Multi-objective decision model for green supply chain management

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Abstract: In this paper, a multi-objective linear programming model was developed which sought to simultaneously optimize total costs and total GHG emissions for the Thai Rubber supply chain. The model was solved by the ε-constraint method which computed the Pareto optimal solution. Each point in the Pareto set entailed a different design of quantity of rubber product flow between the supply chain entities and transport modes and routes. The result obtained show the trade-offs between costs and GHG emissions. It appears that improvements in cost reductions are only possible by compromising on and allowing for higher GHG emissions. From the Pareto set of solutions, each point is equally effective solution for achieving significant cost reductions without compromising too far on GHG emissions. Scenarios analysis were considered to examine the impact of transportation and distribution restructuring on the trade-off between GHG emissions and costs vis-à-vis the baseline model. Overall, the model developed in this research, together with its Pareto optimal solutions analysis, shows that it can be used as an effective tool to design a new and workable GSCM model for the Thai Rubber industry.

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PUBLIC INTEREST STATEMENT

The global rubber industry has witnessed significant growth recently, but efforts to tackle its negative environmental impacts have been limited. This formed the motivation for this study which aims to develop and test a multi-objective decision support model that effectively trades-off environmental performance (GHG emissions) with economic (operational cost) performance. The Thai rubber industry, the world’s largest natural rubber producer is used as the setting. Eight scenarios were considered to examine the impact of transportation and distribution restructuring on the trade-off between GHG emissions and costs vis-à-vis the baseline model. The results show that different GHG emissions target levels will lead to different transport/distribution restructuring strategies for achieving the target. Findings from the study are expected to help policymakers in their supply chain design/redesign decisions so that cost-effective environmental performance improvements can be realized.
1. Introduction

Environmental pollution and global climate change have emerged as one of the major challenges of the twenty-first century with governments worldwide racing to curb their countries’ environmental impacts. This was evident in the recent Paris climate deal where more than 200 countries formally signed an agreement to do this (Salawitch et al., 2017). Thus, industries around the world are looking at options to meet the market demand in a more environmentally responsible way (Dayaratne & Gunawardana, 2015; Habib et al., 2020).

Amongst sectors, rubber-based industries have witnessed significant worldwide growth in recent times (Chanchaichujit & Saavedra-Rosas, 2018; Jawjit et al., 2010) and that is expected to continue in the future; annual growth rate of around 5% is projected for the next 10 years to reach a market size of USD 45 billion globally by 2027 (Kenneth Research, 2019). Today, rubber can be found in more than 50,000 manufactured products today (Rubberworld, 2018). From an environmental standpoint though, the booming rubber industry is a cause for concern given that rubber production is energy-intensive and which also contributes to several environmental pollutions (Dayaratne & Gunawardana, 2015; Jawjit et al., 2015). Importantly, there have been few efforts to tackle its negative environmental impacts (Jawjit et al., 2015).

As in other industries, the environmental consequences of the rubber industry are typically dispersed across different supply chain stages. Greening of the industry, therefore, requires a supply chain-wide focus that includes all key stages and stakeholders; moreover, economic/cost performance implications need to be considered when undertaking environment footprint reduction measures across stages/stakeholders which is essentially the green supply chain management (GSCM) approach/perspective (Rao & Holt, 2005). Given that the rubber industry is struggling to meet the (increased) global demand as also the pressure for cost-competitiveness and environmental friendliness, GSCM is particularly relevant in its case. This forms the motivation for this work which seeks to realize cost-effective improvements in the environmental performance of the rubber industry. The specific objectives are:

1. To develop and apply a multi-objective decision model to achieve trade-offs between environmental and economic performance
2. To conduct multiple scenario analysis for decision support for policymakers

Thailand’s rubber industry was used as the context to test and validate the decision model, and which is because of the following: Thailand is the world’s largest rubber producer (around 5 million tons per year accounting for one-third of the global production (Krungsri Report, 2019); also because the negative environmental impacts from the rubber industry are well recognized there (Pollution Control Department, 2018); and finally because Thailand, is actively engaged in lowering its carbon emissions and developing a climate-resilient society; it not only signed the Kyoto Protocol in 1998 but also developed Nationally Appropriate Mitigation Actions (NAMAs) to lower greenhouse gas emissions below business as usual (BAU) levels by 2020 as well as reduce emissions by a further 20–25% in 2030 compared to the BAU level (ONREPP, 2016). Thailand, therefore, provides an appropriate context for understanding the competing actions required from governments and organizations to lessen the environmental impacts associated with the rubber industry while meeting the increasing global demand of rubber products and sustaining its economic contribution. The latter is equally important given that more than six million people are directly involved in the rubber industry across Thailand (Nobnorb & Fongsuwan, 2015). To date,
very few studies on the rubber industry and even fewer on the Thai rubber supply chain have dealt with environmental and economic issues together. The few studies that were conducted (e.g., Chanchaichujit et al., 2016) only attempted a single-objective optimization. Here we have tried to generate a full set of trade-off solutions for both costs and GHG emissions so that (from a set of alternative solutions) the decision-maker can select the most appropriate (from their perspective) supply chain network design.

The rest of the paper is structured as follows: In the next section, the mathematical modeling approaches in GSCM used in previous studies are discussed to identify the appropriate model for this work. In section three, we give an account of the Thai rubber supply chain. Section four describes our model, including the associated data sets, parameters, and decision variables; it also includes mathematical formulations and solution procedures to solve the multi-objective optimization problem. The Pareto optimal solutions to costs and GHG emissions are then presented and discussed in section five. The study concludes in section six by presenting valuable insights obtained from the Pareto optimal solution and its scenarios analysis, with regard to the design of the Thai rubber supply chain model trade-off between environmental and economic performance, limitations and suggestions for future research.

2. Mathematical modelling based approaches in GSCM
The use of optimization models for decision making in GSCM has seen significant interest in recent years (Ansari & Kant, 2017). The optimization modeling is based on mathematical procedures that strive to find the optimum solution under a given set of relevant assumptions, constraints, and data (Coyle et al., 2004). While these models apply several mathematical programming techniques such as linear programming, mixed-integer programming, and non-linear programming (Ansari & Kant, 2017; Srivastava, 2007), the application of single and multi-objective linear programming techniques were found to be the most popular (Ansari & Kant, 2017).

Single objective linear programming models have one objective function requiring optimization. For example, Chanchaichujit et al. (2016) used the single objective linear programming model to find the association between the quantity of rubber product flow between supply chain entities and the transportation mode and route, to minimize total GHG emissions. The authors considered GHG emissions and costs as two single objective functions and found the relationship between GHG emissions and costs to be in conflict with each other. The main limitation of using single objective linear programming models is that policymakers are likely to make decisions that fulfill one objective but jeopardize the other. On the other hand, the advantage of the multi-objective model is that it provides trade-offs between conflicting objectives. Given that GSCM decisions usually involve trade-offs among different incompatible objectives, such a model is, therefore, more reasonable and practical in application terms (Wang et al., 2011). Therefore, it is recommended to consider both environmental and economic criteria as multi-objective functions to capture the trade-offs between the two in the supply chain network subject to defined constraints. (Bloemhof-Ruwaard et al., 2008; Walther et al., 2009) highlighted that achieving a win-win solution between the environment and economic dimensions is difficult in practice and therefore, they suggested seeking effective trade-offs as a way forward for real-world problems.

Previously, the multiple-objective decision-making approach has been extensively used in the field of operational research and related application areas to find non-inferior solutions (Radin, 1998; Rangan & Poolla, 1996). In GSCM, multi-objective optimization has also been considered by different researchers, this involve minimizing total costs or maximizing total profits while simultaneously minimizing environmental impacts (Buddadee et al., 2008; Guillén-Gosálbez et al., 2010; Hugo & Pistikopoulos, 2005; Kim et al., 2010; Wang et al., 2011). In these studies, total costs are generally the summation of supply chain activities costs such as production, inventory, and transportation (You & Wang, 2011) while total profit is expressed in terms of net profit values (Hugo & Pistikopoulos, 2005). For environmental objectives, various measures used include CO2
emissions (Kim et al., 2010; Wang et al., 2011), GHG emissions (You & Wang, 2011), energy consumption (Winebrake et al., 2008) and Global Warming Potential (Buddadee et al., 2008). For example, Sheu (2008) used a linear multi-objective optimization model to optimize the operations of both the nuclear power generation and the corresponding induced-waste reverse logistics. Similarly, (Gabriel et al., 2007) proposed a multi-objective optimization model to simultaneously minimize the biosolids odor as well as processing and distribution costs. Given that the nature of supply chains including their structure, costs, and environmental impacts differ for each sector, separate studies are needed for each including one for rubber given its significant environmental impact. Despite its potential, we did not come across any study that utilized a multiple-objective decision-making approach in GSCM in the rubber industry in any country let alone Thailand. From Thailand’s perspective, we came across only one study (Buddadee et al., 2008) set in the country that applied a multiple-objective decision-making approach in GSCM. This study, on the sugar cane supply chain provides insights on the following: (i) location and size of the ethanol production plants; (ii) the allocation of bagasse from each sugar mill to the corresponding ethanol plant. Global Warming Potential objective is used to represent the impact of all GHG emissions, while economic objectives are captured through the summation of all operational costs.

There are two general approaches to solving multiple-objective problems (Carrillo & Taboada, 2012). The first approach involves the aggregation of all the objective functions into a single composite objective function. Mathematical methods like the weighted sum method, goal programming, or utility functions pertain to this general approach. The output of this method is a single solution. In contrast, multiple objective evolutionary algorithms offer the decision-maker a set of trade-off solutions usually called non dominated solutions or Pareto-optimal solutions (Carrillo & Taboada, 2012). By definition, a Pareto is a set where none of the objective functions can be improved without worsening the value of another objective function (Caramia & Dell’Olmo, 2008). Therefore, the Pareto set of solutions offers a range of alternative solutions; decision-makers can investigate and select the one that most satisfies their preferences (Caramia & Dell’Olmo, 2008).

Among the studies that applied Pareto optimal solutions, You and Wang (2011) applied a multi-objective optimization model to develop a trade-off between total cost and environmental influence in green supply chain network design. The Pareto optimal curve in each scenario showed that the model as an effective tool in strategic planning for green supply chain in terms of the trade-offs between CO₂ emissions and investment costs. Specifically, improving the capacity of the network and increasing the amount of supplies to the facilities decreased CO₂ emissions and total costs for the whole supply chain network. Similarly, You and Wang (2011) used a Pareto optimal solution in their mixed-integer multi-objective decision model to optimize the design of the biomass-to-liquid (BTL) supply chain to simultaneously minimize economic aspects and environmental pollution. The multi-objective model was solved by using the ε--constraint method to produce a Pareto curve representing the trade-offs between optimal costs and environmental performance. Furthermore, a study by (Kim et al., 2010) used a Pareto optimal solution in their multi-objective optimization problem to find trade-offs between freight costs and CO₂ emissions. Their study examined six scenarios for various routes in the East-West European corridor, with different market demands and freight mode capacities. The results showed that the trade-off curves tended to have a linear relationship with freight costs and CO₂ emissions.

3. The Thai rubber supply chain
The main rubber plantation and production in Thailand is in Southern part of the country which account for approximately 79% of the total Thai rubber production (Thai Rubber Association [TRA], 2010). It is consisting of 14 provinces in Southern Thailand. These comprise Ranong, Chumphorn, Suratthani, Nakhon Si Thammarat, Trang, Phang Nga, Phuket, Krabi, Pattalung, Satun, Songkhla, Pattani, Yala, and Narathiwat. (see Figure 1).
The Thai rubber supply chain is shown in Figure 1 below. As can be seen in the figure, it has divided to rubber plantation, upstream rubber industry and midstream rubber industry. At rubber plantation, farmer grow and harvest rubber to Fresh Latex before delivered to upstream rubber processing plant to processing it into 3 types of upstream rubber products: Field Latex (FL), Unsmoked Sheet (US) and Cup-Lump (CL). Almost all upstream rubber products produced in Thailand will be delivered to midstream rubber industry through trader (dealer, general market, cooperative) before sent to factory processing midstream rubber products of the Concentrated Latex (CL), Block Rubber (BR) and Ripped Smoke Sheet (RS). These products will be delivered to keep as domestic stock or an input for downstream rubber processing such as condom, latex glove, automobile tires, and so on in both domestic and international via 14 routes (R1, R2, R3, R4, R5, R6, R7, R8, R9, R10, R11, R12, R13, R14). R1 to R4 is road freight from midstream rubber processing plants in each province to domestic stock outlet, downstream rubber processing
chains. Figure Chanchaichujit et al., Cogent supply & Management 2020, 7: 1783177 https://doi.org/10.1080/23311975.2020.1783177

plants, Songkhla port and Penang port for export respectively. R5, R6 and R7 route destination is Penang port. R5 is road freight from midstream rubber processing plants in each province to Padang Basar rail station interchange to rail freight to final destination at Penang port while R6 and R7 is road—rail transportation to Hat Yai rail station and Tung Song rail station respectively before arrived to Padang Basar rail station. R8 is direct road freight to Bangkok port. R9 and R10 is a combination between road and rail to Bangkok port via Hatyai rail station for R9 and Tung song rail station for R10 before arriving to Ladkrabang ICD rail station to continue to Bangkok port. R11 is direct road freight to final destination at Laemchabang port. R12 and R13 is a road and rail transportation to Lamchabang port. R14 is a road and shortsea shipping transportation to Laemchabang port.

4. A linear multi-objective optimization model for costs and GHG emissions

A linear programming approach was chosen for studying the association of the quantity of rubber product flow between the supply chain entities at upstream, midstream and downstream rubber industry and the transportation mode and route. The aim was to minimize the total costs and total GHG emissions simultaneously.

There are different techniques for solving problems involving multiple objectives. Guillén-Gosálbez et al. (2010) have classified the techniques for solving multi-objective optimization problems into three approaches. The first approach is based on the transformation of the problem into a single objective and using a single-objective optimization model to solve the problem (Ehrgott, 2005). The second approach is the non-Pareto method which uses search operators based on the objective to be optimized. The general concept of this method can be found in (Blanke et al., 2008). The third approach is the Pareto method. This technique generates a set of solutions to the trade-offs for different objectives (Deb, 2005). This Pareto method will be employed in this study to investigate the trade-offs between cost and GHG emissions minimization in the Thai rubber supply chain. In this way, it will be possible to provide the decision-maker with sufficient alternative options to make trade-off decisions between the objectives (Chanchaichujit et al., 2019).

4.1. Multi-objective optimization and Pareto solutions

In multi-objective optimization problems, no unique solution exists (Deb, 2005). However, there are several solutions that are equal to one another in terms of effectiveness. These solutions are known as Pareto solutions (Miettinen, 2008). The general formulation for multi-objective optimization can be expressed as follows (Blanke et al., 2008):
Min\{f_1(x), f_2(x), \ldots, f_k(x)\}

Subject to \( x \in S \)

Where

- \( k (\geq 2) \) is the conflicting objective functions \( f_i : R^n \to R \), where \( R \) denotes the set of real numbers.
- The decision variable vectors \( x = (x_1, x_2, \ldots, x_n)^T \) belong to the non-empty feasible region \( S \in R^n \).
- Objective vectors are images of decision vectors and consist of the objective function values: \( f(x) = (f_1(x), f_2(x), \ldots, f_k(x))^T \).

A decision vector \( x' \in S \) is known as Pareto optimal if another \( X \in S \) does not exist such that \( f_i(x) \leq f_i(x') \) for all \( i = 1, \ldots, k \) and \( f_i(x) < f_i(x') \) for at least one index. In multi-objective optimization, objective vectors are regarded as optimal if none of their components can be improved without deterioration to at least one of the other components (Blanke et al., 2008).

### 4.2. Research methodology and mathematical formulation

This study builds on the work of Chanchaichujit et al. (2016) in which the authors developed a single-objective optimization model for minimizing costs and GHG emissions for the Thai rubber supply chain. The multi-objective optimization model developed in this study includes objective function 1 for cost minimization, objective function 2 for GHG emission minimization, and constraints 3–16 for the model constraints (See Tables A1 and B1 in the appendix). The sets, parameters, and decision variables of the multi-objective optimization model used in this study for minimizing costs and GHG emissions optimization are provided in the appendix. These were collected from primary and secondary data sets in the public domain such as the Office of Agricultural Economics (OAE, 2017) and Rubber Authority of Thailand (RRI, 2017). In order to validate the secondary data sets taken from published sources, interviews were conducted for data triangulation. Each Pareto optimal solution within the set represents an alternative to the quantity of rubber product flowing between the supply chain entities and the transportation mode and route, to minimize total costs while at the same time minimizing total GHG emissions. In the next section, the procedure for calculating the Pareto set for the above multi-objective model is explored.

### 4.3. Solution procedure and model implementation

For the calculation of the Pareto set, two basic methods exist in the literature. These are the weighting method and the \( \varepsilon \)-constraint method (Miettinen, 2008). In recent years, some literature has pointed out the drawbacks of using the weighting method (Arora, 2017; Khan & Rehman, 2013). Arora (2017) highlighted the main weakness of the weighting method as being that, although the weights were chosen consistently and continuously, an even distribution of Pareto optimal points will not necessarily result, thus, there is no guarantee of an accurate representation of the Pareto optimal set. In contrast, previous works in the literature on GSCM have highlighted the advantage of using the \( \varepsilon \)-constraint method (Caramia & Dell’Olmo, 2008; Gebreslassie et al., 2009; Miettinen, 2008). In addition, the \( \varepsilon \)-constraint method has been widely used to solve many multi-objective problems in GSCM (for e.g., Guillén-Gosálbez et al., 2010; Hugo & Pistikopoulos, 2005; Kim et al., 2010). The \( \varepsilon \)-constraint method was therefore used in the study.

In the \( \varepsilon \)-constraint method, one of the objective functions in the original problem was selected for optimization while the other objective was converted into constraints (Caramia & Dell’Olmo, 2008). In this research, \( Z_1 \) was selected for optimization and \( Z_2 \) was formulated as an additional constraint. The right hand value of the additional constraint is \( \varepsilon \), which represents the limit of GHG emissions. The reformulated model is as follows:
Min\(Z_1 = \sum_{r} \sum_{f} \sum_{u} \sum_{t} X_{fru}(CR_{fu} + CT_{fr} + CG_{fu}) + \sum_{r} \sum_{g} \sum_{m} \sum_{a} Y_{rgma}(CT_{rg} + CF_{rm} + CT_{pa}) + \sum_{m} \sum_{a} \sum_{b} \sum_{d} Z_{mad}(CT_{ab} + CM_{b} + CT_{bd})\)  

Subject to:

Constraints 3–16;  
\(Z_2 \leq \varepsilon\) (additional constraint)

In this model, if the \(\varepsilon\) parameter is set at \(\infty\) (infinity or a very large number), the resulting model then solves the single-objective problem of total cost minimization. In other words, this formulation is a generalization of the cost minimization model as a single objective. In contrast, if the \(\varepsilon\) parameter is set to too small, the resulting problem is infeasible. To avoid these two extreme situations, it is first necessary to determine reasonable bounds for the \(\varepsilon\) parameter.

The procedure to calculate the upper and lower boundaries for the \(\varepsilon\) parameter with the constraints and estimation of the Pareto solution is as follows:

Step 1: Calculate the lower and upper boundaries for the \(\varepsilon\) parameter (Denote them as \(\varepsilon_L\) and \(\varepsilon_U\) respectively). Based on these boundaries, determine a step \(h\) to be used to define a partition of the interval \(\{\varepsilon_k = \varepsilon_L + k \cdot h \mid k \in K\}\) with \(K \subseteq N\) as a finite subset of the natural numbers.

Step 2: For \(k \in K\)

Step 2.1: Initialize all parameters, objective functions, constraints 3–16, and \(\varepsilon\).

Step 2.2: Run linear programming single-objective optimization function 1 \(Z_1\) with \(\varepsilon, k\) to obtain the optimal solution for \(Z_1\) (denoted by \(v_k^*(Z_1)\))

Step 2.3: Save the set of ordered values: tuple \(\varepsilon_k, v_k^*(Z_1)\)

Step 3: The collection of points \(\{(\varepsilon_k, v_k^*(Z_1))\}_{k \in K}\) is a discrete approximation of the Pareto efficiency frontier.

The intervals between the lower and upper boundaries of \(\varepsilon\) parameter were partitioned into 50 sub-intervals of equal length. Calculations in the model were then performed to find every possible value for \(\varepsilon\). The ILOG CPLEX version 12.3 optimization software was used to formulate and solve the model. The respective scope was specified by 10,927 variables subjected to 309 constraints. The multi-objective Pareto solution for the Thai rubber supply chain is presented in the next section.

5. Results and discussions

5.1. Pareto optimal solution

The Pareto set of solutions for minimizing costs and GHG emissions is illustrated in Figure 3 (See Table C1 in the appendix for the corresponding table of the Pareto set of solutions). All the optimal solutions lie on the Pareto curve. Thus, the solutions above the curve are sub-optimal while any solutions below the curve are infeasible. Each point in the Pareto set entails a specific quantity of rubber product flow between the supply chain entities (farmer, trader group and factory) and the transportation modes and routes. The marginal point at the upper left (point A) is the extreme solution for GHG emission minimization whereas the marginal point at the lower right (point C) is the extreme solution for cost minimization.

The Pareto curve demonstrates the trade-offs between costs and GHG emissions. It shows that GHG emission reduction is only possible by compromising costs (which will be higher). The X and Y-axes in the Pareto graph are GHG emissions in tons and costs in millions of Baht (1 Thai Baht equals 0.033 US dollars). These can be used to indicate changes in costs relative to GHG emissions. As seen in Figure 3, the Pareto curve shows two distinct patterns. The first pattern from point B to point A (right to the left) shows a drastic increase in costs relative to minimal decrements in GHG emissions as the curve moves...
towards the extreme solution for GHG emission minimization at point A. The second pattern from point C (extreme solution for cost minimization) to point B shows a minimal increase in costs relative to significant decrements in GHG emissions. The Pareto curve is almost a flat line.

From the alternative solutions, policymakers in the Thai rubber industry can choose the best-fit solution, according to preference and applicable policy. Although environmental responsibility is currently voluntary in the industry, policymakers can begin to consider making environmental improvements for a marginal increase in total costs. Although each point in the Pareto curve is equally effective at representing different solutions to or compromises between these two objectives, it is possible to find a “good choice” solution in the above curves. The solution in point B may be a promising answer given that a significant reduction in GHG emissions can be achieved without compromising too much in terms of costs. In addition, the Thai rubber policymakers can use this Pareto curve as a tool to estimate the potential gain in environmental improvements compared with the costs to obtain this gain. The solution in point B shows that to reduce 1 ton of GHG emissions, the compromise must be an increase of 0.01 million Baht in costs.

5.2. Scenario analysis
From the theoretical standpoint, the existing literature agrees that any changes made to transportation and distribution networks are highly likely to influence the costs and environmental impact of the supply chain (Hugo & Pistikopoulos, 2005). Therefore, different likely scenarios are tested to examine the potential impact of transportation restructure and distribution restructure scenarios on the trade-off to assist policymakers in their supply chain redesign decisions.

5.2.1. Transportation restructure scenario analysis- Pareto solutions
Rail freight is widely regarded as an economical and environmentally friendly mode of transport among the four commonly used modes of transportation: road, rail, sea, and air (Kim et al., 2010; Winebrake et al., 2008). Four different scenarios relating to road-rail intermodal transport service capacity were explored when the rail freight service capacity of routes R5, R6, R7, R10, R11, R12, and R13 (see Figure 2 for each route description) was increased by 25% (Scenario 1), 50% (Scenario 2), 75% (Scenario 3) and 100% (Scenario 4) in relation to the baseline model. The descriptions of the transportation scenarios are presented in Table 1.

The Pareto curve for transportation scenarios compared with the baseline model is presented in Figure 4. In the figure, the four scenarios have the same scale in each panel, while the baseline
Table 1. Transportation restructure scenarios

| Scenario | Description |
|----------|-------------|
| 1        | Increase rail freight service capacity of route R5, R6, R7, R10, R11, R12, R13 by 25% |
| 2        | Increase rail freight service capacity of route R5, R6, R7, R10, R11, R12, R13 by 50% |
| 3        | Increase rail freight service capacity of route R5, R6, R7, R10, R11, R12, R13 by 75% |
| 4        | Increase rail freight service capacity of route R5, R6, R7, R10, R11, R12, R13 by 100% |

Pareto curve was re-scaled to make comparisons with each of the four scenarios. In each scenario, rail freight capacity is increased by 25% to baseline (See Tables C2–C5 in the appendix for the corresponding table to the Pareto set of solutions for each scenario).

These curve patterns strongly suggest that, at the same cost level, an increase in rail freight service capacity leads to lower GHG emissions at the same proportional rate as the increase in rail freight capacity. For the same total GHG emissions, there are two observations related to cost reduction. The first concerns GHG emission levels lower than approximately 190,000 tons. It shows that at the same level of GHG emissions, costs gradually and continuously increase relative to the lower rail freight capacity ratio. The second observation concerns GHG emission levels greater than approximately 190,000 tons. The Pareto curves in all the scenarios become flat and overlapping, meaning that GHG emission levels become increasingly independent of costs. There is no or very minimal increase in costs, but the GHG emissions continue to decrease until entering the realm of extreme solution for GHG emission minimization in which a drastic increase in costs is seen in all scenarios relative to minimal decrements in GHG emissions.

This is a significant finding for policymakers in that any solutions in this curve range may not be effective choices as trade-off solutions. In other words, when GHG emissions reduce to a certain level, it is not worth reducing them further, as a compromise must be made with the greater increases in costs.

It can be seen that when rail freight capacity is increased from the baseline by 25% (Scenario 1), this results in a greater shift of the curve from right to left. The other scenario curves shift (from right to left) consecutively in a relatively smaller proportion. This suggests that an increase in the...
first 25% of rail freight capacity has a greater influence on the reduction of GHG emissions. Consequently, Scenario 1 may be a more effective solution compared with the other scenarios, particularly when considering that a capacity increase of 25% is a more realistic proposal due to the rail freight capacity expansion limitation (State Railway of Thailand, 2019). However, it is worth observing with regard to Scenarios 2, 3 and 4, that the greater the capacity of the rail freight operation is, the lower the GHG emissions become.

Improvements in rail freight capacity will unavoidably incur investment costs. Therefore, the policymakers must decide whether it is worthwhile to make such improvements, using the Pareto curves as a guide. For example, with GHG emissions reduction as a goal, the policymaker will be able to estimate the cost difference between the baseline and each scenario. If the cost difference is significant enough to cover the investment in rail freight capacity improvement, this goal is worthwhile. Otherwise, the search for alternative trade-off solutions must continue. More specifically, if the Thai rubber industry policymakers set GHG emission levels at 191,500 tons as a goal, the cost difference between the baseline and Scenario 1 is 46 million Baht (costs of 16,093 and 16,047 million Baht for the baseline and Scenario 1, respectively). Thus, if the investment costs of upgrading rail track facilities are lower than 46 million Baht, it is worthwhile pursuing the strategy in Scenario 1.

5.2.2. Distribution restructuring scenario analysis—Pareto solutions
This section aims to examine distribution restructuring scenario based on (Chanchaichujit et al., 2017)'s work. The author examined the optimum number of gateway nodes for cost and GHG emission minimization in the Thai rubber industry. The results of cost minimization identified an optimum number of four gateway nodes made up of Songkhla, Suratthani, Nakhon Si Thammarat and Trang. For GHG emission minimization results, five provinces were identified as optimum gateway nodes. These were Songkhla, Suratthani, Nakhon Si Thammarat, Trang and Chumphon. The authors also propose the new transportation route R15 for the distribution restructuring in the Thai rubber supply chain. This new route is made up of road-sea intermodal transport. Here, cargo is transported by truck, from its origin to the Kantang coast's port terminal before being moved by short-sea shipping to Penang (MOT, 2017). Thus, this route is seen as a potential development route for the rubber industry. Figure 5 represents an overview of the optimal network configuration, using the costs and GHG emissions minimization results and new transportation route R15.

Table 2 shows the distribution restructuring scenario analysis considered in this study. This includes the optimal cost solution at four gateway nodes (Scenario 1); optimal cost solution at four gateway nodes with R15 (Scenario 3); optimal GHG emissions at five gateway nodes (Scenario 2); and optimal GHG emissions at five gateway nodes with R15 (Scenario 4). The scenarios with new route R15 aim to provide new insight for policymakers to evaluate the feasibility of developing Kantang port as the western short-sea shipping corridor for the Thai rubber industry.

Figures 6 and 7 illustrate the Pareto curves for the baseline and four different scenarios related to the distribution restructuring (See Tables C6–C9 in the appendix for the corresponding table for the Pareto set of solutions in each scenario). In Figure 6, the Pareto curves only show two visible curves for the baseline and Scenario 4, as the curves for Scenarios 1, 2 and 3 lies under the curve in Scenario 4. Therefore, Figure 7 is presented to view the individual Pareto curves in Scenarios 1, 2 and 3.

The Pareto curves for distribution restructuring show that at the four gateway nodes, the curve moved sharply to the lower bottom panel (see Figure 7 Scenario 1). Likewise, with the five gateway nodes, the curve moved to the lower bottom of the panel. However, for the five gateway nodes, the curve shape changed with a lengthening of the line to the upper left side (see Figure 7 Scenario 2). The curve pattern suggests that at the same GHG emissions level, the more gateway nodes there are, the lower the cost becomes compared with the baseline scenario. In addition to the curve shape, it can be noted that the Scenario 1 curve is a portion of the Scenario 2 curve.
For Scenarios 3 and 4, when the new transportation route R15 is implemented in conjunction with four and five gateway nodes, the graph shows the same pattern as Scenarios 1 and 2 respectively. In other words, the curve pattern for Scenarios 1 and 3, and Scenarios 2 and 4 are almost the same. The differences between these curves are that the scenario curves for route R15 lengthen in a straight horizontal line to the bottom right panel before entering the zone of the extreme cost minimization solution.

Table 2. Distribution restructure scenarios

| Scenario | Description |
|----------|-------------|
| 1        | Four gateway nodes |
| 2        | Five gateway nodes |
| 3        | Four gateway nodes with new route R15 |
| 4        | Five gateway nodes with new route R15 |
Another important insight from Figures 6 and 7 is that the curves of these four scenarios lie under and overlap each other. The curves clearly show that Scenario 1 is a partial duplication of Scenario 3 while Scenario 2 is a partial duplication of Scenario 4. Overall, scenarios 1, 2, and 3 are part duplications of Scenario 4. In addition, these four curves have the same turning point (point A) on a flat horizontal line. This information suggests that Scenario 4 may be the most promising, with point A as an effective solution to achieving significant GHG emissions reduction without compromising too much on increased costs.

### 5.3. Comparison of transportation and distribution Pareto solutions

This section aims to present the Pareto curves for the selected transportation and distribution scenarios. As discussed in the previous section, Scenario 1 for transportation is the most realistic scenario for achieving significant GHG emission reductions without compromising too much in terms of increased costs. In addition, Scenario 4, the distribution restructure, is considered to be one of the most promising possibilities for achieving a notable GHG emissions reduction without compromising greatly on increased costs. Therefore, further examining the relationship between these two scenarios’ Pareto optimal curves is worthwhile.

Figure 8 depicts the Pareto curves for transportation in Scenario 1 (see the Scenario 1: T curve), and distribution Scenario 4 (see the Scenario 4: D curve) and the baseline model.

It is clearly illustrated in Figure 8 that at the same cost level, Scenario 1: T indicates lower GHG emissions while at the same GHG emission level, Scenario 4: D exhibits lower costs. The interesting point about this figure is that the Pareto curve of these two scenarios intersects at point A. This is the point where the transportation and distribution scenarios have the same effectiveness. The optimal solution at this point for simultaneous cost and GHG emission reductions would be where GHG measures are taken at a load level of 189,968 tons and the total costs would be 16,062 million Baht. Therefore, if the policymaker were to select this solution, it could be achieved by adopting either Transportation Scenario 1 or Distribution Scenario 4.

For any solution where GHG emission levels are higher than 189,968 tons, Scenario 4: D provides a better compromise. Scenario 4: D indicates a higher cost reduction with a marginal GHG emissions increase than does Scenario 1:T. In contrast, for a GHG emissions level lower than the 189,968 measure, only Scenario 1: T will produce a feasible solution. For this reason, policymakers must focus clearly on GHG emission targets to achieve their goals. It is important to note that different GHG emissions target levels will lead to different strategies for achieving the target by using the best compromise.
In short, the analysis of the Pareto curves in this section shows that the more stringent the GHG emissions target is, the greater the rail operation needed will be. In contrast, if the GHG emissions target is a consideration, but not the ultimate priority, the strategy for achieving
environmental gains without increasing costs for trade-offs would be to set up more distribution centers.

6. Implications and conclusion

In this study, a multi-objective linear programming model was developed with the aim of optimizing total costs and total GHG emissions simultaneously for the Thai rubber supply chain. The results obtained in this study show the trade-offs between costs and GHG emissions. It appears that improvements in environmental performance are only possible by compromising on and allowing for higher costs and vice versa. From the Pareto set of solutions, although each point is equally effective in representing a compromise solution, it is possible to identify an effective solution for achieving significant GHG emission reductions without compromising too far on costs.

From the scenario analyses, it can be seen that a transportation restructure is more beneficial to the environment than a distribution restructure is. The greater the increase in rail freight, the lower the GHG emissions in the supply chain. In this study, an increase of 25% in the rail freight capacity was seen as the most feasible scenario leading to lower GHG emissions without significant cost compromises. From an economic perspective, restructuring distribution to five gateway nodes, along with the development of route R15, will result in notable cost reductions.

Overall, this paper showed that the model developed together with its Pareto solutions analysis, can be used as an effective tool to design a new and workable supply chain model that optimizes costs and GHG emissions for the Thai rubber industry.

The study has several practical and research implications. From a practical standpoint, the study provides a decision-support model for the Thai rubber industry policymakers to better manage their supply chain, considering costs and environmental improvements. This includes decisions like whether to facilitate the expansion of or investment in distribution and transportation facilities such as distribution centers, roads, railways and port terminals. The increasing global demand and push for environmental sustainability are putting pressure on Thai rubber industry to increase production levels and remain cost-competitive while minimizing its environmental impacts. Unfortunately, to date, the industry does not have a controlled plan or policy guidelines for the expansion of rubber facilities and transport infrastructure. Therefore, the study is timely in the sense of improving the environmental performance of the Thai rubber industry in an organized
manner without losing cost-competitiveness. Moreover, the study is directly aligned with Thailand’s commitment to achieving low GHG emissions, and a climate-resilient society consistent with the strategies of the 12th National Economic and Social Development Plan (NESDP) 2017–2021, and Thailand’s Climate Change Master Plan 2015–2050 (ONREPP, 2016).

In terms of research implications, this research is arguably the first significant attempt to apply a multi-objective decision model to the rubber industry anywhere, let alone in Thailand. Therefore, the contributions of this study are novel. Further researchers could adapt, test and validate this model in other leading rubber-producing countries such as Malaysia, Indonesia, Vietnam and China.

The study has some limitations. It fails to consider the uncertainty inherent in real-world rubber production and distribution networks. Therefore, to address this limitation, future research could consider input uncertainties such as demand, supply, and price. For instance, uncertain rubber production capacities and yield per farm, rubber demand and rubber prices may be incorporated into the model as uncertain parameters. In addition, there could be other potential optimal scenarios that have not been accounted for in this study. The other concern is that the Pareto-optimal solutions sets are typically vast, and the decision-maker usually faces the problem of reducing the size of the set to have a manageable number of solutions to analyze.

Despite the limitations, we think that the application of the proposed model and findings of this study can significantly contribute toward the greening efforts of the rubber industry sector, as well as encourage more research in this field.

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### Appendix A.

**Table A1. Model notation**

| Set | | |
|---|---|---|
| $rR$ | Set of plantation areas ($r = 1,2,3,4,5,6,7,8,9,10,11,12,13,14$) | |
| $uU$ | Set of upstream rubber products ($u =$ Field Latex (FL), Unsmoked Sheet (US), Cup-Lump (CL)) | |
| $fF$ | Set of farmer sizes ($f =$ small, medium, large) | |
| $tT$ | Set of truck types ($t =$ 4 wheels, 10 wheels) | |
| $gG$ | Set of trader groups ($g =$ dealer, general market, cooperative) | |
| $pP$ | Set of midstream rubber processing plants ($p =$ summation of all plants in plantation area: 1,2,3,4,5,6,7,8,9,10,11,12,13,14) | |
| $mM$ | Set of midstream rubber products ($m =$ Concentrated Latex (CL), Ripped Smoked Sheet (RS), Block Rubber (BR)) | |
| $aA$ | Set of gateway nodes ($a =$ 3 (Suratthani), 7 (Nakhon Si Thammarat), 11(Songkhla)) | |
| $bB$ | Set of intermodal freight routes ($b =$ R,R2,R3,R4, ... R14) | |
| $dD$ | Set of domestic destinations and exporting ports ($d =$ Country stock, Midstream Rubber Processing, Songkhla port, Penang port, Bangkok port, Lamchabang port) | |

| Decision Variables | | |
|---|---|---|
| $X_{rufg}$ | Amount of upstream rubber product $u$ produce from farmer $f$ in plantation area $r$ transported by truck type $t$ to trader group $g$ | |
| $Y_{rufgpr}$ | Amount of upstream rubber product $u$ from trader group $g$ in plantation area $r$ transported to midstream processing plant $p$ to produce midstream rubber product $m$ and then transported to gateway node $a$ | |
| $Z_{rufgpr}$ | Amount of midstream rubber product $m$ from gateway node $a$ transported by intermodal freight route $b$ to domestic destinations and exporting port $d$ | |

| Data and Parameters | | |
|---|---|---|
| $RPC_r$ | Aggregated upstream rubber cultivation capacity of farmer $f$ in each plantation area $r$ | |
| $TG_{gur}$ | Aggregated trader group capacity of a given trader group $g$ for upstream rubber product $u$ in each plantation area $r$ | |
| $MC_{pm}$ | Aggregated midstream rubber processing plant production capacity of midstream rubber product $m$ at given midstream rubber processing plant $p$ | |
| $GWC_a$ | Aggregated gateway node capacity in a given gateway node $a$ | |
| $FR_{b}$ | Aggregated freight route capacity for a given freight route $b$ | |
| $DE_{mnd}$ | Aggregated demand for midstream rubber product $m$ at destination $d$ | |

| Cost Parameters | | |
|---|---|---|
| $CR_{u}$ | Costs of farmer $f$ to process upstream rubber product $u$ | |
| $CT_{ng}$ | Costs of transport upstream rubber product from farmer $f$ to trader group $g$ by truck type $t$ | |
| $CG_{ug}$ | Costs of trading upstream rubber product $u$ in trader group $g$ | |
| $CT_{ngp}$ | Costs of transport upstream rubber product from trader group $g$ in plantation area $r$ to midstream rubber processing plant $p$ | |
| $CF_{pm}$ | Costs of midstream rubber processing $p$ to process midstream rubber product $m$ | |
| $CT_{pa}$ | Costs of transport midstream rubber product from midstream rubber processing plant $p$ to gateway node $a$ | |
| $CT_{ab}$ | Costs of transport midstream rubber product from gateway node $a$ to freight route $b$ | |
| $CM_{b}$ | Costs of exporting midstream rubber product via freight route $b$ | |
| $CT_{bd}$ | Costs of transport midstream rubber product from freight route $b$ to destination $d$ | |

| Environmental Parameters | | |
|---|---|---|
| $EB_{u}$ | GHG emissions of farmer $f$ to process upstream rubber product $u$ | |
| $ET_{ng}$ | GHG emissions of transport upstream rubber product from farmer $f$ to trader group $g$ by truck type $t$ | |

(Continued)
Table B1. Mathematical formulation

Objective function for costs minimization:

$$\text{Min} Z_1 = \sum_{r} \sum_{a} \sum_{t} \sum_{g} X_{fttg} (CR_{fu} + CT_{fg} + CG_{gu}) + \sum_{r} \sum_{p} \sum_{m} \sum_{a} Y_{rgpm} (CT_{rmp} + CF_{pm} + CT_{pa})$$
$$+ \sum_{m} \sum_{a} \sum_{b} Z_{mabd} (CT_{ab} + CM_b + CT_{bd})$$  \(1\)

Objective function for GHG emissions minimization:

$$\text{Min} Z_2 = \sum_{r} \sum_{a} \sum_{t} \sum_{g} X_{fttg} (ER_{fu} + ET_{fg} + EG_{gu}) + \sum_{r} \sum_{g} \sum_{m} \sum_{a} Y_{rgpm}$$
$$\left(ET_{rmp} + EF_{pm} + ET_{pa}\right) + \sum_{m} \sum_{a} \sum_{b} Z_{mabd} (ET_{ab} + EM_b + ET_{bd})$$  \(2\)

Constraints:

Upstream Rubber Cultivation capacity:

$$\sum_{u} \sum_{t} \sum_{g} X_{fttg} \leq RPC_{fr}, \forall f, t, r$$  \(3\)

Trader group capacity:

$$\sum_{f} \sum_{t} X_{fttg} \leq TGC_{gur}, \forall g, r, \forall u$$  \(4\)

Midstream rubber processing plant capacity:

$$\sum_{r} \sum_{g} \sum_{m} Y_{rgpm} \leq MC_{pm}, \forall p, r, M$$  \(5\)

Gateway node capacity:

$$\sum_{r} \sum_{g} \sum_{m} \sum_{a} Y_{rgpm} \leq GWC_{a}, \forall a, A$$  \(6\)

Freight route system capacity:

$$\sum_{m} \sum_{a} \sum_{b} Z_{mabd} \leq FRC_{b}, \forall b, B$$  \(7\)

Demand:

$$\sum_{a} \sum_{b} Z_{mabd} = DE_{dm}, \forall d, D, M$$  \(8\)

Production product mix ratio:

$$\alpha \times \left( \sum_{r} \sum_{g} \sum_{p} \sum_{a} Y_{rgp8fa} \right) + \left( 1 - \alpha \right) \times \sum_{r} \sum_{g} \sum_{p} \sum_{a} Y_{rgp8fa}$$
$$= \sum_{r} \sum_{g} \sum_{p} \sum_{a} X_{ftug}, \forall p \in P, \forall u \in U$$  \(9\)

$$\left( 1 - \alpha \right) \times \sum_{r} \sum_{g} \sum_{p} \sum_{a} Y_{rgp8fa} = \sum_{r} \sum_{g} \sum_{p} \sum_{a} X_{ftug}, \forall p \in P, \forall u \in U$$  \(10\)

$$\left( \sum_{r} \sum_{g} \sum_{p} \sum_{a} Y_{rgp8fa} \right) = \sum_{r} \sum_{g} \sum_{p} \sum_{a} X_{ftug}$$  \(11\)

(Continued)
Conservation flow:
\[ \sum r \sum f \sum u \sum t X_{rfgut} = \sum r \sum p \sum m \sum a Y_{rgpma} - Vg \cdot G \] \hspace{1cm} (12)

\[ \sum r \sum g \sum p \sum m \sum a Y_{rgpma} = \sum b \sum d \sum M \cdot V \cdot a \cdot A \] \hspace{1cm} (13)

Non-negativity constraints:
\[ X_{rfgut} \geq 0 \] \hspace{1cm} (14)
\[ Y_{rgpma} \geq 0 \] \hspace{1cm} (15)
\[ Z_{mabd} \geq 0 \] \hspace{1cm} (16)

Table C1. The Pareto set of solutions for minimizing costs and GHG emissions using the \( \varepsilon \) - constraint method

| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|--------------|--------------------------------------|----------------------|
| 1            | 199,550                              | 16,045               |
| 2            | 199,390                              | 16,045               |
| 3            | 199,230                              | 16,046               |
| 4            | 199,070                              | 16,046               |
| 5            | 198,910                              | 16,046               |
| 6            | 198,750                              | 16,046               |
| 7            | 198,590                              | 16,046               |
| 8            | 198,430                              | 16,046               |
| 9            | 198,270                              | 16,046               |
| 10           | 198,110                              | 16,046               |
| 11           | 197,950                              | 16,046               |
| 12           | 197,790                              | 16,046               |
| 13           | 197,630                              | 16,046               |
| 14           | 197,470                              | 16,046               |
| 15           | 197,310                              | 16,046               |
| 16           | 197,150                              | 16,046               |
| 17           | 196,990                              | 16,046               |
| 18           | 196,830                              | 16,046               |
| 19           | 196,670                              | 16,046               |
| 20           | 196,510                              | 16,046               |
| 21           | 196,350                              | 16,046               |
| 22           | 196,190                              | 16,047               |
| 23           | 196,030                              | 16,047               |
| 24           | 195,870                              | 16,047               |
| 25           | 195,710                              | 16,047               |
| 26           | 195,550                              | 16,048               |
| 27           | 195,390                              | 16,048               |

(Continued)
| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|-------------|-------------------------------------|---------------------|
| 28          | 195,230                             | 16,049              |
| 29          | 195,070                             | 16,049              |
| 30          | 194,910                             | 16,050              |
| 31          | 194,750                             | 16,050              |
| 32          | 194,590                             | 16,051              |
| 33          | 194,430                             | 16,052              |
| 34          | 194,270                             | 16,053              |
| 35          | 194,110                             | 16,053              |
| 36          | 193,950                             | 16,054              |
| 37          | 193,790                             | 16,055              |
| 38          | 193,630                             | 16,056              |
| 39          | 193,470                             | 16,057              |
| 40          | 193,310                             | 16,058              |
| 41          | 193,150                             | 16,059              |
| 42          | 192,990                             | 16,060              |
| 43          | 192,830                             | 16,062              |
| 44          | 192,670                             | 16,063              |
| 45          | 192,510                             | 16,064              |
| 46          | 192,350                             | 16,066              |
| 47          | 192,190                             | 16,069              |
| 48          | 192,030                             | 16,072              |
| 49          | 191,870                             | 16,076              |
| 50          | 191,710                             | 16,082              |

Table C2. The Pareto set of solutions for minimizing costs and GHG emissions using the $\epsilon$-constraint method. Transportation restructure scenarios 1 (Increase rail freight service capacity by 25% of route R5, R6, R7, R10, R11, R12, R13)

| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|-------------|-------------------------------------|---------------------|
| 1           | 197,000                             | 16,043              |
| 2           | 196,772                             | 16,043              |
| 3           | 196,544                             | 16,043              |
| 4           | 196,316                             | 16,043              |
| 5           | 196,088                             | 16,043              |
| 6           | 195,860                             | 16,043              |
| 7           | 195,632                             | 16,043              |
| 8           | 195,404                             | 16,043              |
| 9           | 195,176                             | 16,044              |
| 10          | 194,948                             | 16,044              |
| 11          | 194,720                             | 16,044              |
| 12          | 194,492                             | 16,044              |
| 13          | 194,264                             | 16,044              |

(Continued)
| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|--------------|--------------------------------------|---------------------|
| 14           | 194,036                              | 16,044              |
| 15           | 193,808                              | 16,044              |
| 16           | 193,580                              | 16,044              |
| 17           | 193,352                              | 16,044              |
| 18           | 193,124                              | 16,044              |
| 19           | 192,896                              | 16,045              |
| 20           | 192,668                              | 16,045              |
| 21           | 192,440                              | 16,045              |
| 22           | 192,212                              | 16,046              |
| 23           | 191,984                              | 16,047              |
| 24           | 191,756                              | 16,047              |
| 25           | 191,528                              | 16,047              |
| 26           | 191,300                              | 16,049              |
| 27           | 191,072                              | 16,050              |
| 28           | 190,844                              | 16,051              |
| 29           | 190,616                              | 16,052              |
| 30           | 190,388                              | 16,053              |
| 31           | 190,160                              | 16,054              |
| 32           | 189,932                              | 16,056              |
| 33           | 189,704                              | 16,058              |
| 34           | 189,476                              | 16,060              |
| 35           | 189,248                              | 16,062              |
| 36           | 189,020                              | 16,064              |
| 37           | 188,792                              | 16,071              |
| 38           | 188,564                              | 16,071              |
| 39           | 188,336                              | 16,077              |
| 40           | 188,108                              | 16,085              |
| 41           | 187,880                              | 16,095              |
| 42           | 187,652                              | 16,104              |
| 43           | 187,424                              | 16,114              |
| 44           | 187,196                              | 16,124              |
| 45           | 186,968                              | 16,133              |
| 46           | 186,740                              | 16,143              |
| 47           | 186,512                              | 16,152              |
| 48           | 186,284                              | 16,162              |
| 49           | 186,056                              | 16,172              |
| 50           | 185,828                              | 16,183              |
Table C3. The Pareto set of solutions for minimizing costs and GHG emissions using the \( \varepsilon \)-constraint method: Transportation restructure scenarios 2 (Increase rail freight service capacity by 50% of route R5, R6, R7, R10, R11, R12, R13)

| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|--------------|--------------------------------------|----------------------|
| 1            | 195,200                              | 16,041               |
| 2            | 194,974                              | 16,041               |
| 3            | 194,748                              | 16,041               |
| 4            | 194,522                              | 16,041               |
| 5            | 194,296                              | 16,041               |
| 6            | 194,070                              | 16,042               |
| 7            | 193,844                              | 16,042               |
| 8            | 193,618                              | 16,042               |
| 9            | 193,392                              | 16,042               |
| 10           | 193,166                              | 16,042               |
| 11           | 192,940                              | 16,042               |
| 12           | 192,714                              | 16,042               |
| 13           | 192,488                              | 16,042               |
| 14           | 192,262                              | 16,042               |
| 15           | 192,036                              | 16,042               |
| 16           | 191,810                              | 16,042               |
| 17           | 191,584                              | 16,042               |
| 18           | 191,358                              | 16,043               |
| 19           | 191,132                              | 16,043               |
| 20           | 190,906                              | 16,043               |
| 21           | 190,680                              | 16,043               |
| 22           | 190,454                              | 16,043               |
| 23           | 190,228                              | 16,044               |
| 24           | 190,002                              | 16,044               |
| 25           | 189,776                              | 16,045               |
| 26           | 189,550                              | 16,046               |
| 27           | 189,324                              | 16,047               |
| 28           | 189,098                              | 16,048               |
| 29           | 188,872                              | 16,050               |
| 30           | 188,646                              | 16,051               |
| 31           | 188,420                              | 16,052               |
| 32           | 188,194                              | 16,054               |
| 33           | 187,968                              | 16,056               |
| 34           | 187,742                              | 16,058               |
| 35           | 187,516                              | 16,060               |
| 36           | 187,290                              | 16,064               |
| 37           | 187,064                              | 16,070               |
| 38           | 186,838                              | 16,079               |
| 39           | 186,612                              | 16,089               |
| 40           | 186,386                              | 16,098               |
| 41           | 186,160                              | 16,108               |
| 42           | 185,934                              | 16,117               |

(Continued)
### Table (Continued)

| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|--------------|--------------------------------------|----------------------|
| 43           | 185,708                              | 16,127               |
| 44           | 185,482                              | 16,136               |
| 45           | 185,256                              | 16,146               |
| 46           | 185,030                              | 16,155               |
| 47           | 184,804                              | 16,166               |
| 48           | 184,578                              | 16,177               |
| 49           | 184,352                              | 16,189               |
| 50           | 184,126                              | 16,201               |

### Table C4. The Pareto set of solutions for minimizing costs and GHG emissions using the \( \varepsilon \) - constraint method: Transportation restructure scenarios 3 (Increase rail freight service capacity by 75% of route R5, R6, R7, R10, R11, R12, R13)

| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|--------------|--------------------------------------|----------------------|
| 1            | 193,800                              | 16,040               |
| 2            | 193,574                              | 16,040               |
| 3            | 193,348                              | 16,040               |
| 4            | 193,122                              | 16,040               |
| 5            | 192,896                              | 16,040               |
| 6            | 192,670                              | 16,040               |
| 7            | 192,444                              | 16,040               |
| 8            | 192,218                              | 16,040               |
| 9            | 191,992                              | 16,040               |
| 10           | 191,766                              | 16,040               |
| 11           | 191,540                              | 16,040               |
| 12           | 191,314                              | 16,040               |
| 13           | 191,088                              | 16,041               |
| 14           | 190,862                              | 16,041               |
| 15           | 190,636                              | 16,041               |
| 16           | 190,410                              | 16,041               |
| 17           | 190,184                              | 16,041               |
| 18           | 189,958                              | 16,041               |
| 19           | 189,732                              | 16,041               |
| 20           | 189,506                              | 16,041               |
| 21           | 189,280                              | 16,041               |
| 22           | 189,054                              | 16,042               |
| 23           | 188,828                              | 16,042               |
| 24           | 188,602                              | 16,043               |
| 25           | 188,376                              | 16,044               |
| 26           | 188,150                              | 16,045               |
| 27           | 187,924                              | 16,046               |
| 28           | 187,698                              | 16,047               |

(Continued)
Table C5. The Pareto set of solutions for minimizing costs and GHG emissions using the $\varepsilon$ - constraint method: Transportation restructure scenarios 4 (Increase rail freight service capacity by 100% of route R5, R6, R7, R10, R11, R12, R13)

| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|--------------|--------------------------------------|----------------------|
| 29           | 187,472                              | 16,048               |
| 30           | 187,246                              | 16,049               |
| 31           | 187,020                              | 16,051               |
| 32           | 186,794                              | 16,053               |
| 33           | 186,568                              | 16,055               |
| 34           | 186,342                              | 16,057               |
| 35           | 186,116                              | 16,060               |
| 36           | 185,890                              | 16,068               |
| 37           | 185,664                              | 16,078               |
| 38           | 185,438                              | 16,087               |
| 39           | 185,212                              | 16,096               |
| 40           | 184,986                              | 16,106               |
| 41           | 184,760                              | 16,115               |
| 42           | 184,534                              | 16,125               |
| 43           | 184,308                              | 16,134               |
| 44           | 184,082                              | 16,144               |
| 45           | 183,856                              | 16,153               |
| 46           | 183,630                              | 16,163               |
| 47           | 183,404                              | 16,175               |
| 48           | 183,178                              | 16,186               |
| 49           | 182,952                              | 16,199               |
| 50           | 182,726                              | 16,214               |

(Continued)
| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|--------------|-------------------------------------|---------------------|
| 15           | 189,712                             | 16,039              |
| 16           | 189,470                             | 16,039              |
| 17           | 189,228                             | 16,039              |
| 18           | 188,986                             | 16,039              |
| 19           | 188,744                             | 16,040              |
| 20           | 188,502                             | 16,040              |
| 21           | 188,260                             | 16,040              |
| 22           | 188,018                             | 16,040              |
| 23           | 187,776                             | 16,041              |
| 24           | 187,534                             | 16,041              |
| 25           | 187,292                             | 16,042              |
| 26           | 187,050                             | 16,043              |
| 27           | 186,808                             | 16,044              |
| 28           | 186,566                             | 16,045              |
| 29           | 186,324                             | 16,046              |
| 30           | 186,082                             | 16,047              |
| 31           | 185,840                             | 16,048              |
| 32           | 185,598                             | 16,050              |
| 33           | 185,356                             | 16,052              |
| 34           | 185,114                             | 16,054              |
| 35           | 184,872                             | 16,061              |
| 36           | 184,630                             | 16,071              |
| 37           | 184,388                             | 16,081              |
| 38           | 184,146                             | 16,091              |
| 39           | 183,904                             | 16,101              |
| 40           | 183,662                             | 16,111              |
| 41           | 183,420                             | 16,122              |
| 42           | 183,178                             | 16,132              |
| 43           | 182,936                             | 16,142              |
| 44           | 182,694                             | 16,152              |
| 45           | 182,452                             | 16,164              |
| 46           | 182,210                             | 16,177              |
| 47           | 181,968                             | 16,192              |
| 48           | 181,726                             | 16,212              |
| 49           | 181,484                             | 16,235              |
| 50           | 181,242                             | 16,260              |
Table C6. The Pareto set of solutions for minimizing costs and GHG emissions using the $\varepsilon$ - constraint method: Four distribution node (Trang, Songkhla, Nakhon Si Thammarat, Suratthani)

| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|--------------|--------------------------------------|----------------------|
| 1            | 197,500                              | 15,889               |
| 2            | 197,500                              | 15,889               |
| 3            | 197,390                              | 15,889               |
| 4            | 197,280                              | 15,889               |
| 5            | 197,170                              | 15,889               |
| 6            | 197,060                              | 15,889               |
| 7            | 196,950                              | 15,889               |
| 8            | 196,840                              | 15,889               |
| 9            | 196,730                              | 15,889               |
| 10           | 196,620                              | 15,889               |
| 11           | 196,510                              | 15,889               |
| 12           | 196,400                              | 15,889               |
| 13           | 196,290                              | 15,889               |
| 14           | 196,180                              | 15,889               |
| 15           | 196,070                              | 15,889               |
| 16           | 195,960                              | 15,889               |
| 17           | 195,850                              | 15,889               |
| 18           | 195,740                              | 15,889               |
| 19           | 195,630                              | 15,889               |
| 20           | 195,520                              | 15,889               |
| 21           | 195,410                              | 15,889               |
| 22           | 195,300                              | 15,889               |
| 23           | 195,190                              | 15,889               |
| 24           | 195,080                              | 15,890               |
| 25           | 194,970                              | 15,890               |
| 26           | 194,860                              | 15,890               |
| 27           | 194,750                              | 15,890               |
| 28           | 194,640                              | 15,891               |
| 29           | 194,530                              | 15,892               |
| 30           | 194,420                              | 15,892               |
| 31           | 194,310                              | 15,893               |
| 32           | 194,200                              | 15,894               |
| 33           | 194,090                              | 15,894               |
| 34           | 193,980                              | 15,895               |
| 35           | 193,870                              | 15,896               |
| 36           | 193,760                              | 15,897               |
| 37           | 193,650                              | 15,898               |
| 38           | 193,540                              | 15,899               |
| 39           | 193,430                              | 15,900               |
| 40           | 193,320                              | 15,901               |
| 41           | 193,210                              | 15,902               |
| 42           | 193,100                              | 15,903               |
| 43           | 192,990                              | 15,905               |

(Continued)
Table (Continued)

| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|--------------|--------------------------------------|----------------------|
| 44           | 192,880                              | 15,906               |
| 45           | 192,770                              | 15,908               |
| 46           | 192,660                              | 15,910               |
| 47           | 192,550                              | 15,912               |
| 48           | 192,440                              | 15,914               |
| 49           | 192,330                              | 15,916               |
| 50           | 192,100                              | 15,920               |

Table C7. The Pareto set of solutions for minimizing costs and GHG emissions using the ε - constraint method: Five distribution node (Trang, Songkhla,Nakhon Si Thammarat, Suratthani, Chumphorn)

| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|--------------|--------------------------------------|----------------------|
| 1            | 198,000                              | 15,889               |
| 2            | 197,808                              | 15,889               |
| 3            | 197,616                              | 15,889               |
| 4            | 197,424                              | 15,889               |
| 5            | 197,232                              | 15,889               |
| 6            | 197,040                              | 15,889               |
| 7            | 196,848                              | 15,889               |
| 8            | 196,656                              | 15,889               |
| 9            | 196,464                              | 15,889               |
| 10           | 196,272                              | 15,889               |
| 11           | 196,080                              | 15,889               |
| 12           | 195,888                              | 15,889               |
| 13           | 195,696                              | 15,889               |
| 14           | 195,504                              | 15,889               |
| 15           | 195,312                              | 15,889               |
| 16           | 195,120                              | 15,889               |
| 17           | 194,928                              | 15,890               |
| 18           | 194,736                              | 15,890               |
| 19           | 194,544                              | 15,891               |
| 20           | 194,352                              | 15,892               |
| 21           | 194,160                              | 15,893               |
| 22           | 193,968                              | 15,894               |
| 23           | 193,776                              | 15,896               |
| 24           | 193,584                              | 15,896               |
| 25           | 193,392                              | 15,896               |
| 26           | 193,200                              | 15,896               |
| 27           | 193,008                              | 15,903               |
| 28           | 192,816                              | 15,906               |
| 29           | 192,624                              | 15,908               |

(Continued)
| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|--------------|--------------------------------------|----------------------|
| 30           | 192,432                              | 15,912               |
| 31           | 192,240                              | 15,916               |
| 32           | 192,048                              | 15,921               |
| 33           | 191,856                              | 15,928               |
| 34           | 191,664                              | 15,936               |
| 35           | 191,472                              | 15,945               |
| 36           | 191,280                              | 15,958               |
| 37           | 191,088                              | 15,971               |
| 38           | 190,896                              | 15,984               |
| 39           | 190,704                              | 15,997               |
| 40           | 190,512                              | 16,011               |
| 41           | 190,320                              | 16,025               |
| 42           | 190,128                              | 16,039               |
| 43           | 189,936                              | 16,067               |
| 44           | 189,744                              | 16,096               |
| 45           | 189,552                              | 16,126               |
| 46           | 189,360                              | 16,155               |
| 47           | 189,168                              | 16,185               |
| 48           | 188,976                              | 16,223               |
| 49           | 188,784                              | 16,284               |
| 50           | 188,400                              | 16,406               |

(Table C8. The Pareto set of solutions for minimizing costs and GHG emissions using the \( \epsilon \)-constraint method: Four distribution node (Trang, Songkhla, Nakhon Si Thammarat, Suratthani) with new transportation route R15)

| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|--------------|--------------------------------------|----------------------|
| 1            | 210,000                              | 15,876               |
| 2            | 209,620                              | 15,876               |
| 3            | 209,240                              | 15,876               |
| 4            | 208,860                              | 15,876               |
| 5            | 208,480                              | 15,876               |
| 6            | 208,100                              | 15,876               |
| 7            | 207,720                              | 15,876               |
| 8            | 207,340                              | 15,876               |
| 9            | 206,960                              | 15,876               |
| 10           | 206,580                              | 15,876               |
| 11           | 206,200                              | 15,876               |
| 12           | 205,820                              | 15,876               |
| 13           | 205,440                              | 15,876               |
| 14           | 205,060                              | 15,876               |
| 15           | 204,680                              | 15,876               |

(Continued)
| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|-------------|-------------------------------------|---------------------|
| 16          | 204,300                             | 15,876              |
| 17          | 203,920                             | 15,877              |
| 18          | 203,540                             | 15,877              |
| 19          | 203,160                             | 15,877              |
| 20          | 202,780                             | 15,878              |
| 21          | 202,400                             | 15,878              |
| 22          | 202,020                             | 15,879              |
| 23          | 201,640                             | 15,880              |
| 24          | 201,260                             | 15,880              |
| 25          | 200,880                             | 15,881              |
| 26          | 200,500                             | 15,881              |
| 27          | 200,120                             | 15,882              |
| 28          | 199,740                             | 15,882              |
| 29          | 199,360                             | 15,883              |
| 30          | 198,980                             | 15,884              |
| 31          | 198,600                             | 15,884              |
| 32          | 198,220                             | 15,885              |
| 33          | 197,840                             | 15,885              |
| 34          | 197,460                             | 15,886              |
| 35          | 197,080                             | 15,886              |
| 36          | 196,700                             | 15,887              |
| 37          | 196,320                             | 15,887              |
| 38          | 195,940                             | 15,888              |
| 39          | 195,560                             | 15,888              |
| 40          | 195,180                             | 15,889              |
| 41          | 194,800                             | 15,890              |
| 42          | 194,420                             | 15,892              |
| 43          | 194,040                             | 15,894              |
| 44          | 193,660                             | 15,897              |
| 45          | 193,280                             | 15,900              |
| 46          | 192,900                             | 15,904              |
| 47          | 192,520                             | 15,910              |
| 48          | 192,140                             | 15,919              |
| 49          | 191,760                             | 15,932              |
| 50          | 191,000                             | 15,977              |
Table C9. The Pareto set of solutions for minimizing costs and GHG emissions using the $\varepsilon$-constraint method: Five distribution node (Trang, Songkhla, Nakhon Si Thammarat, Suratthani, Chumphorn) with new transportation route R15

| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|--------------|--------------------------------------|----------------------|
| 1            | 208,200                              | 15,876               |
| 2            | 207,608                              | 15,876               |
| 3            | 207,216                              | 15,876               |
| 4            | 206,824                              | 15,876               |
| 5            | 206,432                              | 15,876               |
| 6            | 206,040                              | 15,876               |
| 7            | 205,648                              | 15,876               |
| 8            | 205,256                              | 15,876               |
| 9            | 204,864                              | 15,876               |
| 10           | 204,472                              | 15,876               |
| 11           | 204,080                              | 15,876               |
| 12           | 203,688                              | 15,877               |
| 13           | 203,296                              | 15,877               |
| 14           | 202,904                              | 15,877               |
| 15           | 202,512                              | 15,877               |
| 16           | 202,120                              | 15,879               |
| 17           | 201,728                              | 15,879               |
| 18           | 201,336                              | 15,880               |
| 19           | 200,944                              | 15,881               |
| 20           | 200,552                              | 15,881               |
| 21           | 200,160                              | 15,882               |
| 22           | 199,768                              | 15,882               |
| 23           | 199,376                              | 15,883               |
| 24           | 199,084                              | 15,884               |
| 25           | 198,792                              | 15,884               |
| 26           | 198,500                              | 15,885               |
| 27           | 197,808                              | 15,885               |
| 28           | 197,416                              | 15,886               |
| 29           | 197,024                              | 15,886               |
| 30           | 196,632                              | 15,887               |
| 31           | 196,240                              | 15,888               |
| 32           | 195,848                              | 15,888               |
| 33           | 195,456                              | 15,889               |
| 34           | 195,064                              | 15,889               |
| 35           | 194,672                              | 15,891               |
| 36           | 194,280                              | 15,893               |
| 37           | 193,888                              | 15,895               |
| 38           | 193,496                              | 15,898               |
| 39           | 193,104                              | 15,902               |
| 40           | 192,712                              | 15,907               |
| 41           | 192,320                              | 15,914               |
| 42           | 191,928                              | 15,926               |

(Continued)
| Sub-interval | Parameter value (GHG emissions; Ton) | Costs (Million Baht) |
|--------------|--------------------------------------|----------------------|
| 43           | 191,536                              | 15,941               |
| 44           | 191,144                              | 15,967               |
| 45           | 190,752                              | 15,994               |
| 46           | 190,360                              | 16,022               |
| 47           | 189,968                              | 16,062               |
| 48           | 189,576                              | 16,122               |
| 49           | 189,184                              | 16,182               |
| 50           | 188,400                              | 16,406               |
