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Capacity Allocation and Demand Management of a New Sustainable Product: A Two-Stage Stochastic Programming Model under Carbon Emission Regulations

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A R T I C L E I N F O

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A B S T R A C T

This paper reviews a two-stage stochastic programming model for integrating the decision problems of "determining capacity levels" and "determining environmental policy plans for assembly centers and consumers" for new sustainable products by considering economic and environmental factors. For this model, in the first stage, the capacity level of the new product is determined by the assembly company. Then, the amount of consumer demand is observed, which affects the decision-making of the first stage. In the second stage, the revision decision is made in line with the random scenarios that affect the decisions of the first stage. The main goal is to maximize the benefits of environmental policy programs for assembly centers and consumers by considering consumer demand under carbon policy. This paper provides a model that considers the permissible threshold limit for carbon emissions (carbon emission policy) to achieve this goal. A numerical example of the demand for reusable cars is presented. The results of this paper provide valuable insights for policymakers and assembly centers in implementing environmental policies.

1. Introduction

In recent years, sustainable development has become a highly debated topic. Several companies and business organizations across various industries have adopted measures, guidelines, and programs to address sustainability concerns, particularly those related to environmental sustainability, such as carbon policies, new sustainable products, and government policies. These actions typically enhance the economic, environmental, and social performance of companies and business organizations, generally bringing them closer to the threefold sustainability goals (Khan et al., 2022). Companies developing a product line with a green

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proposal must carefully consider important factors, such as pricing strategies, market coverage, market dynamics, and consumer demand (Yenipazarli & Vakharia, 2015). For environmentally friendly products, companies can balance economic and environmental sustainability according to consumer attitudes and behaviors (Alamsyah et al., 2021). By using sustainable technologies to produce green products, companies can not only significantly improve their performance but also maintain sustainable competition in the market (Qiu et al., 2020). On the other hand, individuals with greater knowledge and awareness of environmental issues are more concerned about the environment and exhibit better behaviors when purchasing sustainable products (Rusyani et al., 2021). However, the level of customer demand for a new sustainable product remains an unknown factor for assembly companies. To mitigate this factor, this paper examines assembly capacity levels and the selection of environmental policy programs for assembly centers and consumers of new sustainable products. There are two types of decision-making in this paper. The first decision relates to the allocation of assembly capacity, while the second concerns the selection of environmental policy schemes for assembly centers and consumers of sustainable products. Initially, decisions regarding the allocation of assembly capacity levels for a new sustainable product are made. Over time, based on the level of customer demand for this product, decisions are made regarding the selection of environmental policy schemes for assembly centers and consumers. The aim of this paper is to investigate a model under carbon emission policies considering various scenarios related to customer demand that can yield favorable outcomes for environmental and economic issues. Consequently, it contributes to improving the quality of human life by aiding in environmental preservation.

Khajuria et al. (2022) refer to the role of the circular economy in achieving sustainable development goals and supporting government policies. Ojha et al. (2020) emphasize the effectiveness of carbon tax policies in achieving the goal of inclusive green growth, while ’Mahony (2020) highlights support for carbon taxes as an economic step to reduce greenhouse gas emissions and the challenges related to their performance. Zhang et al. (2020) recommends incentive-based policies for economic and environmental development through carbon taxes and subsidies. Several studies have forecasted product demand considering consumer sentiment by combining macroeconomic indicators and online surveys. Overall, these approaches provide valuable insights for shaping marketing strategies and creating sustainable products aligned with consumer demand. Hafezi and Zolfagharinia (2018), Cohen et al. (2016), and Yu et al. (2016) emphasize the effectiveness of government policies, subsidies, and regulations on the market. Singh et al. (2013) highlight a two-stage stochastic programming model for designing supply chain networks under uncertainty, focusing on variables for facility locations and product quantities, while Ji et al. (2020) concentrate on cost risk control and uncertainty management to reduce carbon emissions and sustainable energy planning using a stochastic optimization model. Caramia et al. (2023) propose a two-stage model for optimizing waste management to achieve the goal of minimizing greenhouse gas emissions, ensuring facility capacity, and optimizing waste collection routes for efficient vehicle tours.

A significant portion of the literature focuses on sustainable products and environmental policy choices, which play a crucial role in consumer demand, market dynamics, and government policies supporting sustainable product manufacturers. Additionally, the impact of carbon policies on addressing environmental challenges has been highlighted. However, despite the high interest in new sustainable products, no study has focused on bridging the gap between capacity allocation and customer demand uncertainty using a two-stage stochastic programming model and decarbonization policies to improve strategic decision-making processes for new sustainable products and capacity planning.

2. Problem Description and Mathematical Model

This section presents a two-stage stochastic programming model for modeling the uncertainty of assemblers in allocating capacity to a new sustainable product, which arises from the uncertainty related to customer demand for a new sustainable product. The first-stage decisions in this study relate to the allocation of capacity that the assembler assigns to each assembly center. The second-stage decisions concern the environmental policy programs for consumers at each assembly center. This paper considers customer demand for the sustainable product as a random factor.

2.1. Problem Statement

An assembly company is assumed to have n centers. The set of assembly centers is denoted by P, indexed by i where $n=|P|$. The set of available capacity levels for assembly center i is denoted by D_i , indexed by j, where $|D_i|=m_i$. In the first stage, each center must decide on its capacity levels, represented by the binary variable x_{ij}. Then, the new product is sold. The acceptance of this new product leads to various scenarios for consumer demand, and the set of consumer demand scenarios is denoted by S, indexed by s. In the second stage, after observing the scenario that has actually occurred, the assembler must choose the best environmental policy scheme to stimulate demand. The set of potential environmental policy programs for assembly center i at capacity level j is denoted by E_{ij}, indexed by k, and the binary variable y^{sk} is the second-stage variable.

2.1.1. Assumptions of the Proposed Model

- Suppliers can meet the demand of assembly centers, and each assembly center can receive products from all suppliers.
- Capacity levels for each assembly center have been predetermined.
- Three environmental policy schemes are proposed for each center as follows:
    - **Scheme 1**: Advertising, k=1: Launching advertising campaigns to encourage consumers to adopt a sustainable lifestyle by choosing environmentally friendly products and services.
    - **Scheme 2**: Government incentives and support for assemblers, k=2: Providing financial incentives such as low-interest loans and grants for assembly centers.
    - **Scheme 3**: Government incentives and restrictions for assembly centers and consumers regarding environmental protection, k=3: Implementing fines or penalties for non-compliance with environmental regulations for assemblers and consumers, and implementing rewards/penalties for exceeding or falling short of greenhouse gas emissions limits allowed for assembly centers, as well as rewards/penalties for consumers who do not use new sustainable products.
- Several scenarios for different types of consumer demand are considered: high demand for scenario 1, (s =1); medium demand for scenario 2, (s =2); and low demand for scenario 3, (s =3).

Indexes

Symbols	Description
P	Set of assembly centers, indexed by *i*
D_i	Set of capacity levels for assembly center *i*, indexed by *j*
E_{ij}	Set of environmental policy programs for assembly center *i* at capacity level *j*, indexed by *k*
S	Set of consumer demand scenarios, indexed by *s*
L	Set of suppliers, indexed by *l*

Parameters

Symbols	Description
Cp	Overhead cost for assembling a new sustainable product (personnel costs, energy costs, etc.)
R	Revenue from selling a new sustainable product
Rk^1_s	Revenue from selling a new sustainable product under scheme 1, according to scenarios
Rk^2_s	Revenue from selling a new sustainable product under scheme 2, according to scenarios
Rk^3_s	Revenue from selling a new sustainable product under scheme 3, according to scenarios
fcr	Fuel consumption of fully loaded trucks for the product per kilometer (liters)
fde	Carbon emission factor for diesel (grams CO2 per liter)
α	Cost savings due to the use of a new sustainable product
′α′	Cost savings for all assembly centers, regardless of scenario type, due to a new sustainable product
PR	Discount percentage in cost for a new sustainable product compared to a conventional product of the same type
PR′	Discount percentage in cost for all assembly centers, regardless of scenario type, due to the use of a new sustainable product
$CR_{j,s}$	Cost of scheme 1 according to scenario s and capacity j
Rwes	Rate of return under scenario S
$\alpha_{j,s}$	Discount rate for scheme 2 according to scenario and capacity j
$\alpha_{j,s'}$	Discount rate for scheme 3 according to scenario and capacity j
cap_J	Capacity level j
voe	Variable electricity consumption for assembling each unit of product
$d_{l,i}$	Distance from assembly center i to supplier L
$K_{l,i}$	Flow amount from supplier L to assembly center i
$PR_{j,S}$	Discount percentage for scheme 2 according to scenario and capacity j
$PR_{j,S'}$	Discount percentage for scheme 3 according to scenario and capacity j
C	Total cost of a conventional product
C′	Cost of a new sustainable product
sup_l	Number of new sustainable parts produced by suppliers
Ps	Probability of occurrence of scenario S
cfm	Fuel consumption (liters) of forklifts during production operations per unit of product
CO_2f	Amount of carbon emissions (kg CO2) from transporting one unit of product per kilometer between sections
CO_2fl	Amount of carbon emitted (kg CO2) from electricity used to assemble one unit of product
CO_2fi	Amount of carbon emissions (kg CO2) from fossil fuels for assembly operations
CO_2el	Allowed carbon emission (kg CO2) per unit of product
CO_2ei	Carbon emission factor for electricity per kWh (grams CO2 per kWh)

Binary Variables

Symbols	Description
x_{ij}	1 if capacity level *j* is assigned to assembly center *i*
$y_{s,k}$	1 if scheme *k* is assigned to center *i* with capacity *j* under scenario *s*, otherwise 0

2.1.2. Proposed Mathematical Models

The objective function maximizes the assembler's profit, provided that the carbon emitted does not exceed the permissible threshold

$$Max\ z = ((\sum_{i\in P}\sum_{j\in D_i} x_{i,j}cap_J)(R - C)) + (\sum_{s\in S} p_s R^{we} \sum_{i\in P}\sum_{j\in D_i}\sum_{E_{i,j}\in k} (y^{S,1}_{i,j}cap_J((Rk^1_s + \alpha'_{J,s}) - CR_{i,j}) + y^{S,k2}_{i,j}cap_J((Rk^2_s + \alpha'_{J,s}) + \alpha_{J,s}) + y^{S,k3}_{i,j}cap_J((Rk^3_s + \alpha'_{J,s}) + \alpha'_{J,s}))) \quad (1)$$

Subject to:

$$\sum_{j\in D_i} x_{ij} = 1 \qquad \forall i \in P \quad (2)$$

$$\sum_{E_{i},\in k} y_{s,k} = x_{ij} \qquad \forall i \in P, \forall s \in S, \forall j \quad (3)$$

$$\sum_{l\in L} K_{l,i} \le \sum_{j\in D_i} cap_j\, x_{i,j} \qquad \forall i \in P \quad (4)$$

$$sup_l \ge \sum_{i\in P} K_{l,} \qquad \forall l \in L$$

(5)

$$CO2f = (fcr.(\sum_{L\in l} d_{l,i}\, k_{l,i})/10^6 \qquad \forall i \in P \quad (6)$$

$$CO2fl = (voe.CO2(\sum_{j\in D_i} capJx_{ij})/106 \qquad \forall i \in P \quad (7)$$

$$CO2fi = (.cfm\sum_{j\in D_i} capJx_{ij})/106 \qquad \forall i \in P \quad (8)$$

$$KL, \ge 0, x_{i,} = \{0,1\}, y_{s,k} = \{0,1\} \quad (9)$$

Equation (1) is the objective function that maximizes the total profit of the assembler. Equation (2) ensures that only one capacity level *j* can be assigned to each *i*. Equation (3) ensures that if capacity level *j* is selected for *i*, only one of the schemes *k* should be assigned to each *i* with capacity level *j*. Equation (4) specifies that the flow amount (number of products) received from suppliers is less than or equal to the assigned level. Equation (5) establishes the relationship between the flow from suppliers to assembly centers. Equations (6), (7), and (8) calculate the amount of carbon emissions from all stages (transportation and processing operations). Finally, equation (9) ensures the positivity of the flow and the binary modeling of the capacity allocation and scheme variables.

3. Results and Discussion

The following section presents a numerical example using input data for the demand of a reusable automotive component, specifically the body. The input parameter data for the numerical example is shown in Table 1.

Table 1. Input Data

Value	Symbols	Value	Symbols
3	P	$45 * uniform(0,1)$	$\alpha_{J,s}$
2000		$45 * uniform(0,1)$	$\alpha'_{J,s}$
5000		$uniform(4,12) + 2.25 - uniform(0,5)$	Rk^1_s
6000	D_i	$45 * uniform(0,1) + 2.25$	Rk^2_s

7000		$uniform(0.5,3) + 2.25 + 45 * uniform(0,1)$	Rk_s^3
8000		$uniform(1000,1100)$	F_s^{cap}
9000		0.02	fde
10000		$uniform(35000,70000)$	$d_{L,i}$
12000		226	voe
$S_1 = 0.33$	P_s	348	$co2ei$
$S_2 = 0.33$		0.078	cfm
$S_3 = 0.33$		0.0135	$co2el$
$S_1 = 0.25$	R_s^{we}	$uniform(0,1)$	$v_{i,j}^s$
$S_2 = 0.5$		$uniform(550,1300)$	sup_l
$S_3 = 0.25$		$45 * uniform(0,1)$	$\alpha'_{J,s}$
640	C'	$uniform(4,12) + 2.25 - uniform(0,5)$	Rk_s^1
$uniform(0.7,1)$	$Pe_{i,y}$ (%)	$45 * uniform(0,1) + 2.25$	Rk_s^2
1000	R	$uniform(0.5,3) + 2.25 + 45 * uniform(0,1)$	Rk_s^3
2.25	α'	$uniform(1000,1100)$	F_s^{cap}
		$uniform(0,5)$	$CR_{J,s}$

For this study, the GAMS software was used on a system equipped with 16 GB of RAM, an Intel i7 core CPU, and a 1700 MHz processor. The model was solved using CPLEX. The results of the model are presented in Table 2.

Table 2. Results of the Model

Carbon Emissions	Assembler Profit	Selected Scheme under Scenario (s3)	Selected Scheme under Scenario (s2)	Selected Scheme under Scenario (s1)	Selected Capacity Level	Assembly Center
758.436	13080400	k3	k1	k1	6000	1
		k3	k1	k1	6000	2
		k3	k1	k1	6000	3

4. Sensitivity Analysis

Table 3 shows the changes in profit and carbon emissions due to variations in the allowable threshold parameters for carbon emissions. This Table presents the sensitivity analysis and the results regarding the allowable threshold for carbon emissions in the cap-and-trade policy model. In this model, a reduction of more than 20% in the allowable carbon limit renders the model infeasible. However, generally, as the allowable carbon threshold increases, both profit and carbon emissions rise until they reach a stable value.

Policymakers play a significant role in determining an appropriate carbon emission limit, as inappropriate changes can render a project uneconomical. Moreover, setting a limit that is too high for carbon emissions may render the policy ineffective. This situation can assist policymakers in selecting the allowable carbon threshold. It can also help managers of companies operating under this policy to choose a carbon limit that aligns with the policy.

Table 3. Changes in Profit and Carbon Emissions with Changes in the Allowable Threshold Parameter for Emissions

Carbon Emissions	Assembler Profit	Percentage Change (co_2el)
infeasible	infeasible	−60%
infeasible	infeasible	−40%
604.459	10168000	−20%
758.436	13080400	0%
837.089	14103580	20%
994.4	16724210	40%
994.4	16724210	60%
–	–	80%

5. Conclusion and Summary

The goal of this paper is to maximize the assembler's profit under a carbon emission policy that can be utilized by policymakers and companies globally to reduce carbon emissions at all stages. To achieve this goal, a two-stage stochastic programming model is presented for addressing the decision-making issues of "selecting capacity levels" and "determining environmental policy programs" for the demand of new products.

This research has practical applications for both policymakers and manufacturing companies, as they can estimate the threshold at which the model becomes unfeasible by employing the results of this model. In this context, an appropriate allowable threshold for carbon emissions can be determined that is economically viable for the producer without leading to their exit from the production cycle, while also ensuring that the carbon emission policy remains effective to keep emissions controlled and gradually reduced.

As a result, policymakers and manufacturing companies can use the findings of this model to maximize profits while simultaneously reducing carbon emissions in the industry, contributing to a more sustainable future. In the future, other carbon emission policies that affect profitability and carbon reduction in various industries can be considered to expand upon this work. Additionally, research can be conducted to improve the impact of different carbon policies on profitability and carbon reduction across various industries, as well as market research on consumer demand for new sustainable products.

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