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Thematic Section - Sustainability in Transportation and Logistics

Impact of the inclusion of variable CO_2 cost in the distribution network design

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Abstract

Paper aims: This study aims to evaluate the economic-financial impact that the inclusion of environmental variable CO2 cost attributed to transportation (fuel consumption) and manufacturing activities (electricity consumption) represents in a distribution network optimization design.

Originality: This is the first work carried out in Brazil to present a feasible eco-efficient distribution network in the technical and economic aspects considering the tax aspects of ICMS. In addition, this work addresses the inclusion of CO2 as a cost associated with transportation and manufacturing activities. Finally, for the first time in literature, a reference framework that considers environmental variables is presented.

Research method: This study used the systematic literature review method to review the referential framework and carried out a cost reduction using specialist optimization software.

Main findings: The technical and economical feasibility in achieving reduction of both total logistic and CO2 costs in a distribution network design in Brazil and the inexistence of trade-offs without technical solution to the eco-efficient configuration of the distribution network.

Implications for theory and practice: The results of this paper presents a relevant contribution to logistics professionals and researchers, as it was able to present a framework and demonstrated the feasibility of an eco-efficient network design.

Keywords

Distribution network design. Eco-efficient distribution network. Optimization. Strategic decisions. CO_2 cost.

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1. Introduction

In order to remain competitive, the organizations should consider that distribution network design is an important strategic decision (Mohammed & Wang, 2017; Cheshmehgaz et al., 2013; Nurjanni et al., 2017; Chowdhury & Quaddus, 2017; Mangiaracina et al., 2015). According to Mangiaracina et al. (2015), scientific publications on distribution network design have presented the following aims: (1) cost minimization; (2) profit maximization; and (3) service level. To achieve these aims, the logistic network design must make decisions on: (a) facilities; (b) transportation; and (c) inventory allocation (Kadziński et al., 2017).

However, Mohammed & Wang (2017) and Fahimnia et al. (2016) explain that the difficulty in making decisions to adopt the most effective logistics strategy lies in the difficulty of analyzing trade-offs among variables that compose the network design. In 2010, during the COP 16 (Conference of the Parties) of UNFCC (United Nations Framework Convention on Climate Change), the international community undertook to maintain the global average temperature increase at 2 °C above pre-industrial levels for the first time, which is known as The Cancun Agreements (United Nations Framework Convention on Climate Change, 2010). By 2015, during the COP 21, the Paris Agreement was signed, which contributes for countries to sign a more rigorous agreement, keeping the average global temperature increase below 2 °C above pre-industrial levels and seeking efforts to restrict the temperature increase at 1.5 °C above pre-industrial levels (United Nations Framework Convention on Climate Change, 2015).

Considering this global scenario, Brazil has adopted a vanguard position regarding its voluntary contribution in the reduction of greenhouse gases (GHG) by signing a reduction commitment of 37% by 2020 and 43% by 2025 (Fundação Getúlio Vargas, 2018).

These global environmental commitments and regulations mean that companies begin to reevaluate their business objectives and rethink their long-term planning in order to seek their competitive presence in the market in which they operate. According to Shaw et al. (2013), Büyükozkan & Cifci (2012) and Seuring & Gold (2012), the environmental sustainability of supply chains has become a competitive priority for companies.

Das & Jharkharia (2018) argue that the pursuit of GHG emission reduction objectives has been extensively studied in recent years, since the integration of the Carbon Footprint into the decision-making process of the supply network design has received great attention from academicians and professionals; however, the authors claim that the world literature still presents gaps regarding the understanding of economic-financial impacts of CO_2 and the direct and indirect effect of CO_2 in the eco-efficient distribution network design.

In addition, Colicchia et al. (2015) argue that environmental sustainability in supply networks is still a source of disagreements in academic debates, as trade-offs are still unclear and justified in literature, for example, in several studies, the search for CO_2 emission reduction has resulted in an increase of costs; therefore, a consensus on the best method to achieve sustainability in networks has not been achieved; therefore, literature remains subject to the exploration of research with sustainable bias.

Colicchia et al. (2015) reported that the inclusion of environmental variables in the distribution network design not always changes the network configuration, so the deepening of studies on this subject for the academic community is relevant, since the impacts on the supply chain by including variable CO_2 cost in the distribution network design still do not show consensus.

In addition, Ala-Harja & Helo (2015) consider that food supply chains represent an important part of the global economy, so that their high production volumes and high turnover are important characteristics of this chain.

Therefore, using optimization software, this study developed an eco-efficient scenario for the distribution network, with a focus on minimizing costs, and included the CO_2 cost in the objective function, and the results were compared with the cost-effective scenario in order to understand the economic and financial impact of including variable CO_2 cost in the network design.

The study sample was a wheat flour manufacturer company with 5 factories, which distributes its products in almost all the Brazilian territory and occupies a place of leadership in this market.

2. Literature review

2.1. Distribution network design

Over the last few years, several efforts have been made to assist in the formulation of the logistics strategy, so that Perez-Franco et al. (2016) presented a conceptual framework that allows capturing, evaluating and rethinking the supply chain strategy based on the business strategy.

However, despite the search for structuring a generic operation strategy model at supply chain level, Macchion et al. (2015) argue that there is no specific operation strategy that is better than the other in a generalist way, since the choice of the operation strategy must be linked to competitive priorities (cost, quality, speed and flexibility) in order to generate competitive advantage for the organization, and its choice directly depends on the internal and external characteristics of organizations.

2.2. Literature classification on the distribution network design

As shown in Table 1, 70% of academic papers published in internationally relevant journals on the distribution network design subject are concentrated in two main study areas. The Operations & Production Management journal has 49% of publications, followed by the Logistics & Supply Chain Management journal, with 21%.

Papers were classified into quantitative, conceptual and empirical:

a) Quantitative: use mathematical formulation for optimization or simulation of the distribution network design;

b) Conceptual: those that propose a general classification and / or present frameworks;

c) Empirical: use surveys, case studies or interviews to understand the dynamics and factors in order to analyze the network design.

Table 1. Classification by type of Journal.

Type of Journal	Reference Paper*	Researched Papers	Total number of papers	%
Operations & Production Management	60	9	69	49%
Logistics & Supply Chain Management	28	2	30	21%
Industrial & Manufacturing Engineering	22	1	23	16%
Transportation Management	14	4	18	13%
Other journals	2	0	2	1%
Total	**126**	**16**	**140**	**100%**

*Data extracted from the paper by Mangiaracina et al. (2015). Source: Author.

Table 2 shows that most papers use quantitative models (85%), followed by conceptual models (11%), and, few empirically investigate the supply network design (only 4%).

Considering only quantitative models (Table 3), papers were grouped according to their objective function.

It was observed that 87% of papers presented single objective, the most frequent being cost minimization, and only 13% approached the network design considering more than one objective, that is, multiple objective (for example, cost minimization and delivery time reduction, cost minimization and CO_2 emission reductions, and so on).

Table 2. Classification by type of model.

Type of models	Reference Paper*	Researched Papers	Total number of papers	%
Quantitative	108	13	121	85%
Conceptual	13	2	15	11%
Empirical	5	1	6	4%
Total	**126**	**16**	**142**	**100%**

*Data extracted from the paper by Mangiaracina et al. (2015). Source: Author.

Table 3. Classification by objective function of quantitative papers.

Objective Function	Reference Paper*	Researched Papers	Total number of papers	% Total
Single objective	**100**	**5**	**105**	**87%**
Cost minimization	86	5	91	75%
Service Level	7	0	7	6%
Profit Maximization	7	0	7	6%
Multiple objective	**8**	**8**	**16**	**13%**
Total	**108**	**13**	**121**	**100%**

*Data extracted from the paper by Mangiaracina et al. (2015). Source: Author.

According to Mangiaracina et al. (2015), strategic decisions for the network design are divided into: (1) distribution network structure; (2) management policies. As for decisions on network structure (Table 4), although most papers (41%) seek strategic decisions regarding the location of facilities (distribution centers, warehouses, factories, etc.), surveys analyzed in the period between 2015 and 2018 have shown that 7 of 12 works (58%) sought to make decisions regarding the number of facilities required in the distribution network, so it was observed that there was a growth of decisions of this nature compared to the literature review presented by Mangiaracina et al. (2015).

Table 4. Classification by strategic decision: network structure.

Structure strategic decisions	Reference Paper*	Researched Papers	Total number of papers	%
Facility Location	74	3	77	41%
Demand allocation to facility	43	1	44	24%
Number of facilities	41	7	48	26%
Capacity of facilities	11	1	12	6%
Number of echelon	5	0	5	3%
Total	**174**	**12**	**186**	**100%**

*Data extracted from the paper by Mangiaracina et al. (2015). Source: Author.

Regarding strategic decisions on management policies (Table 5), there was no perception of a significant trend change, remaining decisions on the inventory level and route design as the most discussed decisions in the distribution network design.

Table 5. Classification by strategic decision: management policies.

Strategic Management Decisions	Reference Paper*	Researched Papers	Total number of papers	%
Inventory level	40	1	41	33%
Route design	39	0	39	33%
Inventory allocation	16	2	18	14%
Fleet design	16	3	19	13%
Inventory Policy	9	0	9	7%
Total	**120**	**6**	**126**	**100%**

*Data extracted from the paper by Mangiaracina et al. (2015). Source: Author.

2.3. Referential framework review

Recovering the proposal of Mangiaracina et al. (2015) regarding the critical factors that impact the network design, there was absence of a group of critical factors that has been widely approached by academic research: environmental variables.

Thus, by updating Table 6 on the basis of the reference paper, the topic will include 1% of critical factors studied since 1972. However, the recent literature, which was reviewed in this research, presented environmental variables in 6 papers of a total of 16 papers, that is, in 37.5% of publications between 2015 and 2018, with environmental variables decision.

Table 6. Group of critical factors.

Decisions	Reference Paper*	Researched Papers	Total	% of Total
Product Features	23	4	27	6%
Service Requirements	111	2	113	25%
Demand Characteristics	234	2	236	51%
Chain Characteristics	46	11	57	12%
Economic Variables	11	11	22	5%
Environmental Variables	0	6	6	1%
Total	**425**	**36**	**461**	**100%**

*Data extracted from the paper by Mangiaracina et al. (2015). A paper can present more than one type of decision (for example, there are papers that presented Service Requirements and Economic Variables as research decisions), therefore, the total number of decisions in researched papers (36) is greater than the number of researched papers (16). Source: Author.

Therefore, it is possible to conclude that there was a growth of academic papers on the environmental sustainability bias in distribution network design studies.

The emergence of papers with environmental sustainability bias was always perceived together with an existing critical factor, which corroborates the perception of the growth of quantitative surveys with multiple objective optimization approach presented in Table 3.

It was also observed that the sustainable bias for designing the distribution network was significant because 46% (6 papers) of the total of 13 quantitative papers published between 2015 and 2018 proposed single or multiple objective function and included the reduction of environmental impacts to the network design (e.g., CO_2 reduction, particulate matter, recycling of materials, etc.).

The reference framework review (Table 7) includes a new group of critical factors in order to complement the study based on recent literature: environmental variables. This group is represented by the following critical factors:

a) Particulate Matter emission;

b) CO_2 emission.

Thus, this literature review contributes to literature on the subject from the update of the reference framework by Mangiaracina et al. (2015).

Table 7. Clustering of critical factors.

Group	Critical factor	
Product characteristics	· Product value density	· Product variety
	· Weight-cubic volume ratio	· Product price
	· Product life cycle	· Substitutability
	· Level of competition	· Product margin
	· ABC product characteristics	· Shelf life
	· Product type	· Product handling characteristics
Service requirements	· Cycle time	· Customer experience
	· Delivery frequency	· Order visibility
	· Average weight of shipment	· Returnability
	· Average volume of shipment	· Replenishment lead time
	· Item fill rate	Capacity of vehicle
Demand features	· Demand level	· Customer density
	· Demand volatility	· Number of customers
	· Demand density	· Seasonality
Chain characteristics	· Production capability	· Production flexibility
	· Distance between nodes	· Production lead time
	· Production batch size	· Number of suppliers
	· Limitations on raw material	· Location of suppliers
	· Economy of scale	
Economic variables	· Legal restrictions	· Transportation mode availability
	· Customs/duties	
	· Existing infrastructure	· Interest rate
Environmental variables	· Particulate Matter emission	
	· CO_2 emission	

Source: Author "adapted from" Mangiaracina et al. (2015, p. 521).

2.4. Eco-efficient networks

Das & Jharkharia (2018) argue that international regulations since the Kyoto Protocol, which occurred in Japan in 1997, had great influence on the change in corporate sustainability behavior. According to Nurjanni et al. (2017), the industrial sector in developed countries has strengthened the search for more sustainable supply chains in the environmental sphere due to global regulations (Kyoto Protocol, Paris Agreement, United Nations Framework Convention on Climate Change, UNFCCC).

In Brazil, the National Policy on Climate Change (PNMC) was considered as a milestone, which came into force in 2009 through Law No. 12.187, which made official the country's commitment to reduce greenhouse gases emissions (GHG) (Fundação Getúlio Vargas, 2018).

Therefore, with the strengthening of the environmental agenda both at international and national levels, companies have redesigned their supply chains in order to incorporate environmental goals into their operations strategy. Therefore, distribution network designs have increasingly included environmental variables as a critical factor for decision making (Colicchia et al., 2015).

According to Das & Jharkharia (2018), recent studies have adopted two distinct perspectives: one deals with functional and operational aspects of supply chain management, such as sourcing, production and planning, distribution, network design and supply chain coordination; the other deals with the accounting and conceptualization of the Carbon Footprint. To understand this concept, Das & Jharkharia (2018) defined that Carbon Footprint can be understood as a measure of the total exclusive amount of CO_2 emissions directly or indirectly caused by an activity or accumulated throughout the life stages of a product.

For Das & Jharkharia (2018), the management of an Eco-efficient Chain can be defined as a strategy that integrates CO_2 emissions (or CO_2 equivalent - CO_2e) or Greenhouse Gases (GHG) as a restriction or as a goal in the planning and in the supply chain design. Therefore, the ultimate goal of an eco-efficient distribution network is to reduce global carbon emissions from the supply chain without compromising the economic interest of the company as a whole.

In addition, Fahimnia & Jabbarzadeh (2016) indicate that studies on design, planning and management of Eco-efficient Supply Chains have followed at least five important directions:

a) Optimization models for the supply chain strategic design, seeking the balance between chain costs and carbon emission (Brandenburg, 2015; Elhedhli & Merrick, 2012; Wang et al., 2013);

b) Tactical and operational planning tools to analyze trade-offs between costs and emissions (Colicchia et al., 2015; Fahimnia et al., 2016; Zakeri et al., 2015);

c) Design and planning of Closed-loop Supply Chains focused on the cost / emission performance of the distribution and reverse process (John et al., 2017; Banasik et al, 2017);

d) Development and application of multiple performance indicators for the design and management of the Supply Chain (Nurjanni et al., 2017; Pishvaee et al., 2012);

e) Introduction and investigation of the impact of environmental policies on the planning and optimization of the Supply Chain (Zakeri et al., 2015).

2.4.1. CO_2

According to Greenstone et al. (2013), greenhouse gases (GHG) emission changes the Earth's climate, increasing temperature, changing precipitation patterns and increasing climate variability, with transportation activity being one of the potential generators of GHG, which is generated by fuel consumption. John et al. (2017) reported that the main constituents of vehicle emissions are nitrogen oxides (NOx), particulate matter (PM), methane (CH_4) and carbon dioxide (CO_2).

According to Nordhaus (1993), CO_2 cost can be understood as a social cost of carbon, i.e., an economic cost caused by an additional ton of carbon dioxide (in other words, carbon) emissions or its equivalent. Greenstone et al. (2013) reported that monetized estimates of economic damages associated with CO_2 emissions enable cost-benefit analyses to incorporate the social benefits of regulatory actions that should reduce such emissions.

For John et al. (2017), until recently, the cost of transportation, collection, processing and the fixed cost of facilities were the costs most widely considered in distribution network design studies. However, today, in addition to these costs, costs associated with GHG emissions are becoming increasingly important. According to Paksoy et al. (2011), transportation activities among supply chain stages are an important source of GHG emissions.

John et al. (2017) emphasize that there are different studies conducted by governmental and nongovernmental agencies such as the Automotive Research Association of India (ARAI), the United States Environmental Protection Agency (EPA), the Office of Management and Budget (OMB), the Central Pollution Control Board (CPCB) of India, among others, estimate the emission rate and the corresponding cost of transportation activities. In Brazil, this role is played by the Center for Sustainability Studies of the "Getúlio Vargas" Foundation (GVCES).

For Piecyk & McKinnon (2010), transportation is the main source of secondary carbon emissions. These carbon emissions can be significantly reduced by the selection of the transportation mode (Hoen et al., 2014; Bouchery et al., 2016), freight management (Rudi et al., 2016), routing decisions (Validi et al., 2014; Glock & Kim, 2015; Kumar et al., 2016; Suzuki, 2016; Qiu et al., 2017), load consolidation (Brown & Guiffrida, 2014; Van Loon et al., 2015) choice of location (Lam et al., 2010; Rao et al., 2015; Musavi & Bozorgi-Amiri, 2017), logistic outsourcing (Ameknassi et al., 2016; Li et al., 2017) and energy conservation (Müller et al., 2014).

2.5. ICMS in the distribution network

According to Pessôa et al. (2011), the ICMS tax (Imposto sobre operações relativas à Circulação de Mercadoria e sobre a prestação de Serviço de transporte interestadual, intermunicipal e de comunicação) was instituted by Complementary Law 87/1996, also known as "Kandir Law". ICMS is a tax applied on goods or services in commercial transactions and exchanges. The main difference regarding the value-added taxes in other countries is the attribution of the tax incidence the company at the origin.

It is a tax of jurisdiction of states and the Federal District (paper 155, II, of the Federal Consitution of 1988), that is, each state determines the tax rate by means of the ICMS Regulation (RICMS), which is calculated on the sales price (generating fact) (Brasil, 1988). It is applied along the stages of the supply chain only on the value added to the product or service.

After the establishment of ICMS, the states and the Federal District have granted benefits or exemptions with the objective of attracting private investments in order to promote regional development. However, Frias et al. (2013) affirm that these initiatives result in a "tax tourism" in the distribution of products in the national territory, that is, for a company to obtain cost reduction in its distribution operation, the route for the delivery of products is not determined by the shortest distance, but by the route that has the lowest ICMS rate added to transportation costs.

Therefore, the inclusion of ICMS in logistics planning can bring competitive advantages through gains in total logistics costs for companies, since "[...] the use of routes with favorable ICMS rates in the distribution network can bring great economic gains" (Junqueira & Morabito, 2008, p. 369).

Despite the evident importance of ICMS in the distribution network design in order to reduce costs, the trend of networks to adopt "tax tourism" in favor of a better financial result makes transport routes longer compared to the network in which ICMS does not constitute a decisive factor. Thus, with more distant routes, fuel consumption is higher; therefore, increasing CO_2 emissions. In addition to the importance of ICMS in the network with the performance bias in total costs, there can be the relationship of this tax in the environmental sustainability objectives in the distribution network.

3. Methodology

Similarly to Bing et al. (2014), the IBM ILOG LogicNet Plus XE 7.2 optimization software was used for the mapping and optimization of the distribution network under study.

Thus, CO_2e conversion factors were attributed to transportation activities and electricity consumption according to the Brazilian GHG Protocol Program (Fundação Getúlio Vargas, 2018). This study considered one CO_2 conversion factor for each type of vehicle, expressed in kg CO_2e / t.km, and for electricity consumption, expressed in tCO_2e / MWh, in the network design. In addition, the research considered the generation of GHG in Scope 1, Scope 2 and Scope 3 (Fundação Getúlio Vargas, 2018).

A brief summary of scenarios that have been developed is presented below:

a) Scenario 0: represents the company's current distribution network - considered as the base scenario. At this stage, the company's current distribution network was modeled in the software with actual operation conditions. This scenario shows proximity to the company's results during the year 2017 - same period in which data were collected. In order to make development feasible, the facility's capacity and distribution flow constraints were imposed on the model. For the model validation, gross revenue, ICMS (sales tax) and raw-material cost were considered in the SIE (Statement of Income and Expenditure) of the 2017 financial year provided by the company;

b) Scenario 1: based on Scenario 0, distribution flow constraints imposed on the model were relaxed for the purpose of reducing total logistic cost - considered as the cost-effective scenario;

c) Scenario 2: CO_2 cost was included in the total logistic cost and the goal of cost reduction was maintained - considered the eco-efficient scenario. Thus, it was possible to determine the eco-efficient network, i.e., cost and CO_2 goals, simultaneously.

The IBM ILOG LogicNet Plus XE7.2 software uses Mixed Integer Linear Programming (MILP) as optimization algorithm. The classical mathematical MILP model used in this research to optimize the distribution network design considering the CO_2 cost as a variable is presented in the study published by Bing et al. (2014). In summary, MILP can be understood as a general structure of mathematical optimization that has the advantage of allowing a global perspective of all constraints (Jain & Grossmann, 2011).

Huang et al. (2003) reported that this method is used for network optimization and allows comparative computational analysis of different scenarios. In addition, MILP is the technique most frequently used in formulating problems related to the distribution network design (Srivastava, 2007).

Indexes, parameters and variables of the classical MILP model for the distribution network optimization design (Croxton & Zinn, 2005) are described below.

Description of the model indexes:

i: suppliers index

j: factories index

k: warehouse index

l: customer index

m: raw-materials index

p: finished products index

Description of the model parameters:

F_j: fixed factory cost j

V_j^p: variable factory cost j to produce product p

F_k: fixed cost of warehouse k

V_k^p: variable cost of warehouse k to receive, store and ship product p

T_{ij}^m: transport cost from supplier i to factory j of raw material unit m

T_{jk}^p: transport cost from factory j to warehouse k of a unit of product p

T_{kl}^p: transport cost from warehouse k to customer l of a unit of product p

A_{ij}^m: cost of CO_2 emission in transporting raw-material m from supplier l to factory j

A_{jk}^p: cost of CO_2 emission in transporting product p between factory j and warehouse k

A_{kl}^p: cost of CO_2 emission in transporting product p between warehouse k and customer l

A_j: cost of CO_2 emission from the electricity consumption of plant j

C_i^m: capacity of supplier i to supply product m

C_j^p: capacity of factory j to produce product p

C_k^p: capacity of warehouse k to store product p

D_l^p: demand for product p on customer l

E_j: electricity consumed by factory j

M_{kl}^p: tax related to ICMS on the sale of product p from warehouse k to customer l

Description of model variables:

$X_{ij}^m \in \mathbb{R}_+$ units of raw-material m supplied by supplier i to factory j

$X_j^p \in \mathbb{R}_+$ units of product p produced in factory j

$X_k^p \in \mathbb{R}_+$ units of product stored by warehouse k

$X_{jk}^p \in \mathbb{R}_+$ units of product p delivered from factory j to warehouse k

$X_{kl}^p \in \mathbb{R}_+$ units of product p delivered from warehouse k to customer l

$Y_j^p \in \{0,1\}$ binary variable indicating whether factory j is used to produce product p

$Y_k^p \in \{0,1\}$ binary variable indicating whether warehouse k is used to store product p

Thus, the mathematical formulation of the model can be described in generic form by means of the objective function:

Minimize:

$$\sum_{m=1}^{t}\sum_{i=1}^{z}T_{ij}^{m}X_{ij}^{m}+\sum_{j=1}^{w}(F_{j}+V_{j}^{p}X_{j}^{p})Y_{j}^{p}+\sum_{k=1}^{u}\sum_{p=1}^{v}\sum_{j=1}^{w}T_{jk}^{p}X_{jk}^{p}+$$
$$\sum_{j=1}^{w}(F_{k}+V_{k}^{p}X_{k}^{p})Y_{k}^{p}+\sum_{k=1}^{u}\sum_{p=1}^{v}\sum_{l=1}^{n}T_{kl}^{p}X_{kl}^{p}+\sum_{k=1}^{u}\sum_{p=1}^{v}\sum_{l=1}^{n}M_{kl}^{p} \qquad (1)$$

Subject to the following constraints:

$$\sum_{i=1}^{z}\boldsymbol{X_{ij}^{m}}=\sum_{j=1}^{w}\boldsymbol{X_{j}^{p}} \quad \forall\, i \in \{1,...,z\},\ j \in \{1,...,w\},\ m \in \{1,...,t\},\ p \in \{1,...,v\} \qquad (2)$$

$$\sum_{j=1}^{w}\boldsymbol{X_{j}^{p}}=\sum_{k=1}^{u}\boldsymbol{X_{jk}^{p}} \quad \forall\, j \in \{1,...,w\},\ k \in \{1,...,u\},\ p \in \{1,...,v\} \qquad (3)$$

$$\sum_{k=1}^{u}\boldsymbol{X_{jk}^{p}}=\sum_{l=1}^{n}\boldsymbol{X_{kl}^{p}} \quad \forall\, k \in \{1,...,u\},\ l \in \{1,...,n\},\ p \in \{1,...,v\} \qquad (4)$$

$$\sum_{l=1}^{n}\boldsymbol{X_{kl}^{p}}\geq \boldsymbol{D_{l}^{p}} \quad \forall\, l \in \{1,...,n\},\ p \in \{1,...,v\} \qquad (5)$$

$$\boldsymbol{X_{ij}^{m}}\leq \boldsymbol{C_{i}^{m}} \quad \forall\, i \in \{1,...,z\},\ m \in \{1,...,t\} \qquad (6)$$

$$\boldsymbol{X_{j}^{p}}\leq \boldsymbol{C_{j}^{p}Y_{j}^{p}} \quad \forall\, j \in \{1,...,w\},\ p \in \{1,...,v\} \qquad (7)$$

$$\boldsymbol{X_{jk}^{p}}\leq \boldsymbol{C_{j}^{p}Y_{j}^{p}} \quad \forall\, j \in \{1,...,w\},\ p \in \{1,...,v\} \qquad (8)$$

$$\boldsymbol{X_{kl}^{p}}\leq \boldsymbol{C_{k}^{p}Y_{k}^{p}} \quad \forall\, k \in \{1,...,u\},\ p \in \{1,...,v\} \qquad (9)$$

$$\boldsymbol{X_{ij}^{m}},\boldsymbol{X_{j}^{p}},\boldsymbol{X_{jk}^{p}},\boldsymbol{X_{kl}^{p}}\geq 0 \quad \forall\, i, j, k \qquad (10)$$

$$\boldsymbol{Y_{j}^{p}}\in\{0,1\} \quad \forall\, j \qquad (11)$$

$$\boldsymbol{Y_{k}^{p}}\in\{0,1\} \quad \forall\, k \qquad (12)$$

$$\boldsymbol{M_{kl}^{p}}\geq 0 \quad \forall\, k \in \{1,...,u\},\ p \in \{1,...,v\},\ l \in \{1,...,n\} \qquad (13)$$

The objective function (1) minimizes the sum of fixed and variable costs, and transportation costs from supplier to the factory, from factory to the warehouse and from warehouse to customers. Constraints from (2) to (9) are standard constraints of the distribution network design for the maintenance of flow balancing from supplier to the factory, from factory to the warehouse, and from warehouse to customers. Constraint (10) ensures the non-negativity of transported and produced product units and constraints (11) and (12) ensure that variables $\boldsymbol{X_{j}^{p}}$ and $\boldsymbol{Y_{k}^{p}}$ are integers and binary and allow the use (opening) or not (closing or not opening) of factories and warehouses, respectively. Finally, restriction (13) guarantees the non-negativity of tax related to ICMS applied in the sale of product p from warehouse k to customer l.

However, when environmental variable CO_2 is included, the mathematical model is represented as follows:

Minimize:

$$\sum_{m=1}^{t}\sum_{i=1}^{z}(T_{ij}^{m}+A_{ij}^{h})X_{ij}^{m}+\sum_{j=1}^{w}(F_{j}+V_{j}^{p}X_{j}^{p}+A_{j}E_{j})Y_{j}^{p}$$
$$+\sum_{k=1}^{u}\sum_{p=1}^{v}\sum_{j=1}^{w}(T_{jk}^{p}+A_{jk}^{h})X_{jk}^{p}+\sum_{j=1}^{w}(F_{k}+V_{k}^{p}X_{k}^{p})Y_{k}^{p} \qquad (14)$$
$$+\sum_{k=1}^{u}\sum_{p=1}^{v}\sum_{l=1}^{n}(T_{kl}^{p}+A_{kl}^{h})X_{kl}^{p}+\sum_{k=1}^{u}\sum_{p=1}^{v}\sum_{l=1}^{n}M_{kl}^{p}$$

In addition to the previous restrictions, from (2) to (13), the model is also subject to the following restrictions:

$$A_{jk}^{p} \geq 0 \quad \forall \; j, k \tag{15}$$

$$A_{kl}^{p} \geq 0 \quad \forall \; k, l \tag{16}$$

$$A_{ij}^{m} \geq 0 \quad \forall \; i, j \tag{17}$$

$$A_{j}^{p} \geq 0 \quad \forall \; j \tag{18}$$

$$M_{kl}^{p} \geq 0 \quad \forall \; k_{=} \{1,\ldots,u\},\; p_{=} \{1,\ldots,v\},\; l_{=} \{1,\ldots,n\} \tag{19}$$

Therefore, the new objective function, in addition to minimizing the sum of fixed and variable costs, transportation costs from supplier to the factory, from factory to the warehouse, from warehouse to customers and the ICMS tax costs, adds the costs of CO_2 emitted during transportation from supplier and the factory, from factory to the warehouse, from warehouse to the customer, and also includes the CO_2cost rising from the consumption of electricity during manufacturing.

4. Distribution network scenarios

4.1. Scenario 0 (base scenario)

Scenario 0 demonstrates facilities (factories, warehouses, ports), suppliers, customers, raw-materials, finished products and the following flows: factory supply; transfers between warehouses and distribution to customers. Wheat was the raw material inserted in this scenario. Four wheat suppliers were considered (three in Argentina and one in Brazil). The company has 5 factories in Brazil and manufactures two products: wheat flour and wheat bran. Warehouses were divided into three types: (1) wheat silos; (2) warehouses for the shipping of products from factories, and (3) Transit Points (TP). Five wheat silos were mapped. Each factory also has a warehouse integrated to its industrial plant (same latitude and longitude), in total, five warehouses were considered.

TPs are advanced distribution centers that receive products already with their respective destinations; therefore, storage is not the main logistic function, but the distribution of products to customers, being able to use smaller vehicles to meet demands.

Customers are located in 21 states, and are mainly bakeries, restaurants, snack bars, factories (of breads, cakes, pastas and biscuits), markets and distributors.

In addition, sea ships and road shipping (using van, trailer trucks, trucks, and bulk carrier) have been included, which are responsible for factory supply flows and transfers from distribution warehouse to customers. Source-destination flows representing Scenario 0, considering suppliers, factories, warehouses, and customers of the mapped distribution network are represented on the map in Figure 1.

4.1.1. Results of Scenario 0

The results obtained were compared to the managerial SIE provided by the company, from January to December 2017, according to Table 8. According to Junqueira & Morabito (2008), ICMS was considered in the total logistic cost.

Considering Scenario 0, it could be observed that the logistic decisions in this distribution network may be relevant to the contribution of the business result, since the total logistic cost represents 16.6% of sales revenue.

In addition, emission factors for supply and distribution flows were applied for both road and sea transportations (Table 9), as well as the average emission factor of 2017 for electricity generation.

The cost of CO_2 emitted by the distribution network in Scenario 0 was R$ 1,969 million, the main source being road transportation, with 74.4%, followed by sea transportation, with 21.3%, and electricity consumption, with 4.3%. Also, it was observed that the CO_2 cost represented 1.33% of the total logistic cost (R$ 1,969 million in R$ 147,770 million).

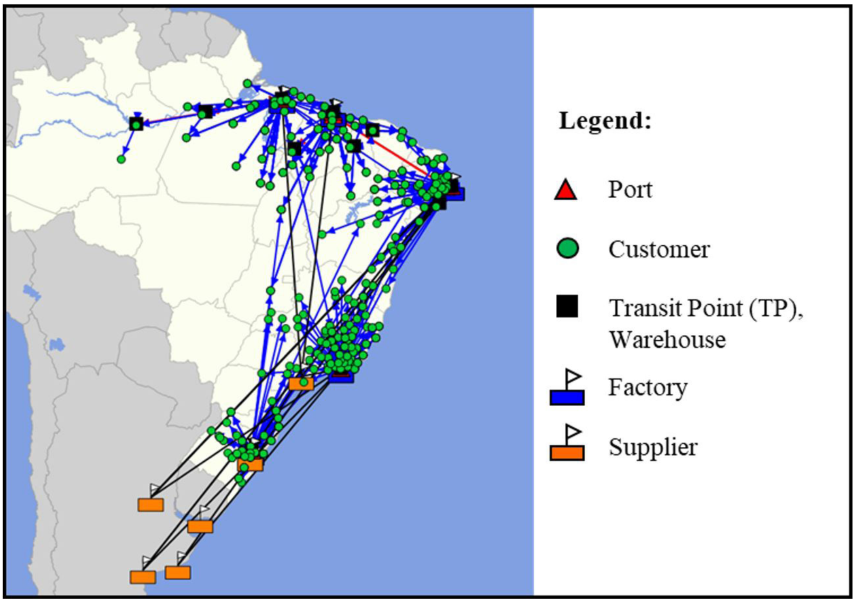

Figure 1. Distribution flows: Scenario 0. Source: Author.

Table 8. Validation of Scenario 0.

Item	SIE* (R$ thousand)	Cost over revenue (%)	Scenario 0 (R$ thousand)	Cost over revenue (%)	Variation (%)
Gross sales revenue	**890,489**	**-**	**889,886**	**-**	**-0.07**
Raw-material cost	**521,054**	**58.6**	**517,327**	**58.1**	**-0.72**
Total logistic cost	**147,519**	**16.6**	**147,770**	**16.6**	**0.17**
Sales Tax	25,257	2.8	25,415	2.9	0.63
Freight - Factory to Warehouse	60,854	6.8	58,352	6.6	-4.11
Freight - Warehouse to Warehouse	12,615	1.4	13,206	1.5	4.68
Freight - Warehouse to Customer	48,793	5.5	50,797	5.7	4.11

*Data obtained from managerial SIE for year 2017 provided by the company and adapted by the Author. Source: Author.

Table 9. Scenario 0: CO_2 cost per source of emission.

Source of emission	CO_2 cost (R$ thousand)	Participation (%)
Road transportation	1,465	74.4
Sea transportation	419	21.3
Electricity	85	4.3
Total emission	**1,969**	**100.0**

Source: Author.

Table 10 presents the demand met per origin from some warehouse or TP. Total demand met was approximately 652 thousand tons. Rio de Janeiro warehouse is the largest distributor, meeting 33% of total demand, followed by Recife (24%) and Belém (18%) warehouses. Thus, it was possible to determine a reference scenario for the comparison of results with future scenarios.

4.2. Scenario 1 (cost-effective)

For the development of Scenario 1, the optimization considered aimed at reducing costs, and the distribution flow constraints were relaxed. Thus, in Scenario 1, it was possible to select distribution flows with the lowest cost for each customer and, therefore, to find the distribution network configuration that resulted in a cost-effective scenario (with the lowest total logistic cost). Table 11 presents the economic-financial results obtained in Scenario 1 and compares them with results of Scenario 0.

Table 10. Scenario 0: demand per origin.

Origin	Demand (ton)	Participation (%)
Rio de Janeiro warehouse	212.406	33%
Recife warehouse	157.503	24%
Belém warehouse	116.705	18%
São Luís warehouse	64.150	10%
Canoas warehouse	63.900	10%
Maceió TP	10.559	2%
Teresina TP	8.675	1%
Imperatriz TP	6.474	1%
Santarém TP	5.824	1%
Manaus TP	4.201	1%
Tianguá TP	1.697	0%
Total	**652.094**	**100%**

Source: Author.

Table 11. Results: Scenario 1.

Item	Scenario 0 (R$ thousand)	Scenario 1 (R$ thousand)	Variation (R$ thousand)	Variation (%)
Gross sales revenue	**889,886**	**889,886**	-	-
Total logistic cost	**147,770**	**142,835**	–4,935	-3.3
Sales Tax	25,415	20,934	–4,481	-17.6
Freight - Factory to Warehouse	58,352	55,712	–2,640	-4.5
Freight - Warehouse to Warehouse	13,206	14,161	955	7.2
Freight - Warehouse to Customer	50,797	52,028	1,231	2.4

Source: Author.

The result of Scenario 1 indicated the closing of Manaus TP and Santarém TP reached reduction of R$ 4,935 million in the total logistic cost of the distribution network. Also, the gain was leveraged by the 17.6% reduction in sales tax (R$ 4,481 million) due to the use of different ICMS tax rates on interstate sales. Also, this result is reinforced by the concomitant increase in freight cost from warehouse to customer at R$ 1,231 million, since, in order to reduce the total logistic cost through sales tax, it was necessary to increase the distances covered in lastmile transport.

The representation of flows of Scenario 1 (Figure 2) indicates that network distribution flows were different from results of Scenario 0. The increase of distances traveled in relation to Scenario 0 and the closure of Manaus TP and Santarém TP can be observed.

Despite the reduction in total logistic cost, CO_2 cost increased by 25.0% (or R$ 493 thousand) in relation to Scenario 0 (Table 12). This increase was predominant in road transportation (34.5%) due to the increase of transfers among warehouses.

When analyzing the results of Scenario 1 in relation to Scenario 0 (Table 13), it could be observed that all demand that was met by Manaus TP (4,201 tons) and Santarém TP (5,824 tons) in Scenario 0 was transferred to Belém warehouse, which presented an increase of 8.6% (or 10,025 tons) in relation to result of Scenario 0. Therefore, both TPs were closed in Scenario 1.

On the other hand, in Scenario 1, part of demands previously met by Recife warehouse and São Luís warehouse migrated to Imperatriz TP, Maceió TP, Teresina TP and Tianguá TP. Finally, Canoas warehouse had an increase of 49.9% (31,878 tons), which were previously met by Rio de Janeiro warehouse.

Therefore, it could be concluded that there is a "cost-effective" distribution network configuration that meets the total demand of 652,094 tons and achieve a lower total cost than that obtained in Scenario 0.

4.3. Scenario 2 (eco-efficient)

The aim of Scenario 2 is to find a configuration of facilities (Scenario 2) that presents reduction in CO_2 cost, in addition to reduction in the total cost of the distribution network. At this stage, flow restrictions were maintained as predefined in Scenario 0 in order to reduce the distances covered in the distribution network,

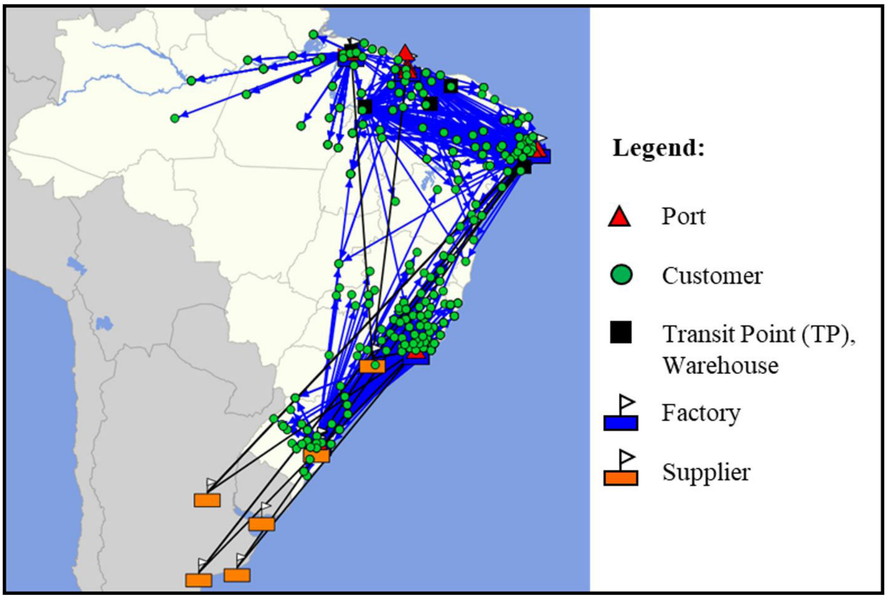

Figure 2. Distribution flows: Scenario 1. Source: Author.

Table 12. Comparison: CO_2 cost per source of emission between Scenario 0 and Scenario 1.

Source of emission	CO_2 cost Scenario 0 (R$ thousand)	CO_2 cost Scenario 1 (R$ thousand)	Variation (%)
Road transportation	1,465	1,971	34.5
Sea transportation	419	406	-3.1
Electricity	85	85	0.0
Total emission	**1,969**	**2,462**	**25.0**

Source: Author.

Table 13. Scenario 1 vs. Scenario 0: demand by origin.

Origin	Scenario 0 (ton)	Scenario 1 (ton)	Variation (ton)	Variation (%)
Rio de Janeiro warehouse	212,405	180,526	-31,878	-15
Recife warehouse	157,503	148,444	-9,059	-5.8
Belém warehouse	116,705	126,730	10,025	8.6
São Luís warehouse	64,150	44,412	-19,738	-30.8
Canoas warehouse	63,900	95,778	31,878	49.9
Maceió TP	10,559	10,710	150	1.4
Teresina TP	8,675	10,679	2,003	23.1
Imperatriz TP	6,474	31,795	25,321	391.1
Santarém TP	5,824	-	-5,824	-100
Manaus TP	4,201	-	-4,201	-100
Tianguá TP	1,697	3,020	1,322	77.9
Total	**652,094**	**652,094**	-	-

Source: Author.

so the optimization of Scenario 2 does not contribute to the reduction of total costs through the distribution network's tax opportunities.

In order to find the eco-efficient solution, similarly to research conducted by Bing et al. (2014), this work tested different optimized cost scenarios, as shown in Table 14. It could be observed that all configuration alternatives tested allowed cost and CO_2 reductions simultaneously in relation to Scenario 0. However, the alternative that results in the lowest total logistic cost was the network configuration with 2 TP (R$ 146.471 million); therefore it was considered the eco-efficient solution.

Table 14. Eco-efficient scenarios.

Item	3 TP (R$ thousand)	2 TP (R$ thousand)	1 TP (R$ thousand)	No TP (R$ thousand)
Number of active TP	3	2	1	0
CO_2 cost	**1,873**	**1,868**	**1,862**	**1,860**
Total logistic cost	**14 7,666**	**146,471**	**146,735**	**146,662**
Sales Tax	26,589	26,303	26,410	26,871
Freight - Factory to Warehouse	58,352	58,352	58,352	58,352
Freight - Warehouse to Warehouse	10,080	9,100	8,929	8,207
Freight - Warehouse to Customer	52,445	52,716	53,044	53,232

Source: Author.

From results of Table 15, it could be observed that Scenario 2 reached 5.1% reduction in CO_2 emission cost and 0.9% in total cost. The eco-efficiency reached in Scenario 2 resulted from the closure of Manaus TP, Santarém TP, Teresina TP and Maceió TP. The closure of the 4 (four) TPs contributed to the reduction of R$ 4.106 million (-31.1%) in the cost of transfer among warehouses in relation to Scenario 0.

Table 15. Scenario 2: eco-efficient.

Item	Scenario 0 (R$ thousand)	Scenario 2 (R$ thousand)	Difference (R$ thousand)	Variation (%)
CO_2 cost	**1,969**	**1,868**	**-101**	**-5.1**
Total logistic cost	**147,770**	**146,471**	**-1,299**	**-0.9**
Sales Tax	25,415	26,303	888	3.5
Freight - Factory to Warehouse	58,352	58,352	-	-
Freight - Warehouse to Warehouse	13,206	9,100	-4,106	-31.1
Freight - Warehouse to Customer	50,797	52,716	1,919	3.8

Source: Author.

As there was no change in the sea route in relation to Scenario 0, the freight between factory and warehouse did not change. Sales tax increased by 3.8% in Scenario 2 in relation to Scenario 0, since, with the closing of 4 TPs, customers started to be supplied directly from shipping warehouses and, therefore, optimization did not take advantage of routes with the lowest effective tax rates as occurred in Scenario 0.

In addition, could be observed that the CO_2 cost in Scenario 2 (R$ 1,868 million) represented 1.28% of the total logistic cost (R$ 146,471 million). Thus, there was reduction in the representativeness of the CO_2 cost in relation to result presented in Scenario 0 (1.33%).

Due to the imposition of restraints, the distribution flows in Scenario 2 were similar to the network flows in Scenario 0, which made sales tax not the main cost-reducing factor. The network configuration in Scenario 2, with maintenance of Tianguá TP and Imperatriz TP, is demonstrated in Figure 3.

It could be observed in Table 16 that the demand met in Scenario 0 by Manaus TP (4,201 tons) and Santarém TP (5,824 tons) migrated in Scenario 2 to Belém warehouse (which increased 10,025) - similarly to result of Scenario 1, which reduced costs by means of the closure of the same TPs.

Table 16. Scenario 2 vs. Scenario 0: demand by origin.

Origin	Scenario 0 (ton)	Scenario 2 (ton)	Variation (ton)	Variation (%)
Belém warehouse	116,705	126,730	10,025	8.6%
Manaus TP	4,201	-	-4,201	-100.0%
Santarém TP	5,824	-	-5,824	-100.0%
Recife warehouse	157,503	168,063	10,559	6.7%
São Luís warehouse	64,150	72,826	8,675	13.5%
Imperatriz TP	6,474	6,474	0	0.0%
Maceió TP	10,559	-	-10,559	-100.0%
Teresina TP	8,675	-	-8,675	-100.0%
Tianguá TP	1,697	1,697	-	0.0%
Canoas warehouse	63,900	63,900	-	0.0%
Rio de Janeiro warehouse	212,405	212,405	-	0.0%
Total	**652,094**	**652,094**	-	**0.0%**

Source: Author.

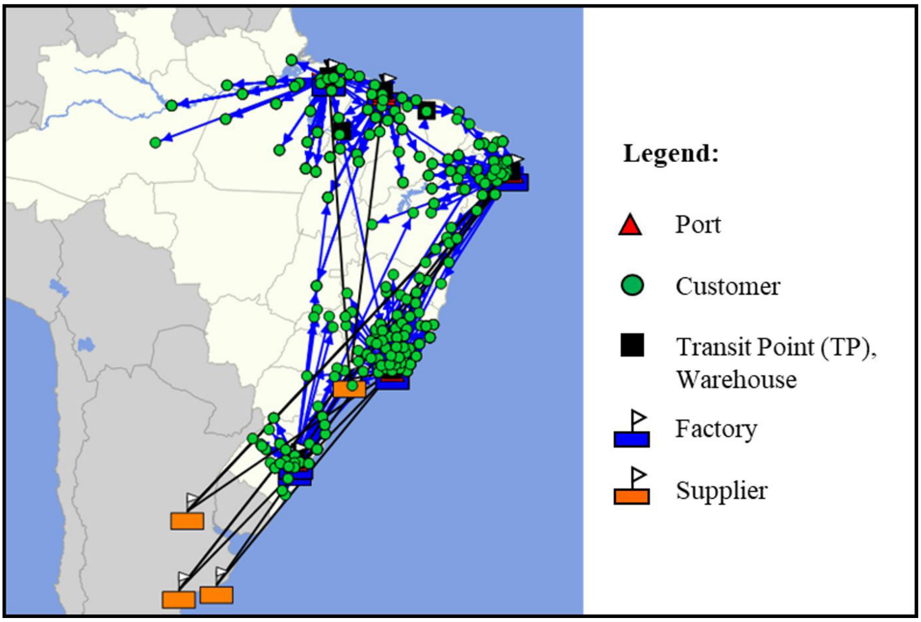

Figure 3. Distribution flow: Scenario 2. Source: Author.

Further, demands met in Scenario 0 by Teresina TP (8,675 tons) migrated to São Luís warehouse (which increased by 8,675 tons in Scenario 2) and the demand of Maceió TP (10,559 tons) migrated to Recife Warehouse (which increased by 10,559 tons ton). In addition, it was observed through the result of Table 16 that it was possible to keep up with the demands of all customers (652,094 tons).

Therefore, this stage of the research confirms that it was possible to achieve eco-efficiency of the distribution network by closing 4 TPs. In this way, it was possible to find a configuration that would achieve the aims of total and CO_2 cost reductions simultaneously.

4.4. Comparing the results of scenarios

This section is devoted to the analysis of cost-effective (Scenario 1) and eco-efficient scenarios (Scenario 2) in relation to the base scenario (Scenario 0).

Table 17 presents the comparison of total logistic costs in relation to CO_2 emission (in cost and tons) of Scenario 1 and Scenario 2 in relation to Scenario 0.

Table 17. Comparison of scenarios: total logistic and CO_2 cost.

Item	Scenario 0 (base)	Scenario 1 (cost-effective)	Scenario 2 (cost-effective)	Variation 1*	Variation 2**
CO_2 cost (R$ thousand)	1,969	2,462	1,868	493	-101
Total logistic cost (R$ thousand)	147,770	142,835	146,471	-4,935	-1,299
tCO_2	105,106	134,415	99,736	26,309	-5,370

*Variation 1: difference between results of Scenario 1 (cost-effective) and Scenario 0 (base); **Variation 2: difference between results of Scenario 2 (eco- efficient) and Scenario 0 (base). Source: Author.

It is noteworthy that although the eco-efficient scenario achieved reduction in total logistics costs of R$ 1,299 million, the best financial result is reached in Scenario 1, which reached reduction of R$ 4,935 million, compared to Scenario 0. Thus, to be financially attractive for the company to implement the eco-efficient scenario, financial compensation of the total logistic cost difference between Scenario 1 and Scenario 2 would be necessary (amount of -R$ 3,636). To achieve this aim, the company should sell the carbon credits generated in the eco-efficient scenario (-R$ 101 thousand) starting from R$ 36.00/tCO_2.

Table 18 shows the comparison of results of Scenario 1 and Scenario 2, regarding total logistic cost and CO_2 cost in relation to Scenario 0.

Table 18. Comparison of scenarios: cost and service.

Item	Scenario 0 (base)	Scenario 1 (cost-effective)	Scenario 2 (eco-efficient)
Active TPs (#)	6	4	2
Total logistic cost (R$ thousand)	147,770	142,835	146,471
CO_2 cost (R$ thousand)	1,969	2,462	1,868
Total logistic cost (R$ thousand)	100.0%	96.7%	99.1%
CO_2 cost (R$ thousand)	100.0%	125.1%	94.9%

Source: Author.

The existence of trade-off between total logistic cost and CO_2 cost (Figure 4) was not evidenced, because with the development of Scenario 2, it was possible to find a scenario that demonstrated the concomitant achievement of both objectives. Thus, the demonstration of the feasibility of an eco-efficient scenario in an academic research based on empirical data contributes to the clarification to academicians and logistics managers.

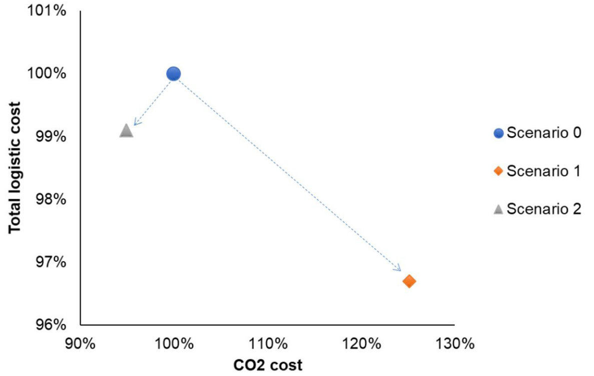

Figure 4. Trade-off: total logistic cost vs. CO_2 cost. Source: Author.

5. Conclusion and recommendations

When applying optimization in a real distribution network in a company that manufactures and sells wheat flour in Brazil, this work answered the research question and showed differences in the distribution network design by including environmental variable CO_2 cost in relation to the distribution network design with the traditional goal of reducing costs.

In the cost-effective scenario, it was possible to reduce costs; however, there was an increase in CO_2 emissions, because in Brazil, ICMS makes the delivery route not the shortest - the transportation cost is increased, but the total logistic cost is compensated by the reduction of tax cost (Frias et al., 2013).

However, in the eco-efficient scenario, there was reduction of CO_2 emissions, but the network did not obtain the same cost reduction generated by the cost-effective scenario. Therefore, for this alternative to be feasible for the company, the saved CO_2 should be converted into revenue through the sale of carbon credits. This alternative is feasible provided that the sale of these carbon credits reaches the price of R$ 36.00 per ton.

In this sense, this research allowed measuring the economic and financial impact that the CO_2 cost arising from transportation (through fuel consumption) and manufacturing activities (electricity consumption) has on the distribution network design under study.

In addition, the research corroborated the work of Colicchia et al. (2015), since it was possible to prove the existence of an alternative configuration of facilities by reducing the amount of TP, which simultaneously reduces the total cost and the CO_2 cost.

In this way, this work contributed to academicians and logistics professionals, as it demonstrated how the configuration of facilities (through TP) was impacted when adopting the goals of reducing total logistic cost and CO_2 cost simultaneously. In addition, this research presented a framework that includes "environmental variables", represented by CO_2 and particulate matter emissions.

A limitation of this study is the fact that it has not addressed the understanding of the result of customer service variation in the generation of sales revenue, which may be a relevant factor for decision making on the closure or not of distribution network facilities.

In addition, since ICMS has been shown to have an impact on the total logistic cost, future studies should address the understanding of this tax in the network design regarding the economic-financial or logistical aspects and also regarding the environmental sustainability bias for the distribution network design.

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