v$   | Set of the departure stations | $v = 1, 2, \ldots, V$ |
| $w$   | Set of the arrival stations | $w = 1, 2, \ldots, W$ |
| $j$   | Index for customers | $j = 1, 2, \ldots, J$ |
| $t$   | Index of the period | $t = 1, 2, \ldots, T$ |

**Parameters**

| Parameter | Description |
|-----------|-------------|
| $D_{nj}$ | Demand of product $m$ from customer $j$ in period $t$ (Ton) |
| $x_{nj}$ | Production rate of product $m$ in plant $p$ in period $t$ (Ton) |
| $L_j$ | The load capacity of truck operating on TL mode (Ton) |
| $K$ | The load capacity of the train (Ton) |
| $M$ | The available load capacity of truck operating on LTL (Ton) Storage capacity of plant $p$ (Ton) |
| $B_v$ | Storage capacity in the departure station $v$ (Ton) |
| $G_w$ | Storage capacity in the arrival station $w$ (Ton) |
| $HCP_{nvm}$ | Holding cost of product $m$ in plant $p$ in $t$ period ($$/ton) |
| $HCV_{nvm}$ | Holding cost of product $m$ in the departure station $v$ in period $t$ ($$/ton) |
| $NCW_{nvmt}$ | Holding cost of product $m$ in the arrival station $w$ in period $t$ ($$/ton) |
| $CTL_{nvmst}$ | Transportation cost of product $m$ by truck TL from plant $p$ to the departure station $v$ in period $t$ ($$/km/ton) |
| $CR_{nvmst}$ | Transportation cost of product $m$ by train from the departure station $v$ to the arrival station $w$ in period $t$ ($$/km/ton) |
| $CLTL_{nvmst}$ | Transportation cost of product $m$ by truck LTL from plant $p$ to the customers $j$ in period $t$ ($$/km/ton) |
| $d_{p}$ | Distance from plant $p$ to departure station $v$ (km) |
| $d_{vw}$ | Distance from departure station $v$ to arrival station $w$ (km) |
| $d_{w}$ | Distance from arrival station $w$ to customer $j$ (km) |
| $MC_{np}$ | Production cost of product $m$ produced in plant $p$ in period $t$ ($$/ton) |
| $MCV_{nvmt}$ | Material handling cost of product $m$ in the departure station $v$ in period $t$ ($$/ton) |
| $MCW_{nvmt}$ | Material handling cost of product $m$ in the arrival station $w$ in period $t$ ($$/ton) |
| $EP_{nmp}$ | The production emission rate of product $m$ in plant $p$ in period $t$ (Ton CO₂-equivalent) |
| $EI\ell_{nmp}$ | The inventory emission rate of product $m$ in plant $p$ in period $t$ (Ton CO₂-equivalent) |
| $EIW_{nvmt}$ | The inventory emission rate of product $m$ at the departure station $v$ in period $t$ (Ton CO₂-equivalent) |
| $EIW_{nvmt}$ | The inventory emission rate of product $m$ at the arrival station $w$ in period $t$ (Ton CO₂-equivalent) |
| $EMP_{nmp}$ | Material handling emission rate of product $m$ in plant $p$ that is distributed to departure station $v$ in period $t$ (Ton CO₂-equivalent) |

(Continued)
| Symbol | Description |
|--------|-------------|
| EMV_{\text{dept}} | Material handling emission rate of product \( m \) at departure station \( v \) in period \( t \) (Ton CO\(_2\)-eq/ton) |
| EMW_{\text{arr}} | Material handling emission rate of product \( m \) at the arrival station \( w \) in period \( t \) (Ton CO\(_2\)-eq/ton) |
| \( E_t \) | Shipping emission rate of product \( m \) from plant \( p \) to departure station \( v \) in period \( t \) (Ton CO\(_2\)-eq/km/ton) |
| ETL_{\text{arr}} | Shipping emission rate of product \( m \) from arrival station \( w \) to the customer \( j \) in period \( t \) (Ton CO\(_2\)-eq/km/ton) |
| Cap_j | Carbon cap emission in period \( t \) (Ton CO\(_2\)-eq) |
| \( \alpha \) | Carbon emission cost (\$/Ton CO\(_2\)-eq) |

**Decision variables**

| Symbol | Description |
|--------|-------------|
| YLT_{\text{dept}} | The number of trips from plant \( p \) to departure station \( v \) in period \( t \). |
| YRT_{\text{arr}} | The trips from station \( v \) to station \( w \) in period \( t \). |
| YLT_{\text{arr}} | The number of trips from station \( v \) to customer \( j \) in period \( t \). |
| U_{\text{dept}} | Total production of product \( m \) in plant \( p \) in period \( t \) (ton) |
| U_{\text{dept}} \succeq X_{\text{dept}} \rightarrow \forall p, \forall t, \forall m | Quantity product \( m \) transported from plant \( p \) to departure station \( v \) in period \( t \) (ton) |
| QP_{\text{dept}}, QV_{\text{dept}}, QW_{\text{dept}}, YLT_{\text{dept}}, YRT_{\text{dept}}, \text{IP}_{\text{dept}}, \text{IV}_{\text{dept}}, \text{IW}_{\text{dept}}, U_{\text{dept}} \geq 0 | Quantity of product \( m \) delivered from departure station \( v \) to arrival station \( w \) at period \( t \) (ton) |
| QW_{\text{arr}} | Quantity of product \( m \) delivered from arrival station \( w \) to customer \( j \) in period \( t \) (ton) |
| IP_{\text{dept}} | Inventory level of product \( m \) in plant \( p \) in period \( t \) (ton) |
| IV_{\text{dept}} | Inventory level of product \( m \) in departure station \( v \) in period \( t \) (ton) |
| IW_{\text{arr}} | Inventory level of product \( m \) in arrival station \( w \) in period \( t \) (ton) |

**Figure 1. Illustration of the system being studied.**

**3.4. Model formulation**

The objective function is to minimize total cost that consists of inventory holding costs, production costs, transportation costs, and emission costs. Total inventory holding cost is the inventory cost...
that is calculated based on the amount of inventory held at the end of the planning periods in the manufacturing plants, departure stations, and arrival stations. Total transportation cost is the total of costs for transporting products from plants to the departure station, then from the departure station to the arrival station by train, and from the arrival station the customer locations. Total production cost consists of variable production cost, material handling, and packing in all plants over the whole planning horizon. The emission costs are due to carbon emissions generated by all the above logistical processes along the supply chain. The model that includes the objective function and the constraints are formulated below.

Minimize

$$\begin{align*}
TC &= \sum_{m} \sum_{p} \sum_{t} HCP_{mpt} IP_{mpt} + \sum_{m} \sum_{v} \sum_{t} HCV_{mvvt} IV_{mvvt} + \sum_{m} \sum_{w} \sum_{t} HCW_{mwt} IW_{mwt} \\
&+ \sum_{m} \sum_{p} \sum_{v} \sum_{t} CTL_{mpt} QP_{mpt} dp_{pv} + \sum_{m} \sum_{v} \sum_{w} \sum_{t} CR_{mwvt} QV_{mwvt} dv_{vw} \\
&+ \sum_{m} \sum_{p} \sum_{v} \sum_{w} \sum_{t} CLTL_{mvt} QW_{mvtj} dw_{wtj} + \sum_{m} \sum_{v} \sum_{w} \sum_{t} \sum_{j} MCP_{mpt} (U_{mpt} + QP_{mpt}) \\
&+ \sum_{m} \sum_{v} \sum_{w} \sum_{t} MCV_{mvvt} QV_{mvvt} + \sum_{m} \sum_{w} \sum_{j} \sum_{t} MCW_{mwt} QW_{mwtj} + \\
&\times \left( \sum_{m} \sum_{p} \sum_{v} \sum_{t} EIP_{mpt} U_{mpt} + \sum_{m} \sum_{p} \sum_{t} EIP_{mpt} IP_{mpt} + \sum_{m} \sum_{v} \sum_{t} EIV_{mvvt} IV_{mvvt} \\
&+ \sum_{m} \sum_{v} \sum_{w} \sum_{t} EIP_{mvvt} OP_{mvvt} + \sum_{m} \sum_{v} \sum_{w} \sum_{t} EMV_{mvvt} QM_{mvvt} + \sum_{m} \sum_{w} \sum_{v} \sum_{t} EMW_{mvwt} QW_{mvwt} \\
&+ \sum_{m} \sum_{v} \sum_{w} \sum_{t} ETL_{mvwt} QP_{mvwt} dp_{pv} + \sum_{m} \sum_{v} \sum_{w} \sum_{t} ER_{mvwt} QV_{mvwt} dv_{vw} \\
&+ \sum_{m} \sum_{w} \sum_{j} \sum_{t} ETL_{mvwt} QW_{mvwtj} dw_{wtj} \right) \\
\end{align*}$$

(1)

Subject to:

$$IP_{mpt} + \sum_{v} QP_{mvpt} = IP_{mpt-1} + U_{mpt} \forall p, \forall m, \forall t$$

(2)

$$\sum_{p} QP_{mvpt} + IV_{mvvt} = \sum_{v} QV_{mvvt} + IV_{mvvt} \forall v, \forall m, \forall t$$

(3)

$$\sum_{v} QV_{mvvt} + IW_{mvvt} = \sum_{j} QW_{mvwt} + IW_{mvwt} \forall v, \forall w, \forall t$$

(4)

$$U_{mpt} \geq X_{mpt} \rightarrow \forall p, \forall t, \forall m$$

(5)

$$\left[ \sum_{m} \frac{QP_{mvpt}}{L} \right] \leq YLT_{pvt} \forall p, \forall t, \forall v$$

(6)

$$\left[ \sum_{m} \frac{QV_{mvwt}}{K} \right] \leq YRT_{vwt} \forall v, \forall t, \forall w$$

(7)

$$\left[ \sum_{m} \frac{QW_{mvwtj}}{L} \right] \leq YLTL_{wjt} \forall w, \forall t, \forall j$$

(8)
Table 2. Data for numerical example

| Parameter   | Value          | UoM   | Parameter   | Value          | UoM   |
|-------------|----------------|-------|-------------|----------------|-------|
| \( D_{mp} \) | U [5,000; 6,000] | Ton   | \( dW_{mp} \) | U [20; 50] | Km |
| \( \lambda_{mp} \) | U [10,000; 15,000] | Ton   | \( M_{mp} \) | U [20; 30] | S/ton |
| \( L \) | 20 | Ton | \( M_{mv} \) | U [2; 3] | S/ton |
| \( K \) | 400 | Ton | \( M_{EW} \) | U [2; 3] | S/ton |
| \( M \) | 7.5 | Ton | \( E_{mp} \) | U [0.12; 0.14] | Ton CO₂-eq/ton |
| \( Z_{p} \) | 28,000 | Ton | \( E_{mp} \) | U [0.0016; 0.0018] | Ton CO₂-eq/ton |
| \( B_{s} \) | 50,000 | Ton | \( E_{W} \) | U [0.0014; 0.0016] | Ton CO₂-eq/ton |
| \( G_{w} \) | 50,000 | Ton | \( E_{W} \) | U [0.0014; 0.0016] | Ton CO₂-eq/ton |
| \( H_{mp} \) | U [0.6; 0.7] | S/ton | \( E_{mp} \) | U [0.0016; 0.002] | Ton CO₂-eq/ton |
| \( H_{C} \) | U [0.6; 0.7] | S/ton | \( E_{mp} \) | U [0.0016; 0.002] | Ton CO₂-eq/ton |
| \( H_{W} \) | U [0.6; 0.7] | S/ton | \( E_{mp} \) | U [0.0016; 0.002] | Ton CO₂-eq/ton |
| \( CLT_{mp} \) | U [0.15; 0.2] | S/km/ton | \( E_{L} \) | U [0.0006; 0.0008] | Ton CO₂-eq/ton/km |
| \( CR_{mv} \) | U [0.01; 0.03] | S/km/ton | \( E_{R} \) | U [0.0006; 0.0008] | Ton CO₂-eq/ton/km |
| \( CL_{l} \) | U [0.25; 0.3] | S/km/ton | \( E_{L} \) | U [0.0008; 0.00096] | Ton CO₂-eq/ton/km |
| \( dv_{x} \) | U [10; 50] | Km | Cap | 31,000 | Ton CO₂-eq |

\[
\sum_{w} QW_{mv} = D_{mp} \forall t, \forall m, \forall j
\] (9)

\[
\left( \sum_{p} \sum_{t} \sum_{m} E_{mp} U_{mp} + \sum_{m} \sum_{p} E_{mp} I_{mp} + \sum_{m} \sum_{v} E_{W_{mv}} I_{W_{mv}} + \sum_{m} \sum_{v} \sum_{t} E_{mp} Q_{mp} + \sum_{m} \sum_{v} \sum_{j} E_{W_{mv}} Q_{W_{mv}} + \sum_{m} \sum_{v} \sum_{j} E_{W_{mv}} Q_{W_{mv}} + \sum_{m} \sum_{v} \sum_{j} E_{W_{mv}} Q_{W_{mv}} + \sum_{m} \sum_{v} \sum_{j} E_{W_{mv}} Q_{W_{mv}} \right) \leq \sum_{t} C_{ap_{t}} \]

(10)

\[
\sum_{m} I_{mp_{t} \cdot 1} + \sum_{m} U_{mp_{t} \cdot 1} \leq Z_{p} \forall p
\] (11)

\[
\sum_{p} QP_{mp_{t} \cdot 1} + IV_{mv_{t} \cdot 1} \leq B_{s} \forall m, \forall v
\] (12)

\[
\sum_{p} QP_{mp_{t} \cdot \cdot 1} + IV_{mv_{t} \cdot \cdot 1} \leq G_{w} \forall m, \forall w
\] (13)

\[
Q_{mp_{t} \cdot 1}, Q_{mv_{t} \cdot 1}, Q_{W_{mv_{t} \cdot 1}}, Y_{LT_{pv}}, Y_{R_{mv}}, Y_{LT_{w}} \leq I_{mp_{t} \cdot 1}, I_{mv_{t} \cdot 1}, I_{W_{mv_{t} \cdot 1}}, U_{mp_{t} \cdot 1} \geq 0
\] (14)
| No | Component Cost                                      | Cost ($) | (%)  |
|----|-----------------------------------------------------|----------|------|
| 1  | Inventory holding cost                              |          |      |
|    | - Inventory cost at plant                           | 0.00     | 0.00 |
|    | - Inventory cost at departure station               | 0.00     | 0.00 |
|    | - Inventory cost at arrival station                 | 8,670.00 | 0.04 |
|    | Total Inventory holding cost                        | 8,670.00 | 0.04 |
| 2  | Transportation cost                                  |          |      |
|    | - Transportation cost via truck TL from plant to departure station | 1,673,998.00 | 7.76 |
|    | - Transportation from via train cost departure to arrival station | 3,462,455.00 | 16.05 |
|    | - Transportation cost via truck LTL from arrival station to customers | 3,379,939.00 | 15.67 |
|    | Total Transportation cost                           | 8,516,392.00 | 39.48 |
| 3  | Variable cost at plants                             |          |      |
|    | - Production cost at plant                          | 10,862,000.00 | 50.35 |
|    | - Material handling cost at departure station       | 964,900.00 | 4.47 |
|    | - Material handling cost at arrival station         | 938,000.00 | 4.35 |
|    | Total Variable Cost                                 | 12,764,900.00 | 59.17 |
| 4  | Emission cost                                       |          |      |
|    | - Production emission cost at plant                 | 111,035.40 | 0.51 |
|    | - Inventory emission cost at plant                  | 0.00     | 0.00 |
|    | - Inventory emission cost at departure station      | 0.00     | 0.00 |
|    | - Inventory emission cost at arrival station        | 43.22    | 0.00 |
|    | - Material handling emission cost at plant          | 5,851.02 | 0.03 |
|    | - Material handling emission cost at departure station | 5,073.39 | 0.02 |
|    | - Material handling emission cost at arrival station | 5,162.64 | 0.02 |
|    | - Shipping emission cost via truck TL from plant to departure station | 14,555.56 | 0.07 |
|    | - Shipping ems. cost via train from departure station to arrival station | 117,902.04 | 0.55 |

(Continued)
| No | Component Cost | Cost ($) | (%) |
|----|----------------|----------|-----|
| - Shipping ems. cost via truck LTL from arrival station to customers | 22,784.59 | 0.11 |
| Total Emission Cost | 282,407.86 | 1.31 |
| Total System Cost | 21,572,369.86 | 100.00 |

Figure 2. The number of trips in each period for each mode.

| Period | Truck TL | Train | Truck LTL |
|--------|----------|-------|-----------|
| 1      | 4200     | 212   | 10923     |
| 2      | 4200     | 212   | 11257     |
| 3      | 4200     | 212   | 10898     |
| 4      | 4200     | 212   | 10895     |
| 5      | 3870     | 196   | 11162     |

Equation (1) is the objective function of the model that minimizes the total cost of the supply chain. Constraints (2–4) are the inventory balance equations at each stage (plants, departure stations, and arrival stations). Constraints (5) are to ensure that the production quantity does not exceed production capacity of each plant. Constraints (6–8) are to calculate the number of trips needed in each transportation mode used. Constraint (9) describes that the products sent from the arrival station are equal to the customer demand. Constraint (10) ensures that the total inventory, production, material handling, and transportation emissions in each planning period does not exceed the threshold value or the allocated carbon cap. Constraints (11) to (13) indicate that inventory level and quantity of production or delivery in each plant do not exceed the warehouse capacity. Constraints (14–15) indicate that the decision variables are non-negative.

4. Numerical example
The numerical example includes three plants ($p = 1, 2, 3$). These plants supply three types of products ($m = 1, 2, 3$) to the departure stations ($v = 1, 2, 3$) by using truckload with distance following a uniform distribution ($U/10:50/km$). Then, the products will be transported to the arrival stations ($w = 1, 2, 3$) by using train with the distance also following a uniform distribution of ($U/750; 1000/km$). Next, from arrival stations, the products will be sent to multiple customers ($j = 1, 2, 3, 4, 5$) with a distance ($U/20:50/km$). The demand in each period coming from each customer was generated based on a uniform distribution between 5000 and 6000 tons. The planning horizon in this study is five periods. In this case, we consider the carbon cap and carbon footprint of
the emission from the production, material handling, inventory, and transportation. The mixed-integer linear programming problem was solved by using Opensolver software and Microsoft Excel 365. The input parameters are hypothetical data and are presented in Table 2. These data somehow reflect the situation of low-value products like fertilizer. Some other data like the carbon tax and emission rate of different logistical activities were modified from some relevant publications, including Mohammed et al. (2017) for some emission and cost data. Other information are taken from the web, for example, that the emission cost is about $2.1 per ton of carbon emission (www.Jakartaglobe.com).

The results in terms of detailed cost breakdown for each activity is shown in Table 3. The cost figures are in USD ($). We also show the percentage of each cost component. The overall figure shows that the logistical costs dominate the emission costs. The results also show that the production and material handling costs are the highest, followed by the transportation costs. This makes sense for low-value products like fertilizers, building materials, and the like. The emission cost is substantially lower as the volume of emissions emitted from each ton of product is relatively low. Likewise, the carbon tax per ton is also much lower than the production, material handling, and transportation costs. The inventory holding cost is very small as the inventory level is low in any stage of the supply chain. However, all these results would be affected by the relative magnitude of the parameter values. The type of products, the magnitude of demand, the distances and other parameter values together affect the results.

The number of trips for each mode is exhibited by Figure 2. As expected, the number of LTL trips is much higher than the TL trips that reflect the comparative magnitude in the capacity of these two truck modes. The number of train trips is even much lower compared to TL that is obvious as the train capacity was set to be much higher compared to TL capacity.

Figure 3 shows the total inventory held in each stage at the end of each planning period. There is a dynamic of inventory level from period to period, which is sensible. On the other hand, the arrival stations hold the highest inventory level. These inventories are due to unbalanced flow in and flow out. The arrival station is likely to have higher inventory because the train has much higher capacity than the trucks. In addition, this is also affected by the variation in the demand rate at each customer from period to period and the batch size of delivery in each transportation mode. The model also requires that the delivery to the end customers is exactly the same as the amount of demand. This also explains why the inventory level is quite high in arrival station and virtually zero in two other locations.
Figure 4 presents the quantity delivered from period to period. The delivery from arrival station to the customers seems to be governed by the demand of each customer in each period. Note that the demand in each customer is set at a uniform distribution between 5,000 and 6,000 units per period. There are three types of products and five customer locations. Hence, it makes sense to have the final delivery to customers at an average rate about 82,500 units per period.

Figure 5 shows the magnitude of carbon emissions. The figure shows that production and transportation activities emit the most carbons, followed by material handling and storage activities. Inventory is resulting the less emissions because the inventory level is relatively low in all stages. From the transportation activity, the train in total result in much higher emission due to the very long distance travelled compared to the trucks in both sides. In this study, we have used railway distance somewhere between 750 and 1000 kilometers. As many sources indicate, the train is much less polluted compared to trucks. One article published in www.railfreight.com stated that train produces six times less CO2 compared to trucks, which we have used to set the input parameters in this study. Note that in this study, we have assumed that the amount of carbon emitted is less than 15% of the products yielded. This figure is likely to be much larger in some industries like aluminum and steel.

5. Sensitivity analysis
Sensitivity analysis is commonly used to show how decision variables change with the fluctuations in input parameters’ values. In this paper, we explore the impact of changes in the customer's demand ($D_{mjt}$), carbon tax ($c_t$), and distance ($dp_{pv}$, $dv_{wv}$, $dw_{wi}$) on the total supply chain cost, emitted total emissions, the delivered quantity, and the number of trips needed where we varied the values of input parameters in the range of $-15\%$ to $+15\%$.

5.1. Impact of customer demand($D_{mjt}$)
The impact of changes in customer demand on total carbon emission and the total cost is presented in Figure 6a. The graph shows that the system cost has moderately increased when customers demand increases. The two components of the supply chain costs (variable and transportation) increase following the pattern of the total cost (Figure 6b). It also happens for the emission costs, but it is not clearly visible in the graph as its magnitude is relatively very small. The changes in the number of trucks needed, the number of trains, the number of LTL shipment, and the quantity delivered are presented in (Figures 6c–f), respectively. The increase in demand results in more trips.
for both trucks and trains, which is sensible. The inventory level changes slightly when the demand level is varied. These inventory levels are the results of the differences in transportation capacities of TL trucks, train, and LTL truck. However, it does not give any significant managerial implications except if the storage capacities are tight. It is also obvious from the graph that the total emission is proportionally affected by the increase in demand. This is also sensible to say that every quantity added in production, storage, handling, and transportation will create additional carbon emission.
Figure 7. The effect of changes in carbon tax on decision variables and performance output.

(a) Total cost vs. total emission

(b) Total component cost

(c) Quantity delivered vs. number of truckloads

(d) Quantity delivered vs. number of trains

(e) Quantity delivered vs. number of less-than-truckloads

(f) Inventory level at each node

Figure 8. The effect of changes in distances on decision variable and performance output.

(a) Total cost vs. total emission

(b) Total component cost

(c) Quantity delivered vs. number of truckloads

(d) Quantity delivered vs. number of trains

(e) Quantity delivered vs. number of less-than-truckloads

(f) Inventory level at each node
5.2. Impact of a carbon tax

Changes in carbon tax parameters significantly impact the total supply chain cost but not significantly affecting the total emissions produced. Figure 7 shows that the total cost increased slightly with higher carbon tax. In Figure 7b, we can see that the emission cost is the element that significantly change from left to right, but its magnitude is very small compared to other costs. The relatively small proportion of emission costs compared to logistical costs make it less powerful to change the values of the decision variables and hence other graphs do not show any change with the variation in the values of carbon tax. In this example, we have used a relatively small carbon tax which is $2.1 per ton of CO2 as a base case. This low carbon tax is reflecting some countries like Indonesia and Brazil. As indicated by the OECD (2021) report on carbon pricing, there is a large discrepancy in the amount of carbon tax among different countries. The results would be different if the model was applied to those countries with high tax rate like the United Kingdom, Italy, and France. The inventory level is not much affected by the magnitude of carbon tax. This could be due to the way the model was formulated, which gave much more emphasis on the flows of goods in order to meet the demand.

5.3. Impact of distance ($dpw$, $dvw$, $dwa$)

Figure 8(a–f) show the effect of changes in distances, from the plants to the departure stations, from departure stations to arrival stations, and from arrival stations to customers. Sensitivity analysis showed a significant increase in both the total cost and total emissions produced. Figure 8b shows that the distance affects the transportation costs. It also affects the emission costs as the emission in transportation is proportionally affected by the distance. However, this is not visible enough in the graph as the proportion of emission cost is very much dominated by the logistic cost. The other cost components (production and material handling), as expected, are not affected by the distance. The values of the decision variables do not seem to be affected by changes in distances. The decision is very much robust with the changes in distance and the distance is basically only affecting the transportation-related performance. The number of trips is not affected by the distance. There is a slight change in the inventory level, which might be affected by the volume discrepancies of different transportation modes. It might have some effect on the solutions if we start imposing constraints on, for example, the transportation capacities.

6. Discussions, future works, and managerial implications

This research develops an integrated model for a supply chain system that consists of production, storage, handling, and transportation of goods to customers. In particular, we consider an intermodal transportation that connects manufacturing plants to customers. We consider multi-products that can be produced in multiple manufacturing plants to serve customers at different locations. The model was developed in the form of a mixed-integer linear programming (MILP) with an objective function to minimize total cost, which consists of logistical and emission costs. Our contribution is in the development of the model that consider intermodal integration with emission factor. In addition, we present the experimental results to explore the sensitivity of the decisions with respect to changes in the parameters’ values.

The sensitivity analysis suggests that the costs and emissions are significantly affected by changes in the values of most parameters. More specifically, both cost and emission levels are affected by the changes in demand, the carbon tax charged by the government, and the distance between the plants and the customers. It is also interesting to see that the logistical costs very much outweigh the emission costs. This could mean that the decisions in the supply chain are much more governed by the logistical costs rather than the objective to reduce emissions. This could be especially true in the situation where: (1) the products handled are of low value and high volume, (2) the carbon tax is low. However, this proposition needs to be further explored in future studies. Another important extension from the current study is to develop alternative models that will be able to compare different intermodal combinations. For example, in this study, we only have truck—rail—truck combination. It would be interesting to have
more than one combination and the decision makers could then compare the costs and other performance of using different intermodal combinations.

From managerial point of view, this paper provides important insights on the importance of considering a more holistic cost components when making supply chain decisions. Production, storage, handling, and transportation affect both costs and emissions. When emissions are explicitly charged, as it was assumed in this paper, it would be easier to make decisions as we finally have a single objective to minimize costs. The managers must also be aware that in most situation the increase in logistical costs will be followed by the increase in emission level. However, when we include intermodal consideration, choosing the right combination of transportation modes would be able to reduce emission level. For example, the use of rail transport for long-haul transportation would affect the overall emission level compared to the case when the manager decided to use a single truck mode from the origin to the destination.

The results also suggest that the costs from logistical activities very much dominates the emission costs even though in this paper we roughly mimic the situation of industries that emits a moderate amount of CO2 in their production process. An important implication from this is that charging emission tax would not much affect the supply chain decisions. It is the logistical costs that will mainly govern the decision and the carbon tax will only lightly contribute to it. This will be even more obvious in the industries that is cleaner. For the government, this should be clear that attempting to influence emissions would probably be more effective with the use of stringent carbon cap restriction rather than the carbon tax especially in countries where the carbon tax is relatively small like Indonesia.

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Appendix A. The contribution of the parameter changes on the total cost

| % Change | Effect     | Demand       | Carbon Tax  | Distance    |
|----------|------------|--------------|-------------|-------------|
| −15%     | Total cost ($) | 17,857,108.33 | 21,530,008.68 | 20,271,378.76 |
|          | Saving (%)  | 17.22        | 0.20        | 6.03        |
| −10%     | Total cost ($) | 19,033,712.74 | 21,544,129.08 | 20,705,180.80 |
|          | Saving (%)  | 11.77        | 0.13        | 4.02        |
| −5%      | Total cost ($) | 20,261,613.47 | 21,558,249.47 | 21,138,788.15 |
|          | Saving (%)  | 6.08         | 0.07        | 2.01        |
| 0%       | Total cost ($) | 21,572,369.86 | 21,572,369.86 | 21,572,369.86 |
|          | Saving (%)  | 0.00         | 0.00        | 0.00        |
| +5%      | Total cost ($) | 23,141,495.03 | 21,586,490.26 | 22,005,774.08 |
|          | Saving (%)  | −7.27        | −0.07       | −2.01       |
| +10%     | Total cost ($) | 25,042,584.41 | 21,600,610.65 | 22,439,124.82 |
|          | Saving (%)  | −16.09       | −0.13       | −4.02       |
| +15%     | Total cost ($) | 26,709,487.89 | 21,614,731.04 | 22,872,357.40 |
|          | Saving (%)  | −23.81       | −0.20       | −6.03       |
Appendix B. The contribution of the parameter changes on the total emission

| % Change | Effect                                      | Demand | Carbon Tax | Distance |
|----------|---------------------------------------------|--------|------------|----------|
| −15%     | Total emission (Ton CO₂-eq)                 | 114,199| 134,480    | 123,333  |
|          | Saving (%)                                  | 15.08  | 0.00       | 8.29     |
| −10%     | Total emission (Ton CO₂-eq)                 | 120,904| 134,480    | 127,026  |
|          | Saving (%)                                  | 10.09  | 0.00       | 5.54     |
| −5%      | Total emission (Ton CO₂-eq)                 | 127,554| 134,480    | 130,784  |
|          | Saving (%)                                  | 5.15   | 0.00       | 2.75     |
| 0%       | Total emission (Ton CO₂-eq)                 | 134,480| 134,480    | 134,480  |
|          | Saving (%)                                  | 0.00   | 0.00       | 0.00     |
| +5%      | Total emission (Ton CO₂-eq)                 | 141,318| 134,480    | 138,080  |
|          | Saving (%)                                  | −5.08  | 0.00       | −2.68    |
| +10%     | Total emission (Ton CO₂-eq)                 | 149,074| 134,480    | 141,774  |
|          | Saving (%)                                  | −10.85 | 0.00       | −5.42    |
| +15%     | Total emission (Ton CO₂-eq)                 | 155,000| 134,480    | 145,488  |
|          | Saving (%)                                  | −15.26 | 0.00       | −8.19    |
