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Article

New Sustainable Approach for Multi-Objective Production and Distribution Planning in Supply Chain

Kanchanitch Nupet[a] **and Pisal Yenradee**[b,*]

Logistics and Supply Chain Systems Engineering Program, School of Manufacturing Systems and Mechanical Engineering, Sirindhorn International Institute of Technology, Thammasat University, Pathum-Thani 12120 Thailand
E-mail: [a]kanchanitch1999@gmail.com, [b,*]pisal@siit.tu.ac.th (Corresponding author)

Abstract. The paper aims to introduce a sustainable approach for aggregate production and distribution planning in a supply chain (APDP-SC) that considers multiple objectives and fuzzy parameters. The proposed approach addresses sustainability concerns, including maximizing total profit and total sales of the entire supply chain, balancing profit satisfaction between supply chain members, minimizing CO_2 emissions from raw materials, production processes, and transportation of goods in the supply chain, and maximizing goodwill score from corporate social responsibility (CSR) activities. To determine the compromised solution, this paper develops a fuzzy multiple objectives mixed integer linear programming (FMOLP) model and a de-fuzzified model. The results of a simplified real case demonstrate that the proposed approach and model effectively determine the compromised solution and outperform comparison models that lack important features. Notably, this manuscript is the first to integrate the decision on conducting CSR activities with the APDP-SC decisions.

Keywords: Sustainability, corporate social responsibility, profit allocation, supply chain, production, distribution planning.

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1. Introduction

Supply chain systems refer to the inter-organizational systems that enable companies to efficiently manage the movement of products from suppliers to customers. Centralized decision-making is a fundamental aspect of supply chain (SC) management, where suppliers, production managers, distributors, and retailers share complete information [1]. It is commonly understood that sharing information about their domain with other channel partners can help decision-makers reduce supply chain costs [2, 3]. The effectiveness of information sharing, however, depends on the quality and accuracy of the shared information, and the intended recipients [1].

For a supply chain to be sustainable or long-lasting, it must be able to effectively manage economic, environmental, and social issues. Economic concerns encompass low costs, high profits, and competitiveness across the entire supply chain [4, 5, 6, 7]. It is also essential to ensure that profits are distributed evenly among all supply chain members, as concentrating profits on some members but not others could render the supply chain unsustainable. However, only limited research has attempted to balance or compromise profits among supply chain members during planning [8, 9, 10].

Environmental concerns involve addressing pollution, greenhouse effects, and CO_2 emissions, with most supply chain planning research papers addressing environmental issues using CO_2 emissions as a measure [1, 11-16]. Peng et al [17] considered emission abatement and procurement strategies. Biofuel supply chain planning was developed to reduce total consumed energy for biofuel production and carbon emission [14]. On the other hand, social issues are typically addressed through corporate social responsibility (CSR) activities, which are carefully managed by large business organizations. Proper CSR activities can increase goodwill and sales significantly, as demonstrated by various practical examples such as the pharmaceutical supply chain study [10, 18]. However, unlike economic and environmental issues, social issues have been overlooked in supply chain planning research, with limited research considering this aspect.

To enhance the goodwill of a distribution channel, Yadlapalli et al [18] conducted an ontological framework of corporate social responsibility activities, categorizing them into environmental, social, economic, stakeholder, and voluntariness dimensions. Notably, no research in supply chain planning considers the effect on customer demand when an organization conducts CSR activities.

This paper proposes a novel approach to supply chain planning that effectively addresses all sustainability issues, including economic, environmental, and social concerns. The economic issue is addressed by considering the total profit of the entire supply chain and the profit of individual members and distributing profits fairly among them using a new method proposed in this paper. Additionally, maximizing the total sales and market share of the supply chain is proposed to achieve sustainable economic outcomes.

The environmental issue is tackled through the consideration of CO_2 emissions generated from three sources: the production process of raw materials, the production process of products, and delivery trucks.

The paper also addresses social issues by considering CSR activities. No prior research has considered CSR activities in supply chain planning. This paper assumes that conducting proper CSR activities can increase the goodwill of the supply chain, leading to increased customer demand. Conversely, a lack of CSR activities may decrease customer demand.

This paper aimed at the aggregate production and distribution planning in a supply chain (APDP-SC) problem, which focuses on determining production and distribution quantities, inventory with safety stocks, and sales quantities over 12 months, considering seasonal demands. Figure 1 illustrates the structure of the supply chain, which consists of two stages: manufacturers and wholesalers.

Manufacturers make decisions on production quantity and inventory level with safety stock, while wholesalers make decisions on inventory level with safety stock and sales quantity. Additionally, determining the transportation quantities from manufacturers to wholesalers is necessary. The supply chain deals with two products.

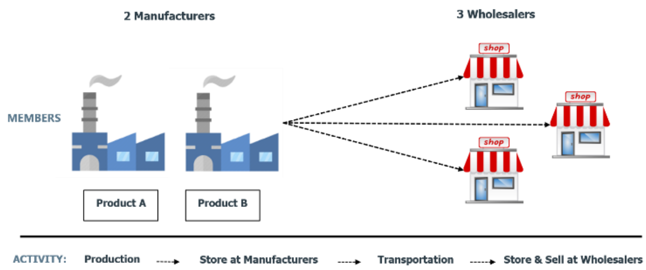

Fig. 1. Supply chain structure.

This paper has specific objectives as follows:

1. To propose a new sustainable approach for APDP-SC that maximizes the profit of the entire supply chain, balances profits between supply chain members, maximizes sales of the supply chain, minimizes CO_2 emissions, and organizes CSR activities to manage goodwill of the supply chain and customer demands.
2. To propose a fuzzy multi-objective linear programming (FMOLP) model to determine a compromised solution following the new sustainable approach
3. To evaluate the performance of the proposed FMOLP model by comparison with models without important features.
4. To recommend some managerial insights on how to effectively manage a sustainable supply chain.

This paper is arranged as follows: A review of the related literature and how this paper is different from others is presented in the next section. The methodological steps, description, notation, and mathematical formulation of the FMOLP model, and methods to defuzzify fuzzy constraints and to handle fuzzy objective functions. Section 4 aims at the validation of results and compromised solutions from the proposed model and comparison models. Finally, the results, and theoretical, and practical contributions are concluded in Section 5.

2. Literature Review

According to the content of our research in this paper, the literature review can be presented in Table 1 to compare related works in supply chain optimization problems in terms of production, distribution, and transportation planning. The table presents objective types, objective functions, methods, fuzzy parameters, and sustainability. Note that MILP, FMOLP, MOLP, MOMILP, and i-FMOLP stand for mixed integer linear programming, fuzzy multi-objective linear programming, multi-objective linear programming, multi-objective mixed integer linear programming, and interactive fuzzy multi-objective linear programming respectively.

Based on APDP-SC problems, most researchers consider issues of customer demand, production time, production quantity, safety stock level, inventory level, and delivery time [3, 4, 19, 20, 21]. Most APDP-SC is linear that involves reducing total costs, including production, inventory holding, labor, hiring, and other cost components [22, 23, 24].

For current situations, some parameters related to APDP-SC are uncertain and unable to control exactly, such as customer demand, productivity rates, various related costs, and holding costs [10, 14, 16, 23]. Most APDP-SC considers multiple products and multiple periods [4-7, 24, 25]. Pham & Yenradee [26] developed MILP models for supply chain network design problems with process networks and BOM under uncertainties in the toothbrush industry. Ondeck et al [27] proposed a MILP model for the production and transportation planning of a multi-system shale gas development area. For a pharmaceutical chain, Georgiadis & Georgiadis [28] generated optimal decisions regarding the transferred quantities between locations, and the inventory profiles of central hubs and vaccination centers. A model for integrated blood supply chain planning for disaster relief was developed by Samani et al [29].

Some research works consider supply chain problems with multiple objectives, which apply the MOLP (multiple objective linear programming) models. Altiparmak et al [30] applied Genetic Algorithm (GA) to solve the MOLP problem in supply chain networks. Rafiei et al [6] developed a model based on production process coefficients, customer service level, and capacity utilization balance.

Several MOLP models for APDP-SC focus on sustainability, specifically on greenhouse gas emissions driven by concerns over urban air pollution and global warming [8, 9, 15]. Sriklab & Yenradee [31] developed models for consistent and sustainable supplier evaluation and order allocation based on evaluation scores. MOMILP models [1, 13, 14] also focus on these concerns. Horng & Yenradee [32] developed a two-phase LP-based heuristic (cluster-first route-second) for the Capacitated Vehicle Routing Problem (CVRP). Oh & Jeong [33] developed the closed-loop supply chain model in the fashion industry that involves greenhouse gas emissions.

In addition to these models, it is important to consider the role of corporate social responsibility (CSR) in the supply chain. Various approaches have been used to incorporate CSR concepts across different industrial fields. CSR is a multidimensional concept in supply chain management and involves voluntary actions taken by members of the supply chain to address social, environmental, marketing, and human rights issues, which can improve the overall image and reputation of the pharmaceutical supply chain [10, 29, 30]. An ontological framework developed by Yadlapalli et al [18] defines and organizes CSR in this context.

The economic aspects of the entire supply chain include low cost, high profit, and high competitiveness, as noted in recent research [2-5]. Additionally, profits must be distributed fairly among all members of the supply chain to ensure sustainability. However, there is limited research on balancing or compromising profits among supply chain members [8, 9].

In the supply chain, the distributors are equally important as the productions since they significantly impact the supply chain's profitability and costs. Effective distribution planning is crucial, as this stage involves receiving and storing products in a distribution center for retailers or customers. These distributors have several factors such as customer demand, inventory level, holding cost, transportation, and available space in a warehouse.

Most articles on APDP-SC consider multiple objectives, such as minimizing total cost, maximizing total profit, reducing production cost, minimizing total delivery time, minimizing carrying and backordering costs, minimizing maximum unsatisfied demand, maximizing customer service, and maximizing total sales [5, 9, 11, 12, 19-22]. Some of these papers address both multiple objectives and fuzzy parameters in objective functions and constraints [11, 12, 16]. Fuzzy parameters, such as forecasted demand and production capacity, are included in mathematical models for these problems, which are referred to as FMOLP models [5, 19, 20, 22, 25]. Darbari et al [34] configured a model for a sustainable reverse supply chain network design for an Indian manufacturing company to manage its end-of-life and end-of-use electronic products. Shaw et al [16] also conducted a supplier selection model addressing the carbon emission issue, using FMOLP.

Table 1. Comparison of this paper and previous research works.

Related works	Obj. types		Objective functions																					Methods					Fuzzy parameters	Sustainability		
	Single objective	Multiple objectives	Minimize total costs	Maximize customer services level	Minimize the amount of feet-of-pay	Maximize total profit	Minimize capacity utilization balance	Minimizes production costs	Maximize robustness to various scenarios	Minimize total delivery time	Minimize backordering costs	Minimize the rate of change in labor levels	Minimize unsatisfied demand	Maximize local incentives	Minimize carbon emission	Maximize total value of purchasing	Minimize total consumed energy	Maximize sustainable performance	Maximize total sales	Minimize rejection quality	Maximize total profit at manufacturer	Maximize total profit at wholesaler	Maximize goodwill of CSR	MILP	FMOLP	MOLP	MOMILP	i-FMOLP		Profit allocation	Reduce carbon emission	Organize corporate social responsibility
Altiparmak et al. (2006) [30]		✓	✓	✓			✓																			✓						
Ahmad et al. (2020) [11]		✓	✓	✓											✓										✓				✓		✓	
Alemany et al. (2021) [12]		✓				✓							✓		✓										✓				✓		✓	
Asrol et al. (2020) [9]	✓					✓																		✓						✓		
Chen et al. (2007) [24]		✓	✓						✓	✓				✓													✓					
Darbari et al. (2017) [34]		✓	✓															✓							✓				✓			
Felfel et al. (2016) [22]		✓	✓	✓																					✓				✓			
Georgiadis (2021) [28]	✓		✓																					✓								
Guardiola et al. (2007) [8]	✓					✓																		✓						✓		
Haque et al. (2020) [1]		✓				✓									✓						✓	✓					✓				✓	
Horng & Yenradee (2020) [32]		✓	✓	✓						✓																	✓					
Hossain & Hossain (2018) [25]		✓						✓		✓	✓														✓				✓			
Hugo et al. (2005) [13]		✓	✓												✓									✓							✓	
Jiang et al. (2020) [23]		✓		✓		✓																					✓					
Jung et al. (2008) [2]	✓		✓																					✓								
Lee & Kim (2002) [4]	✓		✓																					✓								
Liang (2006) [36]		✓	✓							✓																		✓	✓			

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Related works	Obj. types		Objective functions																					Methods					Fuzzy parameters	Sustainability		
	Single objective	Multiple objectives	Minimize total costs	Maximize customer services level	Minimize the amount of feet-of-pay	Maximize total profit	Minimize capacity utilization balance	Minimizes production costs	Maximize robustness to various scenarios	Minimize total delivery time	Minimize backordering costs	Minimize the rate of change in labor levels	Minimize unsatisfied demand	Maximize local incentives	Minimize carbon emission	Maximize total value of purchasing	Minimize total consumed energy	Maximize sustainable performance	Maximize total sales	Minimize rejection quality	Maximize total profit at manufacturer	Maximize total profit at wholesaler	Maximize goodwill of CSR	MILP	FMOLP	MOLP	MOMILP	i-FMOLP		Profit allocation	Reduce carbon emission	Organize corporate social responsibility
Liang (2008) [5]		✓	✓							✓															✓				✓			
Mula et al. (2010) [35]	✓		✓																					✓								
Oh & Jeong (2014) [33]		✓				✓									✓												✓					
Ondeck et al. (2019) [27]	✓				✓																			✓								
Peng et al. (2020) [17]																															✓	
Pham & Yenradee (2017) [26]	✓		✓																					✓								
Prasad et al. (2019) [3]	✓		✓																					✓								
Rafiei et al. (2018) [6]		✓	✓	✓																						✓						
Ren et al. (2016) [14]		✓													✓		✓										✓				✓	
Roghanian & Cheraghalipour (2019) [15]		✓	✓	✓											✓											✓					✓	
Samani et al. (2018) [29]		✓	✓										✓														✓					
Shaw et al. (2012) [16]		✓	✓							✓					✓					✓					✓				✓		✓	
Sriklab & Yenradee (2022) [31]		✓																✓								✓					✓	
Tat et al. (2021) [10]	✓	✓				✓																		✓						✓		✓
Torabi & Hassini (2008) [20]		✓	✓													✓									✓				✓			
Tuan & Chiadamrong (2021)[7]		✓	✓	✓								✓				✓									✓				✓			
Wang & Liang (2004) [19]		✓						✓			✓	✓													✓				✓			
Yadlapalli, et al. (2020) [18]																																✓
This work		✓				✓													✓		✓	✓	✓		✓				✓	✓	✓	✓

In terms of multi-objectives, the objectives are often conflicting, and it is not possible to achieve the goal for all objectives simultaneously. In such cases, an interactive fuzzy multi-objective linear programming (i- FMOLP) technique can be used to determine compromised solutions, where targets or goals are set for each objective. If the manager considers that some objectives have more weight than others, the compromised solutions can be determined by maximizing a weighted average of satisfaction. It is important to note that the objective values are converted to a common scale ranging from 0.0 to 1.0, which is referred to as the "satisfaction level," to avoid high-value objectives, such as sales, dominating other objectives with lower values, such as profit. Mula [35] proved the effectiveness of the FMOLP approach to model a production planning problem with uncertainty in demand. Liang [36] aims to simultaneously optimize the total distribution costs and the total delivery time concerning fuzzy available supply and total budget at each source.

Table 1 indicates that prior research has not considered the goal of maximizing sales. What sets this paper apart is that it incorporates this objective by maximizing total profits at each stage. This study utilizes four concepts to address sustainability issues in supply chain mathematical models: multiple objectives, profit allocation and profit ratio, fuzzy demand, and the effect of CSR activities on goodwill and customer demand.

3. Methodology

This section presents the methodological steps of this paper, followed by designing mathematical models, and data of a case study.

The methodology of this paper has 6 steps as presented in Fig. 2. Steps 1-5 are presented in Section 3 and Steps 6-8 are presented in Section 4.

Step 1: Design how to handle important sustainability issues in the APDP-SC problem

This study utilizes four concepts to address sustainability issues in supply chain mathematical models: multiple objectives, profit allocation and profit ratio, fuzzy demand, and the effect of CSR activities on goodwill and customer demand.

The multiple objective concepts deal with the various aspects of sustainability in supply chain management by identifying and compromising solutions among multiple objectives. These objectives include maximizing profits for manufacturers, wholesalers, and the entire supply chain, maximizing sales revenue, minimizing total CO_2 emissions tax, and maximizing goodwill through CSR activities. To determine compromised solutions among these objectives, the study suggests maximizing the weighted average satisfaction of all objectives in all fuzzy scenarios.

The profit allocation and profit ratio concept highlights the importance of fair profit distribution between manufacturers and wholesalers to ensure the sustainability of the entire supply chain. The study suggests transferring profits from one member to another to maintain an acceptable level of profit ratio.

The fuzzy demand concept acknowledges the uncertainty of customer demand and represents it using triangular fuzzy numbers. The level of demand can be adjusted by changing its membership value, or satisfaction level.

Finally, the effect of CSR on the goodwill and demand concept focuses on determining the optimal portfolio of CSR activities. Conducting socially perceived CSR activities can increase the goodwill score, which in turn affects customer demand. If the goodwill score reaches a high level, customer demand will increase, but if it falls below a low level, customer demand will decrease, thereby affecting sales and profits of the supply chain. Mathematical models in Step 2 of the methodology are developed based on these four concepts.

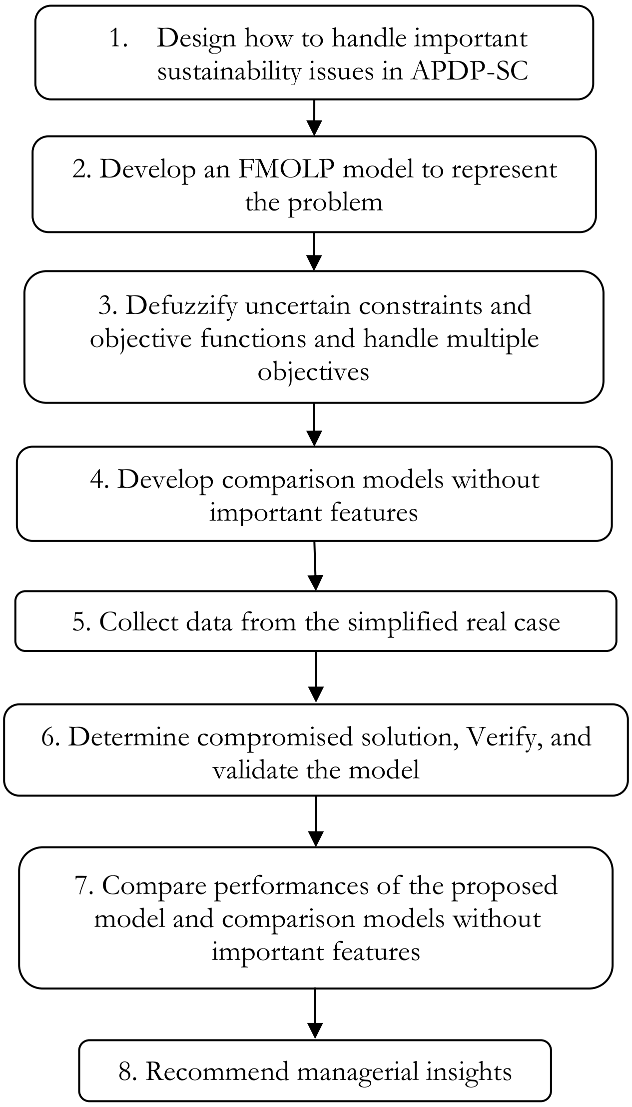

Fig. 2. Methodological steps.

Step 2: Develop an FMOLP model to represent the problem

In step 2 of the methodology, the fuzzy multiple objective linear programming (FMOLP) models are developed.

Mathematical model
Notations

Indices, parameters, and decision variables are defined as follows:

Indices

i	Set of manufacturers $(i = 1, 2, 3, \ldots, I)$
j	Set of wholesalers $(j = 1, 2, 3, \ldots, J)$
k	Set of products $(k = 1, 2, 3, \ldots, K)$
l	Set of corporate social responsibility activities $(l = 1, 2, 3, \ldots, L)$
c	Set of levels of demand $(c = 1, 2, 3, \ldots, C)$
f	Set of fuzzy scenarios *(f = pessimistic (p), most likely (m), optimistic (o))*
v	Set of weights of satisfaction $(v = 1, 2, 3, \ldots, V)$
t	Set of time periods (month) $(t = 1, 2, 3, \ldots, T)$

Parameters

$\widetilde{Dr}_{jkt}$	Fuzzy forecasted customer demand for wholesalers j of product k during time t (unit)
Dr^f_{jkt}	Forecasted customer demand under fuzzy scenario f for wholesalers j of product k during time t (unit)
sd	Satisfaction of customer demand (unitless)
$\widetilde{Cp}_{ik}$	Fuzzy overall manufacturing cost at manufacturer i of product k (Baht/unit)
Cp^f_{ik}	Overall manufacturing cost under fuzzy scenario f at manufacturer i of product k (Baht/unit)
$\widetilde{SPm}_k$	Fuzzy unit selling price from manufacturers to wholesalers of product k (Baht/unit)
SPm^f_k	Unit selling price under fuzzy scenario f from manufacturers to wholesalers of product k (Baht/unit)
$\widetilde{SPr}_k$	Fuzzy unit selling price from wholesalers to end customer of product k (Baht/unit)
SPr^f_k	Unit selling price under fuzzy scenario f from wholesalers to the end customer of product k (Baht/unit)
$\widetilde{TU}_{ik}$	Fuzzy unit processing time at manufacturer i of product k (minutes)
TU^f_{ik}	Unit processing time under fuzzy scenario f at manufacturer i of product k (minutes)
$\widetilde{TA}_i$	Fuzzy total production time available at manufacturer i (minutes)
TA^f_i	Total production time available under fuzzy scenario f at manufacturer i (minutes)
Ar_j	Inspection and receiving cost at wholesalers j per number of trips (Baht/number of trips)
hm_{ik}	Inventory holding cost per unit per period at manufacturer i of product k (Baht/unit/period)
hr_{jk}	Inventory holding cost per unit per period at wholesaler j of product k (Baht /unit/ period)
$Space_k$	Pallet capacity for product k (unit/ pallet)
hm_{imax}	Maximum inventory storage capacity for manufacturer i (pallets)
hr_{jmax}	Maximum inventory storage capacity for wholesaler j (pallets)
SSM_{ik}	Safety stock at manufacturer i of product k (units)
SSW_{jk}	Safety stock at wholesaler j of product k (units)
CSL_{kt}	Customer service level of product k at period t (%)
FTC_{ij}	Transportation cost per trip from manufacturer i to wholesaler j of a 6-wheel truck (Baht)
Dis_{ij}	Distance from manufacturer i to wholesaler j (km)
COF	CO_2 emission coefficient of diesel fuel (kg.CO_2/liter)
$\widetilde{RF}$	Fuzzy fuel consumption of a 6-wheel truck per km (liter/km)
RF^f	Fuel consumption under fuzzy scenario f of a 6-wheel truck per km (liter/km)
Tax	Tax of CO_2 emission (Baht/ kg.CO_2)
$\widetilde{ER}_k$	Fuzzy CO_2 emission coefficient from the raw material of product k per unit of product k (kg.CO_2/unit)
ER^f_k	CO_2 emission coefficient from the raw material of product k per unit under fuzzy scenario f (kg.CO_2/unit)
$\widetilde{EP}_{ik}$	Fuzzy CO_2 emission coefficient from producing product k at manufacturer i (kg.CO_2/unit)
EP^f_{ik}	CO_2 emission coefficient from producing product k at manufacturer i under fuzzy scenario f (kg.CO_2/unit)
Qr	Capacity of 6-wheel truck (pallets)
VSr_{jk}	Variable administration cost per sale at wholesaler j of product k (%)
$FACr_j$	Fixed administration cost of wholesaler j per period (Baht)
$\widetilde{COI}$	Fuzzy budget for CSR activities as a percentage of profit (%)

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COI^f	Budget for CSR activities under fuzzy scenario f as a percentage of profit (%)
$CSRE_l$	Expense of CSR activity l per time (Baht)
$\widetilde{GS}_l$	Fuzzy goodwill score of CSR activity l per time (unitless)
GS_l^f	Score of CSR activity l per time under fuzzy scenario f (unitless)
$MCSR_l$	Minimum number of times to organize CSR activity l per year (unitless)
$LCSR_l$	Maximum number of times to organize CSR activity l per year (unitless)
$\widetilde{ID}$	Fuzzy percentage that the demand is increased depending on the score of goodwill of CSR activities (%)
ID^f	Percentage that the demand is increased depending on the score of goodwill of CSR activities under fuzzy scenario f (%)
$\widetilde{DD}$	Fuzzy percentage that the demand is decreased depending on score of goodwill of CSR activities (%)
DD^f	Percentage that the demand is decreased depending on score of goodwill of CSR activities under fuzzy scenario f (%)
w_v	Weighted of target satisfaction v (unitless)
R	Profit ratio of manufacturer per wholesaler (unitless)
$MSat$	Minimum satisfaction of profit at any member of SC (unitless)
LS	Low level of goodwill score (unitless)
HS	High level of goodwill score (unitless)
M	A big positive number (unitless)

Decision variables

Ym_{ijkt}	Distribution quantity from manufacturer i to wholesaler j of product k in period t (unit)
Yr_{jkt}	Sales quantity from wholesaler j to end customer of product k at time t (unit)
Xm_{ikt}	Production quantity at manufacturer i of product k at time t (unit)
$Invm_{ikt}$	Inventory at manufacturer i of product k at the end of period t (unit)
$Invr_{jkt}$	Inventory at wholesaler j of product k at the end of period t (unit)
Vr_{ijt}	Number of trips of the 6-wheel truck from manufacturer i to wholesaler j in period t (unitless)
CSR_l	Number of times to organize CSR activities l in a planning horizon (unitless)
Bin_c	Binary number to control levels of demand $Bin_c=1$, if level of demand equal to c $Bin_c=0$, otherwise
Δ	Amount of profit transferred from wholesaler to manufacturer (Baht)

Intermediate decision variables

$\widetilde{TSm}$	Fuzzy total sale revenue at manufacturers (Baht)
TSm^f	Total sale revenue at manufacturers under fuzzy scenario f (Baht)
$\widetilde{TCm}$	Fuzzy total cost at manufacturers (Baht)
TCm^f	Total cost at manufacturers under fuzzy scenario f (Baht)
$\widetilde{TPm}$	Fuzzy total profit at manufacturers (Baht)
TPm^f	Total profit at manufacturers under fuzzy scenario f (Baht)
$\widetilde{TSw}$	Fuzzy total sale revenue at wholesalers (Baht)
TSw^f	Total sale revenue at wholesalers under fuzzy scenario f (Baht)
$\widetilde{TCw}$	Fuzzy total cost at wholesalers (Baht)
TCw^f	Total cost at wholesalers under fuzzy scenario f (Baht)
$\widetilde{TPw}$	Fuzzy total profit at wholesalers (Baht)
TPw^f	Total profit at wholesalers under fuzzy scenario f (Baht)
$\widetilde{TS}$	Fuzzy total sale revenue (Baht)
TS^f	Total sale revenue under fuzzy scenario f (Baht)
$\widetilde{TP}$	Fuzzy total profit (Baht)
TP^f	Total profit under fuzzy scenario f (Baht)
$\widetilde{TE}$	Fuzzy total tax from CO_2 emission (Baht)
TE^f	Total tax from CO_2 emission under fuzzy scenario f (Baht)
$\widetilde{GCSR}$	Fuzzy goodwill score from CSR activities (unitless)
$GCSR^f$	Goodwill score of CSR activities under fuzzy scenario f (unitless)
WAS	Weighted average satisfaction (unitless)
TPm_{sat}^f	Satisfaction of manufacturer's profit under fuzzy scenario f (unitless)
TPw_{sat}^f	Satisfaction of wholesaler profit under fuzzy scenario f (unitless)
TP_{sat}^f	Satisfaction of total profit under fuzzy scenario f (unitless)
TS_{sat}^f	Satisfaction of total sales under fuzzy scenario f (unitless)
TE_{sat}^f	Satisfaction of CO_2 emission under fuzzy scenario f (unitless)
$GCSR_{sat}^f$	Satisfaction of goodwill of CSR activities under fuzzy scenario f (unitless)
$\overline{TPm}$	Defuzzied total profit of manufacturers (Baht)
$\overline{TPw}$	Defuzzied total profit of wholesalers (Baht)

Fuzzy multi-objective linear programming (FMOLP) model

Objective functions:

There are six objectives in total, with the first three relating to maximizing profits. These objectives aim to increase the profits of manufacturers, wholesalers, and the entire supply chain while maintaining a balance between them and are tied to the economic issue of supply chain sustainability. Objective four also addresses an economic issue, with a focus on ensuring the total sales revenue of the supply chain is competitive with rival supply chains. The fifth objective is centered around an environmental issue, seeking to minimize the total tax incurred from CO_2 emissions. Lastly, the sixth objective relates to the social issue of sustainability and involves the supply chain organizing CSR activities to promote goodwill and enhance customer demand.

1. Maximize total profit of Manufacturers

The aim of objective function Eq. (1) is to maximize the manufacturers' total profit. This profit is calculated by subtracting the overall manufacturing costs and inventory holding costs from the total revenue earned by the manufacturers. Additionally, the profit transferred from wholesalers to manufacturers (Δ) is also included in the calculation.

$$\widetilde{TPm}=\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Ym_{ijkt}*\widetilde{SPm_k}-\left(\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} Xm_{ikt}*\widetilde{Cp}_{ik}+\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} Invm_{ikt}*hm_{ik}\right)+\Delta \quad (1)$$

2. Maximize total profit of Wholesalers

The wholesalers maximize their total profits as shown in Eq. (2). The total profit function of wholesalers comprises seven components as follows:

Wholesaler's profit = Sales revenue - (Purchasing cost paid to manufacturer + Inspection and receiving cost + Inventory holding cost + Inbound transportation cost + Fixed and variable administration cost) − Amount of profit transferred from wholesalers to manufacturers

$$\widetilde{TPw}=\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Yr_{jkt}*\widetilde{SPr_k}-\Big(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Ym_{ijkt}*\widetilde{SPm_k}+\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} Ar_j*Vr_{ijt}+\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Invr_{jkt}*hr_{jk}+\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} Vr_{ijt}*FTCr_{ij}+\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Yr_{jkt}*VSr_{jk}*\widetilde{SPr_k}+\sum_{j=1}^{J} FACr_j\Big)-\Delta \quad (2)$$

3. Maximize total profit of the entire SC

The overall profit of the supply chain is calculated by adding the profits of the two stages of the chain and subtracting the cost of carrying out CSR activities, which is represented by Eq. (3). It is important to note that the CSR cost is a shared expense of the entire supply chain and not a cost incurred by manufacturers or wholesalers. Therefore, it impacts the profit of the entire supply chain but does not affect the profits of individual manufacturers and wholesalers.
Total Profit of SC = Manufacturers Profit + Wholesalers Profit – CSR expense

$$\widetilde{TP}=\widetilde{TPm}+\widetilde{TPw}-\sum_{l=1}^{L} CSRE_l*CSR_l \quad (3)$$

4. Maximize sales revenue of the entire SC

The total sales revenue in the supply chain is the sum of the sales revenue of both stages of the supply chain as shown in Eq. (4).

$$\widetilde{TS}=\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Ym_{ijkt}*\widetilde{SPm_k}+\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Yr_{jkt}*\widetilde{SPr_k} \quad (4)$$

5. Minimize total tax of CO_2 emission

This study handles the environmental issue of sustainability by CO_2 emissions. The objective function in Eq. (5) is to minimize the total tax calculated from the CO_2 emission of diesel trucks that transport products from manufacturers to wholesalers, CO_2 emission from a production process of raw materials, and CO_2 emission from a production process of manufacturers.

$$\widetilde{TE}=\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} Vr_{ijt}*Dis_{ij}*\widetilde{RF}*COF*Tax+\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} Xm_{ikt}*\widetilde{ER}_k*Tax+\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} Xm_{ikt}*\widetilde{EP_{ik}}*Tax \quad (5)$$

6. Maximize goodwill of CSR activities

Most companies conduct CSR activities to promote social acceptance and goodwill to satisfy the social issue of sustainability. The objective function in Eq. (6) is to maximize goodwill score created by CSR activities.

$$\widetilde{GCSR}=\sum_{l=1}^{L} CSR_l*\widetilde{GS}_l \quad (6)$$

Constraints of the FMOLP model:

$$\sum_{k=1}^{K} \widetilde{TU_{ik}}*Xm_{ikt} \le \widetilde{TA}_i \quad ,\forall i,t \quad (7)$$

$$Invm_{ikt}=Invm_{ik(t-1)}+Xm_{ikt}-\sum_{j=1}^{J} Ym_{ijkt} \quad ,\forall i,k,t \quad (8)$$

$$Invm_{ikt}\ge SSM_{ik} \quad ,\forall i,k,t \quad (9)$$

$$\sum_{k=1}^{K} \frac{Invm_{ikt}}{Space_k} \leq hm_{imax} \quad ,\forall i ,t \quad (10)$$

$$Invr_{jkt} = Invr_{jk(t-1)} + \sum_{i=1}^{I} Ym_{ijkt} - Yr_{jkt} \quad ,\forall j, k ,t \quad (11)$$

$$Invr_{jkt} \geq SSW_{jk} \quad ,\forall j, k ,t \quad (12)$$

$$\sum_{k=1}^{K} \frac{Invr_{jkt}}{Space_k} \leq hr_{jmax} \quad ,\forall j ,t \quad (13)$$

$$Yr_{jkt} \geq CSL_{kt} * [(1-\widetilde{DD}) * Bin_1 * \widetilde{Dr_{jkt}} + (Bin_2 * \widetilde{Dr_{jkt}}) + (1+\widetilde{ID}) * Bin_3 * \widetilde{Dr_{jkt}}] \quad ,\forall j, k ,t \quad (14)$$

$$Yr_{jkt} \leq [(1-\widetilde{DD}) * Bin_1 * \widetilde{Dr_{jkt}} + (Bin_2 * \widetilde{Dr_{jkt}}) + (1+\widetilde{ID}) * Bin_3 * \widetilde{Dr_{jkt}}] \quad ,\forall j, k ,t \quad (15)$$

$$\sum_{l=1}^{L} CSR_l * \widetilde{GS}_l \leq LS + (1-Bin_1) * M \quad (16)$$

$$\sum_{l=1}^{L} CSR_l * \widetilde{GS}_l \geq LS - (1-Bin_2) * M \quad (17)$$

$$\sum_{l=1}^{L} CSR_l * \widetilde{GS}_l \leq HS + (1-Bin_2) * M \quad (18)$$

$$\sum_{l=1}^{L} CSR_l * \widetilde{GS}_l \geq HS - (1-Bin_3) * M \quad (19)$$

$$\sum_{c=1}^{3} Bin_c = 1 \quad (20)$$

$$\sum_{k=1}^{K} \frac{Ym_{ijkt}}{Space_k} \leq Qr * Vr_{ijt} \quad ,\forall i, j ,t \quad (21)$$

$$\sum_{l=1}^{L} CSRE_l * CSR_l \leq \widetilde{TP} * \widetilde{COI} \quad (22)$$

$$CSR_l \geq MCSR_l \quad ,\forall l \quad (23)$$

$$CSR_l \leq LCSR_l \quad ,\forall l \quad (24)$$

$$\overline{TPm} = R * \overline{TPw} \quad (25)$$

$$Xm_{ikt}, Ym_{ijkt}, Invm_{ikt}, Yr_{jkt}, Invr_{jkt} \geq 0 \quad ,\forall i, j, k ,t \quad (26)$$

$$Vr_{ijt}, CSR_l \text{ are integer} \quad ,\forall i, j, l, t \quad (27)$$

$$Bin_c \text{ is binary} \quad ,\forall c \quad (28)$$

$$\Delta \text{ is unrestricted in sign} \quad (29)$$

Constraint (7) is the production time limit at manufacturers. Constraints (8) and (9) maintain inventory balance and safety stock at manufacturers. Constraint (10) ensures that an inventory kept at manufacturers is not beyond the available storage space. Similarly, constraints (11-13) control inventory balance, safety stock, and maximum storage space at wholesalers. Constraint (14) controls sales at wholesalers not to be lower than a required service level while constraint (15) controls sales at wholesalers not to exceed customer demand. The level of customer demand in constraints (14 and 15) is dependent on a variable Bin_1, Bin_2, and Bin_3, which are dependent on CSR activities in constraints (16-20). Constraints (17 and 18) ensure that when the total goodwill score from CSR activities is within a moderate range, the variable, Bin_2 equals 1 and the customer demand is not affected. Constraint (16) ensures that when the total goodwill score is lower than a minimum level (LS), the variable Bin_1 equals 1 and the customer demand is reduced. On the contrary, Constraint (19) ensures that when the total goodwill score is higher than a high level (HS), the variable Bin_3 equals 1 and the customer demand is increased. Constraint (21) is a truck capacity constraint in pallets. Constraint (22) controls CSR expense not to exceed the CSR budget as a percentage of the total profit of the supply chain. Constraints (23 and 24) control the minimum and maximum limits of CSR activities. Constraint (25) maintains a profit ratio of manufacturer per wholesaler. The non-negativity, integer, and binary conditions are specified by constraints (26-28). Constraint (29) allows the amount of profit transferred from wholesaler to manufacturer to be either positive or negative values.

Step 3: Defuzzify uncertain constraints and objective functions, and handle multiple objectives

Defuzzification of fuzzy constraints

There are fuzzy Constraints (7), (14-19), (22), and (25). They must be defuzzied before being solved for optimal solutions. For Constraint (7), the left and right sides of the constraint have fuzzy parameters of $\widetilde{TU_{ik}}$ and $\widetilde{TA_i}$. This paper proposes to defuzzify the constraint with fuzzy parameters on both sides using a ranking method. This method is used by research works [37, 38, 39]. The concept of defuzzification techniques for the analysis of non-interval data was developed by Mogharreban & Dilalla [40]. Constraint (7) is defuzzied using the ranking method as constraints (7´) which compose of three constraints for three fuzzy scenarios (pessimistic, most likely, and optimistic). An advantage of the ranking method is that any one of the three constraints may be a binding constraint that controls the solution, which means that fuzzy parameters can affect the solution.

$$\sum_{k=1}^{K} TU_{ik}^{p} * Xm_{ikt} \leq TA_i^{p} \quad ,\forall i, t \quad (7´)$$

$$\sum_{k=1}^{K} TU_{ik}^{m} * Xm_{ikt} \leq TA_i^{m} \quad ,\forall i, t \quad (7´)$$

$$\sum_{k=1}^{K} TU_{ik}^{o} * Xm_{ikt} \leq TA_i^{o} \quad ,\forall i, t \quad (7´)$$

Only the right-hand side of Constraints (14), (15), and (22) is fuzzy with fuzzy parameters of $\widetilde{ID}$, $\widetilde{DD}$, $\widetilde{TP}$, $\widetilde{COI}$, and $\widetilde{Dr_{jkt}}$. The fuzzy parameters $\widetilde{ID}$, $\widetilde{DD}$, $\widetilde{TP}$, $\widetilde{COI}$, and $\widetilde{Dr_{jkt}}$ are defuzzied into constants using a centroid method. This method is used by some research works [41]. For example, $\widetilde{DD}$ is defuzzied as $\frac{DD^p+2*DD^m+DD^o}{4}$. Note that the ranking method is not used when only one side of the constraint is fuzzy because only the tightest constraint will control the solution, which means that the fuzzy parameter under only one scenario will determine the solution.

The fuzzy forecasted customer demand $\widetilde{Dr_{jkt}}$ is defuzzied using a satisfaction method as $Dr_{jkt}^{m} + \left(Dr_{jkt}^{o} - Dr_{jkt}^{m}\right)(1\text{-}sd)$. The satisfaction method assumes that the customer demand is equal to the most likely value when the satisfaction value is 1.0. However, the customer demand is allowed to be increased from the most likely to optimistic values when the satisfaction value is decreased. Therefore, a sensitivity analysis of variable customer demand can be easily conducted by changing the satisfaction value (sd).

Therefore, Constraints (14), (15), and (22) are defuzzied as Constraints (14´), (15´), and (22´), respectively.

$$Yr_{jkt} \geq CSL_{kt} * [(1-\frac{DD^p+2*DD^m+DD^o}{4})*Bin_1*(Dr_{jkt}{}^m + (Dr_{jkt}{}^o - Dr_{jkt}{}^m)(1-sd)) + Bin_2*(Dr_{jkt}{}^m + (Dr_{jkt}{}^o - Dr_{jkt}{}^m)(1-sd)) + (1+\frac{ID^p+2*ID^m+ID^o}{4})* Bin_3*(Dr_{jkt}{}^m + (Dr_{jkt}{}^o - Dr_{jkt}{}^m)(1-sd))] \quad ,\forall\, j, k, t \qquad (14')$$

$$Yr_{jkt} \leq [(1-\frac{DD^p+2*DD^m+DD^o}{4})*Bin_1*(Dr_{jkt}{}^m + (Dr_{jkt}{}^o - Dr_{jkt}{}^m)(1-sd)) + Bin_2*(Dr_{jkt}{}^m + (Dr_{jkt}{}^o - Dr_{jkt}{}^m)(1-sd)) + (1+\frac{ID^p+2*ID^m+ID^o}{4})* Bin_3*(Dr_{jkt}{}^m + (Dr_{jkt}{}^o - Dr_{jkt}{}^m)(1-sd))] \quad ,\forall\, j, k, t \qquad (15')$$

$$\sum_{l=1}^{L} CSRE_l * CSR_l \leq (\frac{TP^p+(2*TP^m)+TP^o}{4})*(\frac{COI^p+(2*COI^m)+COI^o}{4}) \qquad (22')$$

The condition of the satisfaction level of demand is controlled by Constraint (30).

$$sd \geq 0, \;\; sd \leq 1 \qquad (30)$$

From Constraints (16-19), only the left-hand side is fuzzy with fuzzy parameter $\widetilde{GS}_l$. These constraints are defuzzied using the Centroid method as constraints (16´-19´).

$$\sum_{l=1}^{L} CSR_l * \frac{GS_l^p+2*GS_l^m+GS_l^o}{4} \leq LS + (1-Bin_1)*M \qquad (16')$$

$$\sum_{l=1}^{L} CSR_l * \frac{GS_l^p+2*GS_l^m+GS_l^o}{4} \geq LS - (1-Bin_2)*M \qquad (17')$$

$$\sum_{l=1}^{L} CSR_l * \frac{GS_l^p+2*GS_l^m+GS_l^o}{4} \leq HS + (1-Bin_2)*M \qquad (18')$$

$$\sum_{l=1}^{L} CSR_l * \frac{GS_l^p+2*GS_l^m+GS_l^o}{4} \geq HS - (1-Bin_3)*M \qquad (19')$$

From Constraint (25), both the left and right sides are fuzzy with fuzzy parameters $\widetilde{TPm}$ and $\widetilde{TPw}$. This study applies the centroid method to defuzzify both fuzzy parameters as shown by Constraint (25´). Constraint (25) is an equality constraint; therefore, it cannot be defuzzied using the ranking method as it would result in an infeasible solution.

$$\frac{(TPm^p+2*TPm^m+TPm^o)}{4} = R * \frac{(TPw^p+2*TPw^m+TPw^o)}{4} \qquad (25')$$

How to handle multiple uncertain objectives

The paper applies a method called "weighted average satisfaction" for handling multiple fuzzy objective functions in a multi-objective optimization problem. The method involves converting objective functions with different units of measure and magnitudes to satisfaction levels on a common scale of 0.0 to 1.0 to prevent one objective from dominating others [24, 30]. The method is applied to a problem with six objectives in three fuzzy scenarios, resulting in 18 individual objectives and corresponding weights (w_1-w_{18}). In addition, the satisfaction level of demand (sd) is varied through a sensitivity analysis and its weight (w_{19}) is used to represent its relative importance compared to the other 18 objectives. The objective function based on this method is presented in Eq. (31).

Proposed Model:

Maximize WAS

$$WAS = (w_1 TPm_{sat}^p + w_2 TPm_{sat}^m + w_3 TPm_{sat}^o) + (w_4 TPw_{sat}^p + w_5 TPw_{sat}^m + w_6 TPw_{sat}^o) + (w_7 TP_{sat}^p + w_8 TP_{sat}^m + w_9 TP_{sat}^o) + (w_{10} TS_{sat}^p + w_{11} TS_{sat}^m + w_{12} TS_{sat}^o) + (w_{13} TE_{sat}^p + w_{14} TE_{sat}^m + w_{15} TE_{sat}^o) + (w_{16} GCSR_{sat}^p + w_{17} GCSR_{sat}^m + w_{18} GCSR_{sat}^o) + w_{19} sd \qquad (31)$$

Subject to:

$$TPm_{sat}^f = 1-(TPm_{max}^f - TPm^f)/(TPm_{max}^f - TPm_{min}^f) \quad ,\forall f \qquad (32)$$

$$TPw_{sat}^f = 1-(TPw_{max}^f - TPw^f)/(TPw_{max}^f - TPw_{min}^f) \quad ,\forall f \qquad (33)$$

$$TP_{sat}^f = 1-(TP_{max}^f - TP^f)/(TP_{max}^f - TP_{min}^f) \;,\forall f \qquad (34)$$

$$TS_{sat}^f = 1-(TS_{max}^f - TS^f)/(TS_{max}^f - TS_{min}^f) \;,\forall f \qquad (35)$$

$$TE_{sat}^f = (TE_{max}^f - TE^f)/(TE_{max}^f - TE_{min}^f) \;,\forall f \qquad (36)$$

$$GCSR_{sat}^f = 1-(GCSR_{max}^f - GCSR^f)/(GCSR_{max}^f - GCSR_{min}^f) \quad ,\forall f \qquad (37)$$

$$TPm^f = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Ym_{ijkt} * SPm_k^f - (\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} Xm_{ikt} * Cp_{ik}^f + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} Invm_{ikt} * hm_{ik}) + \Delta \quad ,\forall f \qquad (38)$$

$$TPw^f = \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Yr_{jkt} * SPr_k^f - (\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Ym_{ijkt} * SPm_k^f + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} Ar_j * Vr_{ijt} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Invr_{jkt} * hr_{jk} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} Vr_{ijt} * FTCr_{ij} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Yr_{jkt} * VSr_{jk} * SPr_k^f + \sum_{j=1}^{J} FACr_j) - \Delta \quad ,\forall f \qquad (39)$$

$$TP^f = TPm^f + TPw^f - \sum_{l=1}^{L} CSRE_l * CSR_l \;,\forall f \qquad (40)$$

$$TS^f = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Ym_{ijkt} * \widetilde{SPm}_k + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Yr_{jkt} * \widetilde{SPr}_k \quad ,\forall f \qquad (41)$$

$$TE^f = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} Vr_{ijt} * Dis_{ij} * RF^f * COF * Tax + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} Xm_{ikt} * ER_k^f * Tax + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} Xm_{ikt} * EP_{ik}^f * Tax \;,\forall f \qquad (42)$$

$$GCSR^f = \sum_{l=1}^{L} CSR_l * GS_l^f \quad ,\forall f \qquad (43)$$

and constraints (7´, 8-13, 14´-19´, 20-21, 22´, 23-24, 25´, and 26-30)

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Constraints (32-37) transform objective values in fuzzy scenarios to the satisfaction levels on a common scale from 0.0 to 1.0, while Constraints (38-43) calculate the values of six specific objectives in fuzzy scenarios.

Step 4: Develop comparison models without important features

This step of the methodology provides comparison models to demonstrate that the proposed model is effective to balance profit between manufacturers and wholesalers while it can maintain high total profit of the entire supply chain. There are two comparison models.

Comparison Model 1: Model without profit allocation

This model is modified from the proposed model in that it does not allow profit transfer between manufacturers and wholesalers (Δ). The constraints (38) and (39) are modified to (38´) and (39´) by deleting Δ. Constraints (25´and 29) are not used.

Maximize total profit of manufacturers without profit allocation.

$$TPm^f = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Ym_{ijkt} * SPm_k^f - \left(\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} Xm_{ikt} * Cp_{ik}^f + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} Invm_{ikt} * hm_{ik}\right) \quad ,\forall f \quad (38´)$$

Maximize total profit of wholesalers without profit allocation.

$$TPw^f = \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Yr_{jkt} * SPr_k^f - \Big(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Ym_{ijkt} * SPm_k^f + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} Ar_j * Vr_{ijt} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Invr_{jkt} * hr_{jk} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} Vr_{ijt} * FTCr_{ij} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Yr_{jkt} * VSr_{jk} * SPr_k^f + \sum_{j=1}^{J} FACr_j\Big) \quad ,\forall f \quad (39´)$$

Comparison Model 1:
The objective function in Eq. (31) is used.
Constraints are 7´, 8-13, 14´-19´, 20, 21, 22´, 23- 24, 26-28, 30, 32-37, 38´, 39´, and 40-43.

Comparison Model 2: Model without profit allocation that controls minimum satisfaction of profit at a member of SC

This model is the same as Comparison Model 1 with an additional constraint (44) that sets the minimum satisfaction level of profit at the manufacturers since the optimal result from Comparison Model 1 has a much lower satisfaction of profit at the manufacturers than at the wholesalers.

$$TPm_{sat}^f \geq MSat \quad ,\forall f \quad (44)$$

Comparison Model 2:
The objective function in Eq. (31) is used.
Constraints are 7´, 8-13, 14´-19´, 20, 21, 22´, 23, 24, 26-29, 32-37, 38´, 39´, and 40-44.

Step 5: Collect data from the simplified real case

A simplified real case is used to evaluate the effectiveness of the proposed model. Situations and relations between parameters and variables are adapted and simplified based on a real case. The data are hypothetical. The supply chain under consideration has two stages: manufacturers (MTR), and wholesalers (WS). There are two manufacturers and three wholesalers. All related data are summarized in Tables 2 - 13.

Unit processing time and available production time are presented in Table 2. The unit processing time is TFNs since it is uncertain and cannot be accurately estimated as constants. The available production time is also uncertain and estimated as TFNs. The available production time under an optimistic situation is affected by overtime work and is significantly higher than that under a most likely situation. Beginning inventory, safety stock, pallet capacity, and maximum inventory at manufacturers and wholesalers are presented in Table 3.

The customer service level of both products for 12 periods is set by the management team of the supply chain as presented in Table 4. When the supply chain conducts various CSR activities many times in a year, the goodwill score of the supply chain will be increased. This will affect customer demand. The percentage of increasing or decreasing demand affected by the goodwill score and the budget of CSR as a percentage of profit and fuel consumption per km of 6-wheel diesel trucks are presented in Table 5.

The monthly demands for 12 periods of both products are difficult to forecast accurately as constants. Thus, they are estimated by TFNs under three fuzzy scenarios as shown in Table 6. Table 7 shows three CSR activities with different scores and expenses. The minimum and maximum number of times to conduct CSR activities per year are set by the management team. The score of CSR activities is uncertain and should be estimated by TFNs.

The CO_2 emission coefficient from the raw material used to produce products, and CO_2 emission coefficient from the production process are uncertain and cannot be easily estimated as constants. Thus, they are estimated by TFNs and presented in Table 8. Distances from manufacturers to wholesalers and the associated transportation costs per trip are presented in Table 9. The capacity of a truck, the CO_2 emission coefficient of diesel fuel, and tax of CO_2 emission are presented in Table 10.

The overall manufacturing cost at manufacturers and unit selling prices from manufacturers to wholesalers and from wholesalers to end customers are estimated by TFNs and presented in Table 11. These data are uncertain and cannot be accurately estimated as constants. The inventory holding cost, inspection and receiving cost, variable cost per sale, and fixed cost per period are presented in Table 12.

There are six objectives under three fuzzy scenarios, resulting in 18 elements. These elements may have different weights. The level of fuzzy demand is controlled by weight. The management team of this supply chain determines 19 weights as shown in Table 13.

The maximum and minimum values of fuzzy objectives (for example TPm^f_{max} and TPm^f_{min}) are required as input data to calculate the satisfaction levels of fuzzy objectives (for example TPm^f_{sat}). These maximum and minimum values of the fuzzy objectives are determined based on the opinions and experiences of the management team of the supply chain and are presented in Table 14.

<u>Noted:</u> manufacturers (i) = MTR i, wholesalers (j) =WS j, product (k) = Prod k, Pessimistic = Pessi-, and Optimistic = Opti-.

Table 2. Unit processing time and available production time at manufacturers.

	Unit processing time of product 1 (TU^f_{i1}), (minutes/unit)			**Unit processing time of product 2 (TU^f_{i2}), (minutes/unit)**			**Available production time (TA^f_i), (minutes)**		
	Pessi-	Most likely	Opti-	Pessi-	Most likely	Opti-	Pessi-	Most likely	Opti-
MTR 1	0.41	0.45	0.48	0.265	0.3	0.332	8,400	9,600	12,000
MTR 2	0.487	0.52	0.555	0.342	0.38	0.407	9,000	9,600	11,400

Table 3. Beginning inventory, safety stock, pallet capacity, and maximum inventory at both stages.

	Beginning inventory ($Invm_{ik0}$, $Invr_{jk0}$), (Units)		**Safety stock (SSM_{ik}, SSW_{jk}), (Units)**		**Pallet capacity ($Space_k$), (units/pallet)**	**Maximum inventory (Hm_{imax}, Hr_{jmax}), (pallets)**
	Prod 1	Prod 2	Prod 1	Prod 2	For both products	For both products
MTR 1	500	500	500	500	40	50
MTR 2	550	550	550	550	40	50
WS 1	850	850	850	850	40	80
WS 2	1,000	1,000	1,000	1,000	40	80
WS 3	900	900	900	900	40	85

Table 4. Customer service level.

Period t	**Customer service level Prod 1 (CSL_{1t})**	**Customer service level Prod 2 (CSL_{2t})**
1	0.975	0.95
2	0.975	0.95
3	0.975	0.95
4	0.98	0.98
5	0.98	0.98
6	0.98	0.98
7	0.99	0.975
8	0.99	0.975
9	0.99	0.975
10	0.99	0.98
11	0.99	0.98
12	0.99	0.98

Table 5. Percentage of increasing/decreasing demand, a budget of CSR as a percentage of profit, and fuel consumption.

Scenario	**Percentage that the demand is increased depending on score of CSR activities (ID^f), (%)**	**Percentage that the demand is decreased depending on score of CSR activities (DD^f), (%)**	**Budget for CSR activities as a percentage of profit (COI^f), (%)**	**Fuel consumption per km (RF^f),(liter/km)**
Pessi-	1%	2%	10%	0.171
Most likely	2%	3%	15%	0.1835
Opti-	3%	5%	18%	0.196

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Table 6. Forecasted customer demand.

WS j	Prod k	Period t	Customer demand (Dr^f_{jkt}), (units)			WS j	Prod k	Period t	Customer demand (Dr^f_{jkt}), (units)		
			Pessi-	Most likely	Opti-				Pessi-	Most likely	Opti-
1	1	1	2760	3000	3300	1	1	7	3423	3720	4092
2	1	1	3128	3400	3740	2	1	7	2981	3240	3564
3	1	1	3864	4200	4620	3	1	7	2834	3080	3388
1	2	1	3128	3400	3740	1	2	7	2834	3080	3388
2	2	1	3496	3800	4180	2	2	7	2760	3000	3300
3	2	1	3349	3640	4004	3	2	7	3128	3400	3740
1	1	2	3496	3800	4180	1	1	8	3128	3400	3740
2	1	2	4012	4360	4796	2	1	8	4232	4600	5060
3	1	2	3864	4200	4620	3	1	8	3276	3560	3916
1	2	2	3496	3800	4180	1	2	8	3570	3880	4268
2	2	2	4048	4400	4840	2	2	8	3276	3560	3916
3	2	2	3496	3800	4180	3	2	8	3496	3800	4180
1	1	3	3128	3400	3740	1	1	9	3496	3800	4180
2	1	3	3496	3800	4180	2	1	9	2981	3240	3564
3	1	3	3165	3440	3784	3	1	9	2834	3080	3388
1	2	3	3570	3880	4268	1	2	9	3496	3800	4180
2	2	3	3276	3560	3916	2	2	9	3496	3800	4180
3	2	3	3128	3400	3740	3	2	9	3717	4040	4444
1	1	4	2908	3160	3476	1	1	10	3864	4200	4620
2	1	4	2760	3000	3300	2	1	10	3349	3640	4004
3	1	4	3349	3640	4004	3	1	10	3276	3560	3916
1	2	4	2834	3080	3388	1	2	10	3349	3640	4004
2	2	4	3423	3720	4092	2	2	10	3570	3880	4268
3	2	4	2760	3000	3300	3	2	10	3349	3640	4004
1	1	5	3276	3560	3916	1	1	11	3644	3960	4356
2	1	5	3423	3720	4092	2	1	11	3312	3600	3960
3	1	5	3496	3800	4180	3	1	11	3717	4040	4444
1	2	5	3018	3280	3608	1	2	11	3423	3720	4092
2	2	5	3644	3960	4356	2	2	11	3349	3640	4004
3	2	5	3276	3560	3916	3	2	11	3496	3800	4180
1	1	6	3128	3400	3740	1	1	12	3011	3272	3600
2	1	6	3496	3800	4180	2	1	12	2834	3080	3388
3	1	6	3423	3720	4092	3	1	12	3717	4040	4444
1	2	6	3276	3560	3916	1	2	12	3276	3560	3916
2	2	6	2613	2840	3124	2	2	12	3496	3800	4180
3	2	6	2760	3000	3300	3	2	12	3496	3800	4180

Table. 7 score of CSR activities, minimum/maximum number of CSR activities, and CSR expense.

CSR activities (l)	Score of CSR per time (GS^f_l), (unitless)			Minimum number of CSR ($MCSR_l$), (unitless)	Maximum number of CSR ($LCSR_l$), (unitless)	CSR expense ($CSRE_l$), (Baht)
	Pessi-	Most likely	Opti-			
Tree planting	63	70	77	4	12	220,000
Scholarship giving	54	60	66	3	12	180,000
Garbage picking	36	40	44	5	12	120,000

Table 8. CO_2 emission from raw material and production process.

	Product Type	CO_2 emission coefficient from the raw material of the product (ER_k^f), (kg.CO_2/unit)			CO_2 emission coefficient from producing a product (EP_{ik}^f), (kg.CO_2/unit)		
		Pessi-	Most likely	Opti-	Pessi-	Most likely	Opti-
For both MTR	Prod 1	0.078	0.094	0.11	-	-	-
For both MTR	Prod 2	0.068	0.084	0.1	-	-	-
MTR 1	Prod 1	-	-	-	0.0589	0.062	0.0651
	Prod 2	-	-	-	0.0532	0.056	0.0588
MTR 2	Prod 1	-	-	-	0.0722	0.076	0.0798
	Prod 2	-	-	-	0.0608	0.064	0.0672

Table 9. Distance from manufacturer to wholesaler and transportation cost per trip.

		Distance from manufacturer to wholesaler (Dis_{ij}), (km)	Transportation cost per trip from manufacturer to wholesaler ($FTCr_{ij}$), (Baht)
MTR 1	WS 1	99.7	4,500
	WS 2	100	4,500
	WS 3	48.7	3,500
MTR 2	WS 1	43	3,200
	WS 2	34.6	3,000
	WS 3	84	4,500

Table. 10 Capacity of a truck, CO_2 emission coefficient of diesel fuel, and tax of CO_2 emission.

Parameters	Value
Capacity of truck (Qr), (pallets)	8
CO_2 emission coefficient of diesel fuel per liter (COF), (kg.CO_2/liter)	2.64
Tax of CO_2 emission (Tax), (Baht/ kg.CO_2)	2.49

Table 11. Overall manufacturing cost at manufacturers and selling prices at both stages.

Product		Overall manufacturing cost (Cp_{ik}^f), (Baht/unit)			Unit selling price from manufacturers to wholesalers (SPm_k^f), (Baht/unit)			Unit selling price from wholesalers to the end customer (SPr_k^f), (Baht/unit)		
		Pessi-	Most likely	Opti-	Pessi-	Most likely	Opti-	Pessi-	Most likely	Opti-
MTR 1	Prod 1	421.34	443.52	465.70	-	-	-	-	-	-
	Prod 2	399.07	420.07	441.07	-	-	-	-	-	-
MTR 2	Prod 1	404.47	425.76	447.05	-	-	-	-	-	-
	Prod 2	382.19	402.31	422.43	-	-	-	-	-	-
For both MTR	Prod 1	-	-	-	526.7	554.4	582.1	877.8	924	970.2
For both MTR	Prod 2	-	-	-	505.6	532.2	558.8	842.7	887	931.4

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Table 12. Holding cost, inspection and receiving cost, variable cost per sale, and fixed cost per period.

	Holding cost (hm_{ik}), (Baht/unit)		**Holding cost (hr_{jk}), (Baht/unit)**		**Variable admin cost per sale (VSr_{jk}), (%)**		**Fixed admin cost ($FACr_j$), (Baht)**	**Inspection and receiving cost (Ar_j),(Baht/trip)**
	Prod 1	Prod 2	Prod 1	Prod 2	Prod 1	Prod 2	both products	both products
MTR 1	13.86	13.305	-	-	-	-	-	-
MTR 2	13.86	1.3305	-	-	-	-	-	-
WS 1	-	-	23.10	22.175	6.85%	6.85%	48,500	800
WS 2	-	-	23.10	22.175	6.75%	6.75%	48,000	1,000
WS 3	-	-	23.10	22.175	6.50%	6.50%	47,500	900

Table 13. Weight of fuzzy objectives from the management team.

Objective function	**Scenario**	**Weight (w_v)**
Total Profit at Manufacturers	Pessi-	0.03
	Most likely	0.04
	Opti-	0.03
Total Profit at Wholesalers	Pessi-	0.05
	Most likely	0.06
	Opti-	0.05
Total Profit in SC	Pessi-	0.08
	Most likely	0.085
	Opti-	0.08
Total Sales in SC	Pessi-	0.12
	Most likely	0.12
	Opti-	0.12
Total Tax from CO_2 Emission	Pessi-	0.005
	Most likely	0.005
	Opti-	0.005
Score of Goodwill of CSR activities	Pessi-	0.025
	Most likely	0.03
	Opti-	0.025
Satisfaction of demand		0.04

Table 14. Maximum and minimum values of fuzzy objectives for calculation of the satisfaction levels.

Values	TPm^p	TPm^m	TPm^o	TPw^p	TPw^m	TPw^o
Max	39,000,000	41,040,000	43,180,000	79,120,000	83,570,000	88,020,000
Min	31,450,000	33,130,000	34,870,000	60,880,000	64,800,000	68,730,000

Values	TP^p	TP^m	TP^o	TS^p	TS^m	TS^o
Max	111,500,000	117,900,000	124,000,000	408,780,000	430,295,000	451,810,000
Min	87,590,000	93,290,000	98,990,000	342,870,000	360,914,000	378,960,000

Values	TE^p	TE^m	TE^o	$GCSR^p$	$GCSR^m$	$GCSR^o$
Max	297,000	325,800	354,450	1,850	2,050	2,250
Min	121,300	135,980	150,650	600	660	730

4. Results and Discussion

Steps 6-8 of the proposed methodology are presented in this section. All models were solved using the optimization software, CPLEX Studio IDE 20.1.0 on an AMD RYZEN 7 processor with 16.00 GB RAM and a 3.40 GHz CPU. The required computational times of the proposed model, Comparison Model 1, and Comparison Model 2 are on average 8.3, 7.01, and 7.25 seconds, respectively, which are very short and not much different.

Step 6: Determine compromised solutions, verify, and validate

4.1. Determine Compromised Solutions

To determine the compromised solution from the proposed model, the satisfaction of demand (*sd*) and the profit ratio of manufacturer per wholesaler (*R*) must be suitably determined. These two parameters affect the overall performance of the supply chain system; thus, they should be determined carefully using a sensitivity analysis method.

From constraints (14') and (15'), the customer demand is allowed to be increased from the most likely value to the optimistic value when the satisfaction of demand is decreased. A sensitivity analysis is conducted by varying the satisfaction of demand (*sd*) from 0.1 to 1.0 and solving the proposed model. The relationship between the satisfaction of demand and the optimal value of the objective function (31), which is the weighted average satisfaction, is shown graphically in Fig. 3. From Fig.3 when the satisfaction of demand is reduced, the weighted average satisfaction is increased linearly, and the highest weighted average satisfaction (0.821) has occurred when the satisfaction of demand is 0.0 or when the demand is equal to the optimistic demand. This indicates that although the satisfaction of demand is reduced, the satisfaction of other objectives increased significantly. Based on this sensitivity analysis result the satisfaction of demand (*sd*) should be fixed at 0.0 for all analyses that will follow.

From constraint (25´), the profit ratio of manufacturer per wholesaler (*R*) is varied from 0.48 to 0.50 with a step of 0.0025, and the fuzzy profits of manufacturer and wholesaler are determined by solving for the compromised solution of the proposed model. A graph between the profit ratio and the satisfactions of fuzzy profits of manufacturer and wholesaler is presented in Fig. 4. It clearly shows that when the profit ratio is 0.4925, the satisfactions of fuzzy profits of manufacturer and wholesalers are approximately equal, which ranges from 0.85 to 0.88. When the satisfactions of profits of manufacturer and wholesalers are not much different, both members of the supply chain will feel that the profits are fairly allocated, which satisfies an aspect of the sustainable supply chain.

From the results of the sensitivity analyses, the satisfaction of demand (*sd*) and the profit ratio of manufacturer per wholesaler (*R*) are set at 0.0 and 0.4925, respectively, and the proposed model is solved for the compromised solution. The satisfaction of the fuzzy objectives of the compromised solution is summarized in Table 15.

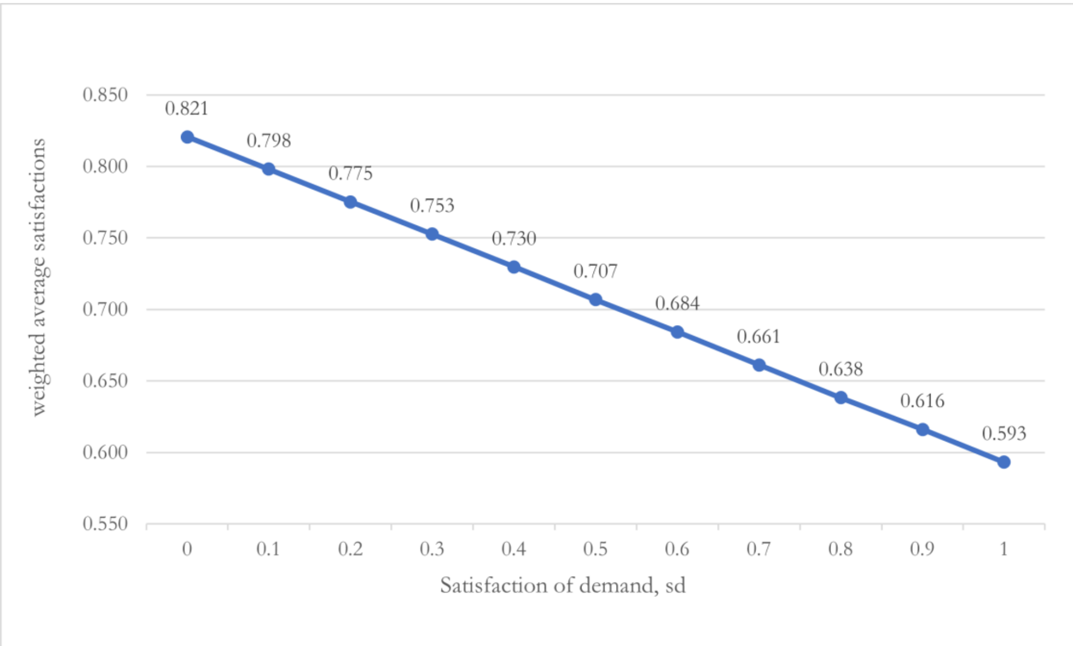

Fig. 3. Sensitivity analysis of satisfaction of demand.

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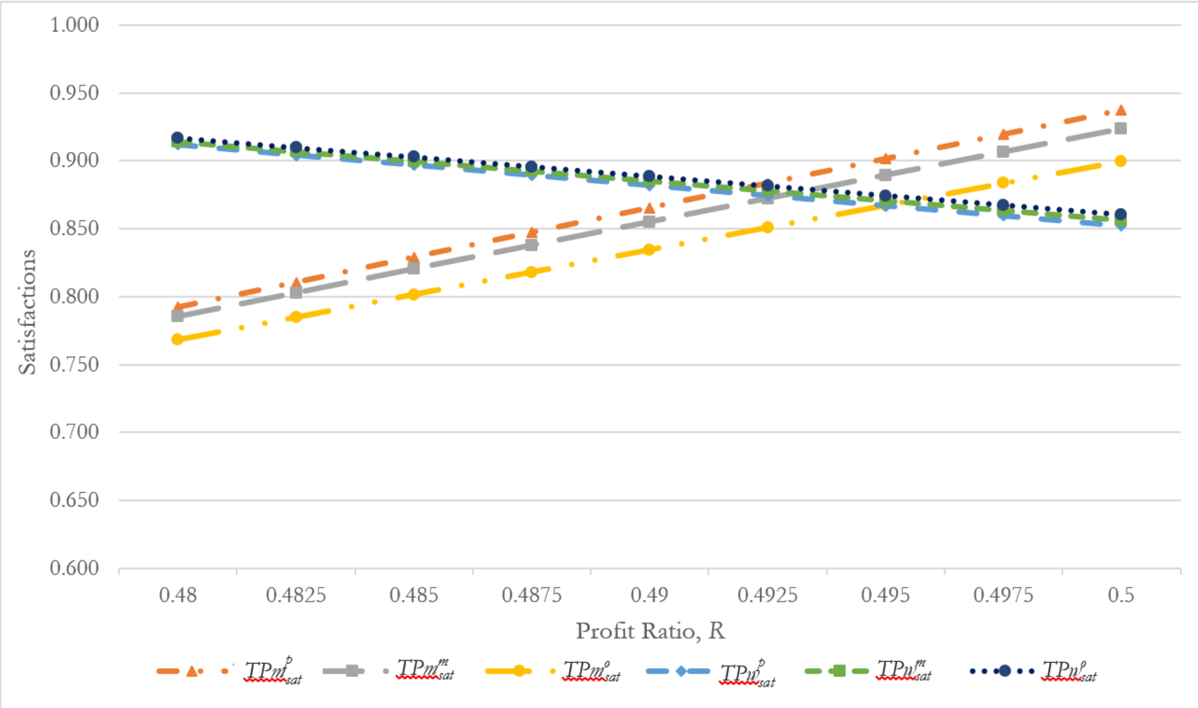

Fig. 4. Sensitivity analysis of profit ratio of manufacturer per wholesaler.

4.2. Validation of Results and Characteristics of the Compromised Solution from the Proposed Model

From Table 15, the weighted average satisfaction of 19 elements of the fuzzy objectives is very high at 0.8761. These results confirm that the proposed model can determine the compromised solution with very good performance. The satisfaction of profits of manufacturer and wholesaler is very high and almost the same, which indicates that the profits are fairly allocated between the manufacturer and wholesaler, resulting in equally high satisfaction of total profit of the entire supply chain. This result is achieved because the proposed model suggests transferring the profit of 2,081,013 Baht from wholesaler to manufacturer (Δ) to balance the satisfaction of profit of both supply chain members. The satisfaction of the total sales of the supply chain is very high since the fuzzy demand is set at the optimistic scenario (satisfaction of demand, sd = 0.0). The satisfactions of the CO_2 emission are still high (greater than 0.8) but they are the lowest in comparison to other satisfactions. Satisfaction with CSR activities is also very high since the compromised solution suggests performing all CSR activities at maximum levels.

To verify that the optimal decisions suggested from the proposed model are reasonable, the detailed decisions of manufacturers and wholesalers are plotted in Figs. 5 and 6 that these values of both figures are total the values of all members in SC. From Fig. 5, the total production quantities are slightly different from or the same as the distribution quantity from the manufacturer to the wholesaler in each period to keep the inventory at the manufacturer as low as possible, which is nearly equal to the safety stock level. Figure 6 shows that the received quantity from the manufacturer to the wholesaler, the total capacity of all trucks arrived at the wholesaler, sales quantity, and customer demand at the wholesalers are almost equal and can be seen as the same line (upper one on the graph). These decisions are reasonable since the sales quantity does not exceed the demand. Additionally, the received quantity and the sales quantity are approximately the same to maintain the inventory level at the wholesaler to be equal to the safety stock level (the lower line on the graph). Moreover, the total received quantity at wholesalers are approximately the same as the total capacity of all trucks that arrived at the wholesalers, which means that the proposed model suggests using a suitable number of trucks to transport goods from the manufacturer to the wholesalers.

The proposed model also suggests the optimal decisions related to the CSR activities as shown in Table 16. It indicates that the supply chain should conduct the CSR activities at the maximum levels, which is 12 times per year or monthly. At this level of CSR activities, the satisfaction of CSR is very high (see Table 16), which contributes to the weighted average value of 19 elements of the fuzzy objectives. Additionally, the defuzzied goodwill score is high enough (>1,500) to allow the demand to be increased since customers can perceive that the supply chain contributes to social development.

Table 15. Satisfaction of fuzzy objectives from the proposed and comparison models.

Elements of fuzzy objectives		Proposed model		Comparison Model 1		Comparison Model 2	
		Satisfaction	Value (Baht)	Satisfaction	Value (Baht)	Satisfaction	Value (Baht)
Manufacturer Profit	pessimistic	0.883	38,119,614.28	0.608	36,038,960.29	0.667	36,485,993.31
	most likely	0.872	40,030,360.05	0.609	37,949,813.04	0.669	38,420,296.66
	optimistic	0.851	41,941,105.83	0.601	39,860,665.79	0.660	40,354,600.00
Wholesaler Profit	pessimistic	0.874	76,826,830.18	0.988	78,908,444.51	0.865	76,659,776.75
	most likely	0.878	81,279,918.89	0.989	83,361,533.22	0.863	81,002,188.17
	optimistic	0.881	85,733,007.60	0.989	87,814,621.92	0.861	85,344,599.58
Supply chain Profit	pessimistic	0.883	108,706,444.46	0.883	108,707,404.80	0.808	106,905,770.07
	most likely	0.885	115,070,278.94	0.885	115,071,346.26	0.808	113,182,484.82
	optimistic	0.897	121,434,113.43	0.897	121,435,287.71	0.818	119,459,199.58
Total Sales	pessimistic	0.966	406,515,090.52	0.966	406,515,090.52	0.998	408,617,959.08
	most likely	0.966	427,910,621.60	0.966	427,910,621.60	0.998	430,124,167.45
	optimistic	0.966	449,306,152.68	0.966	449,306,152.68	0.998	451,630,375.82
Total Tax from CO_2 Emission	pessimistic	0.817	153,452.93	0.816	153,646.93	0.806	155,463.43
	most likely	0.813	171,533.07	0.812	171,741.20	0.801	173,793.87
	optimistic	0.809	189,613.22	0.808	189,835.46	0.796	192,124.32
Goodwill of CSR	pessimistic	0.989	1,836.00	0.989	1,836.00	0.989	1,836.00
	most likely	0.993	2,040.00	0.993	2,040.00	0.993	2,040.00
	optimistic	0.996	2,244.00	0.996	2,244.00	0.996	2,244.00
Satisfaction of demand	*sd*	0	-	0	-	0	-
Profit Allocation	Δ	-	2,081,012.94	-	-	-	-
Weighted Average Satisfaction (*WAS*)		-	0.8761	-	0.8676	-	0.8325

Fig. 5. Optimal decisions of manufacturers.

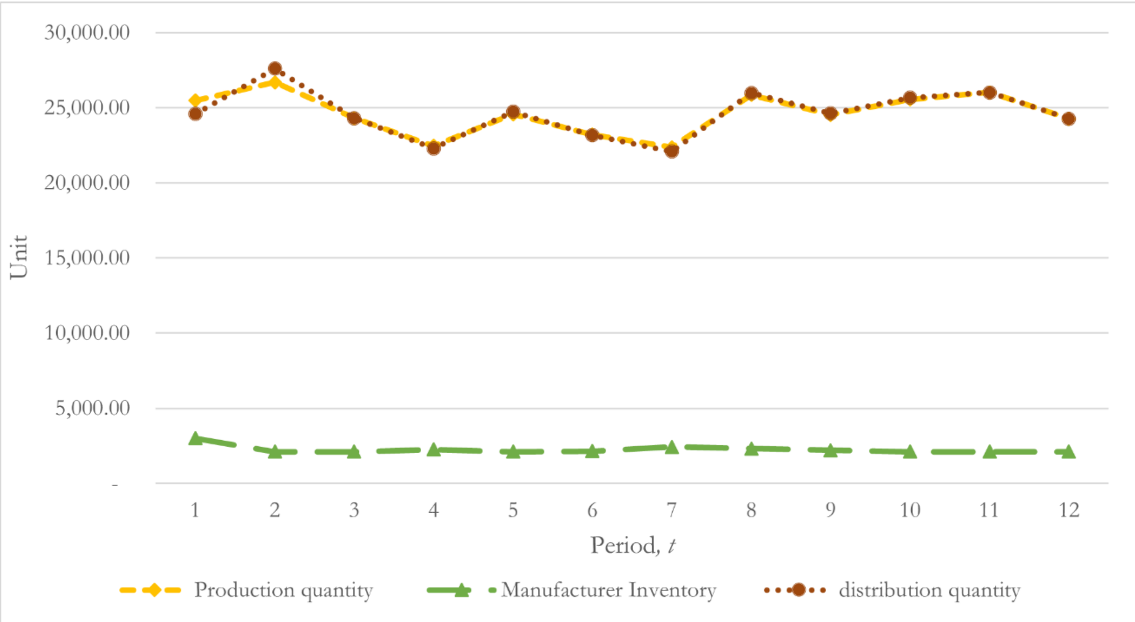

Fig. 6. Optimal decisions of wholesalers.

Table 16. The number of times to do CSR, goodwill score, and effect on demand.

Output	Values
Tree planting (CSR_1), (# times)	12
Scholarship giving (CSR_2), (# times)	12
Garbage picking (CSR_3), (# times)	12
Total CSR expense (Baht)	6.24 million
Pessimistic goodwill CSR ($GCSR^p$), (unitless)	1,836
Most likely goodwill CSR ($GCSR^m$), (unitless)	2,040
Optimistic goodwill of CSR ($GCSR^o$), (unitless)	2,244
Defuzzified goodwill of CSR (unitless)	2,040
Value of goodwill that increased demand (*HS*)	> 1,500
Binary number to control levels of demand (Bin_c)	Bin_3=1

Step 7: Compare performances of the proposed model and comparison models without important features

To demonstrate that the proposed model is effective to determine the compromised solution among fuzzy multiple objectives with good performances, the solutions from the proposed models and comparison models are compared in Table 15. The weighted average satisfaction of 19 elements of fuzzy objectives from Comparison Model 1 is 0.8676, which is lower than that of the proposed model (0.8761). From Comparison Model 1, the satisfactions of the total profit of manufacturers are significantly lower than that of wholesalers, which indicates that the satisfactions of total profits are not well balanced between the manufacturers and the wholesalers, because Comparison Model 1 does not allow the profit transfer between the manufacturers and the wholesalers.

Comparison Model 2 aims to balance the satisfaction of total profit of manufacturers and wholesalers without the profit transfer between members of the supply chain. It uses additional constraints to control the minimum satisfaction of the total profit of manufacturers. A sensitivity analysis is conducted to determine the relationship between the satisfaction of total profit of manufacturers and wholesalers versus the minimum satisfaction (*MSat*). *MSat* is varied from 0.60 to 0.67 with a step of 0.01. Note that when *MSat* is set at 0.67, Comparison Model 2 has no feasible solution. Figure 7 shows that when *MSat* is increased, the satisfaction of total profit of manufacturers increases while that of wholesalers decreases. When *MSat* is set at 0.66 the satisfactions of the total profits of the manufacturers and wholesalers are the closest. However, the satisfactions of the total profit of manufacturers are still significantly lower than that of the wholesalers. This indicates that the model without the profit transfer cannot achieve a balance of satisfaction of total profits of supply chain members. The compromised solution from Comparison Model 2 when *MSat* is set at 0.66 is presented in Table 15. Table 15 clearly shows that the satisfaction of total profit of the entire supply chain of Comparison Model 2 is reduced significantly when compared with that of the proposed model and Comparison Model 1. Comparison Model 2 has higher satisfaction of sales but lower satisfaction of CO_2 emissions than the proposed model and Comparison Model 1 because Comparison Model 2 suggests producing and selling more, which results in higher sales and CO_2 emissions.

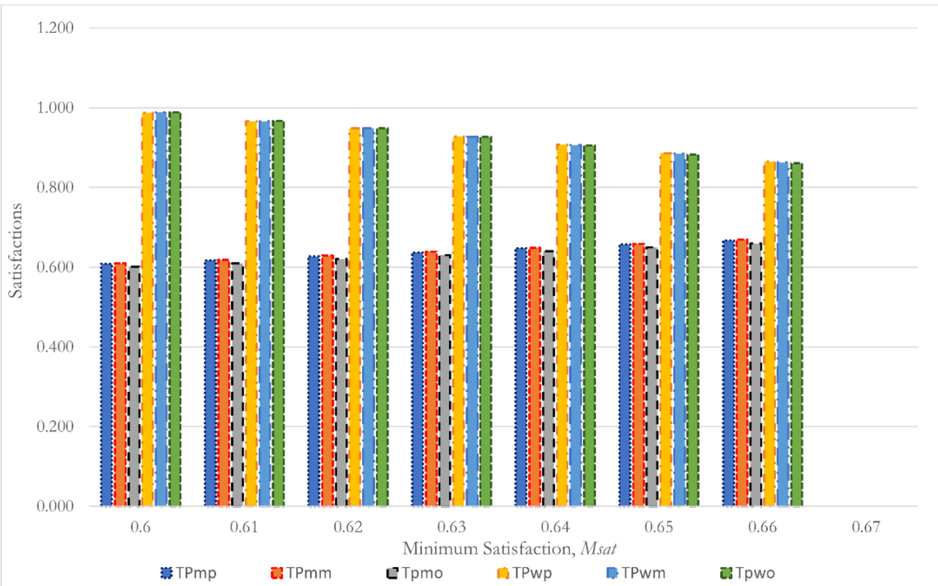

Fig. 7. Satisfactions of total profit from Comparison Model 2.

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4.3. Analysis of the Effect of CSR Activities

The solution of the proposed methods suggested that CSR must be organized because the level of CSR may affect a little bit of increase or decrease in the percentage of customer demand, but this has a huge effect on the solution.

From Table 15, all models have the same satisfaction with CSR activities since all models suggest conducting CSR activities to the maximum allowable level. This means that the supply chain should spend money on CSR activities although the satisfaction of the total profit of the supply chain will be reduced but gain the satisfaction of goodwill of CSR activities.

To demonstrate that the mechanism of CSR activities that can affect demand in the proposed model is very important to enhance the performances of the supply chain, an additional analysis is performed by varying the values of decision variables Bin_1, Bin_2, and Bin_3. First, when Bin_1, Bin_2, and Bin_3 equal 1, 0, and 0, the total goodwill score from CSR activities is lower than the minimum level (*LS*), and the demand is reduced. Second, when they equal 0, 1, 0 the total goodwill score is between the minimum level (*LS*) and the maximum level (*HS*), and the demand does not change. Third, when they equal 0, 0, 1 the total goodwill score is higher than the maximum level (*HS*), and the demand is increased. Based on these three cases, the proposed model is solved and the satisfactions of 18 elements of fuzzy objectives are presented in Fig. 8.

It reveals that when CSR activities are conducted at different levels and the demand is changed, all satisfaction is affected. The case of high CSR activities results in higher satisfaction of all objectives except the satisfaction of CO_2 emission which is slightly lower. This result is reasonable since high CSR activities increase demand, which contributes to higher sales and profit. However, higher production results in higher CO_2 emissions from the production of raw materials and products and from the transportation of goods from the manufacturers to the wholesalers.

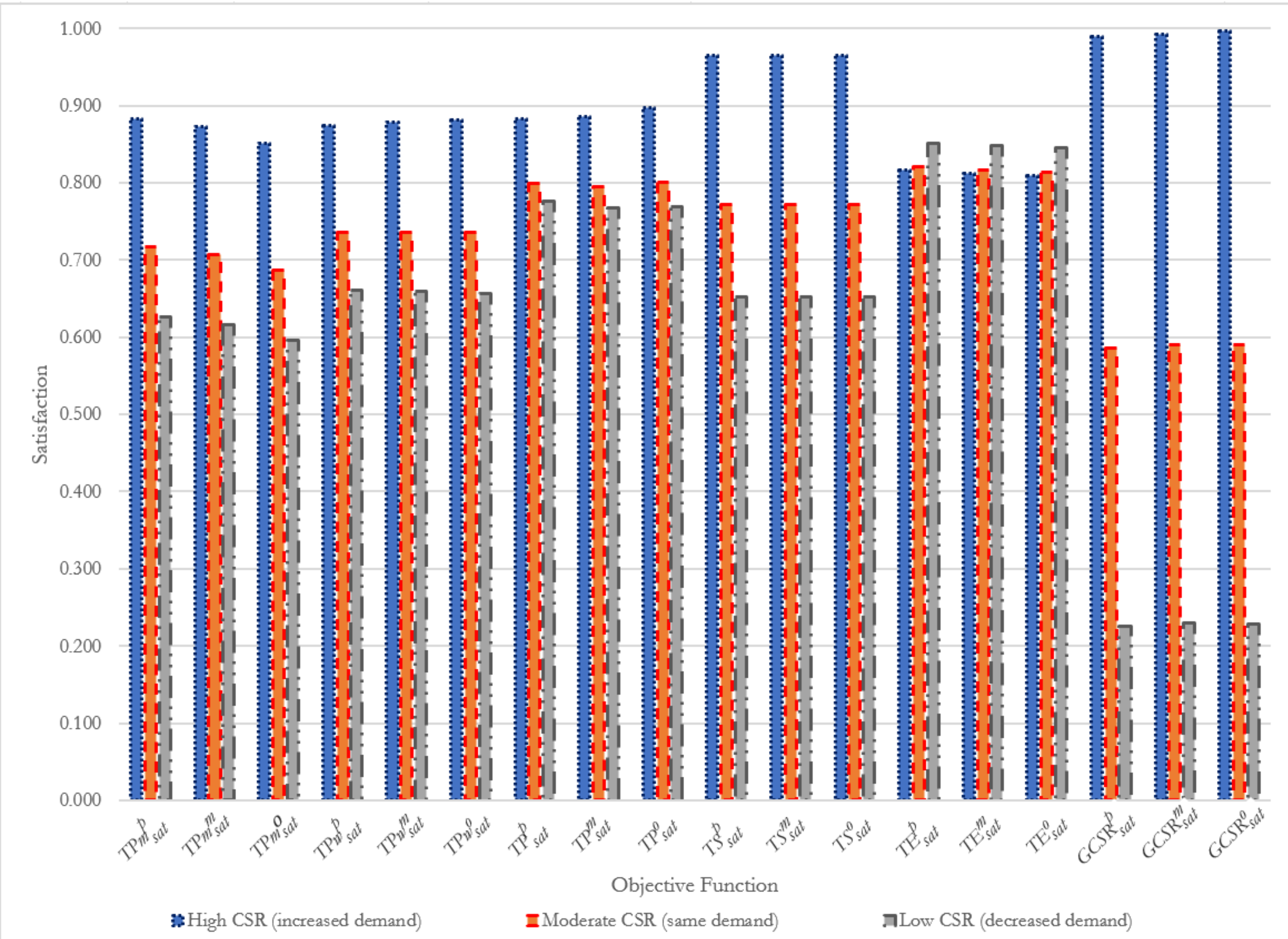

Fig. 8. Effect of CSR activities on performances of the supply chain.

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Step 8: Recommend managerial insights.

Based on the results in this section, some managerial insights can be summarized.

1. Balancing the satisfaction of profit between supply chain members is an important sustainability issue. This issue can be handled in practice when the proposed model with profit transfer between supply chain members is used. When the model without profit transfer is used, the satisfaction of profit of supply chain members may be greatly different (Comparison Model 1). When the constraint that specifies a minimum satisfaction level of profit of a supply chain member is added, the satisfactions of profit of supply chain members are more balanced but not perfectly balanced, however, the satisfaction of the total profit of the entire supply chain is reduced (Comparison Model 2). Therefore, the proposed model offers a win-win situation for supply chain members in that they get approximately the same satisfaction of profit and get a high satisfaction of total profit of the entire supply chain.
2. The proposed model considers a decision to conduct CSR activities because it can improve the goodwill of the supply chain, which results in increasing customer demand, sales, and profit in the supply chain. Table 16 shows that the proposed model suggests conducting CSR activities with a total expense of 6.24 million Baht, which is about 5-6 % of the total profit of the entire supply chain. At this level, the demand is increased by only 1, 2, and 3 % under pessimistic, most likely, and optimistic situations. Although the percentage of increasing demand in this study is quite low, the proposed model still suggests conducting CSR activities to the maximum level because it is worth improving 18 elements of satisfaction of the supply chain. There are pieces of evidence that big corporations in Thailand (e.g., PTT, SCG, CP, and Singha) conduct CSR activities with higher total expenses each year and report their details on the corporation website to promotes the goodwill of the corporation because conducting CSR activities is worth for their expenses.
3. The proposed model has fuzzy multiple objectives which are easily applicable in practice. Supply chain managers may add more objectives to handle other aspects of sustainability. On the contrary, they may exclude some objectives of the proposed model if they are not relevant to their case. When some objectives need parameters that are difficult to be estimated accurately as constants, the parameters should be estimated as TFNs under three fuzzy scenarios. The proposed model that maximizes the weighted average satisfaction of all elements of fuzzy objectives will be able to determine the compromised solution among conflicting fuzzy objectives.

5. Conclusions

This study proposes a new sustainable approach for aggregate production and distribution planning in a supply chain (APDP-SC) that maximizes profit of the entire supply chain, balances profits between supply chain members, maximizes sales of the supply chain, minimizes CO_2 emissions, and organizes CSR activities to manage goodwill of the supply chain and customer demands. The fuzzy multiple objectives mixed integer linear programming model is developed to represent the problem. Then, the fuzzy multiple objectives are transformed into a single crisp objective that maximizes the weighted average satisfaction of all elements of fuzzy objectives. The fuzzy constraints are transformed into crisp constraints using the ranking method and the de-fuzzified value method. A simplified real case is used to demonstrate the effectiveness of the proposed model for determining the compromised solution. The compromised solution is analyzed to verify and validate the proposed model. The compromised solutions from the proposed model and comparison models are compared to show that the proposed model with important features is more effective than the comparison models without important features. The compromised solution from the proposed model suggests transferring the profit from wholesalers to manufacturers. After the transfer, the satisfactions of the profit of manufacturers and wholesalers are almost equal, and the satisfaction of the total profit of the entire supply chain is very high. The satisfaction of CO_2 emissions exceeds 0.8 which is also high. The satisfaction of CSR activities is the highest among all satisfactions since the proposed model suggests conducting CSR activities to the maximum limit. The weighted average satisfaction of the proposed model is 0.8761, which is the highest compared with other comparable models. Some managerial insights are summarized from the results.

5.1. Contributions

This study has significant theoretical and practical contributions. The theoretical contributions include:

1. The proposed model is the first one that considers three sustainability issues for the APDP-SC problem. The economic issue is handled by maximizing profit of the entire supply chain, balancing profits between supply chain members, and maximizing total sales of the supply chain. The environmental issue is addressed by minimizing the carbon tax from CO_2 emissions from the production of raw materials, the production process, and the transportation of goods in the supply chain. The social issue is handled by maximizing the goodwill score from conducting

various CSR activities that contribute to the betterment of society.
2. The proposed model is effective to determine the compromised solution with high satisfaction of all fuzzy objectives using the weighted average satisfaction method. The model allows other aspects of sustainability to be included in the future.
3. The profit transfer feature of the proposed model is effective to balance the satisfaction of profit of supply chain members and the satisfaction of total profit of the entire supply chain is also high.
4. The mechanism to deal with CSR activities allows the proposed model to plan for CSR activities simultaneously with production and distribution planning. Normally these two problems are independently decided. This paper is the first attempt to integrate the decision on conducting CSR activities into the APDP-SC decisions.

The practical contributions include:
1. The methodological steps in Fig. 2 are useful for supply chain planners to follow for developing a workable model for a sustainable APDP-SC problem.
2. From the results, CSR activities should be optimally planned simultaneously with the production and distribution plan. The solution will be better since CSR activities can change customer demand.
3. The fuzzy model and parameters are more practical since some parameters cannot be estimated easily as constants in practice. Fuzzy profits, sales, and tax on CO_2 emissions warn the supply chain planners that the performances of the system are uncertain, and they should recognize the uncertain values.

5.2. Limitations and Further Studies

The environmental issue for sustainability in this study considers CO_2 emissions from the manufacturing process of purchased raw materials, the manufacturing process of manufacturers, and the transportation of goods between supply chain members. The scope of environmental issues can be extended to other aspects, e.g., the use of recycled materials, reuse of resources, waste management, and use of renewable energies. The proposed model can be adjusted to handle these new aspects easily by adding more objectives of environmental issues. To improve the environmental issue, the economic issue, and social issues may be affected. A model that can handle all issues simultaneously is recommended.

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Kanchanitch Nupet is a M.Eng. student in Logistics and Supply Chain Systems Engineering Program (LSCSE), School of Manufacturing Systems and Mechanical Engineering, Sirindhorn International Institute of Technology (SIIT), Thammasat University. He holds a B.S. degree in Integrated Program in Management Mathematics (IMMA), Faculty of Science and Technology, Thammasat University, Thailand. In 2020, he got an SIIT Quota scholarship from Assoc. Pof. Pisal Yenradee for M.Eng. in Sirindhorn International Institute of Technology (SIIT), Thammasat University.

Pisal Yenradee is an Associate Professor in the Industrial Engineering program at Sirindhorn International Institute of Technology (SIIT), Thammasat University. He holds a B.Eng. in Production Engineering from King Mongkut's Institute of Technology and an M.Eng. and D.Eng. in Industrial Engineering and Management from the Asian Institute of Technology. His research interests focus on production planning and inventory control systems, JIT, ERP, TOC, finite capacity scheduling systems, aggregate production planning, master production scheduling, supply chains, and applied operations research. He has published papers and served as a reviewer for many international journals.