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SUSTAINABLE SUPPLY CHAIN NETWORK DESIGN OF THE COLOMBIAN DAIRY SECTOR

LOGISTICS ENGINEERING & SUPPLY CHAIN DESIGN COURSE

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ABSTRACT

The Colombian dairy sector encounters significant challenges in successfully entering the international market and. This comprehensive approach ensures an efficient, cost-effective, and environmentally friendly supply chain network for dairy products. To achieve our objectives, we consolidate within the domestic market. Our project aims to optimize the entire supply chain for dairy products by determining the appropriate locations and capacities for processing and distribution facilities evaluated several methods and discovered that integrating Mixed Integer Linear Programming with the Global Criterion approach effectively addresses the multi-objective problem in sustainable supply chain network design. This method simultaneously considers economic, environmental, and social dimensions. Our findings indicated that an increase in production flow contributes to the rise in total costs, environmental impacts, and social benefits. Furthermore, sensitivity analysis conducted by varying facility costs, showed that fluctuations in business costs significantly affect environmental and social values. Ignoring environmental factors can lead to substantial harm and increased business risk costs. Similarly, cost factors indirectly influence societal aspects such as employee issues and salaries. This model is a valuable example for strategists, offering insights into the internal factors of the issue that enables them to develop an appropriately comprehensive and sustainable supply chain plan.

Keywords*:* sustainable supply chain network design, dairy sector, multi-objective problem, Global Criterion, Mixed Integer Linear Programing.

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Finally, the dedicated contribution of each team member to the project should be acknowledged.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

1.1 Background

1.1.1 Sustainable supply chain network design

Supply chain design is a working model that outlines the structure and network of a supply chain to estimate the time and costs involved in bringing goods to market.

Since supply chain design is a critical part of any company's operation process, it entails making essential decisions about the various stages involved. The goal of this design is to optimize the flow of goods and ensure maximum efficiency. When achieved through a well-considered design, this translates to profits for the company.

To make sound decisions, the company must consider many important factors. These include suppliers' location, potential plant locations, infrastructure availability, transportation options, and the accuracy of forecasting of customer requirements. Additionally, specific supply chain models may require further consideration. All this analysis informs the decision of facility location, with the aim of ensuring timely delivery to customers at the lowest cost.

However, a sustainable supply chain goes beyond just the economic aspect. It also pays close attention to environmental and social practices at every stage, prioritizing the safety of people and the environment across the entire chain. In essence, this means an organization promotes not only economic efficiency, but also environmental and social responsibility within its own operations and those of its suppliers.

Environmental standards encompass issues like environmental degradation, deforestation, greenhouse gas emissions, pollution, and water security. Social standards, on the other hand, focus on areas such as working conditions, forced labor, fair labor practices, health, and safety.

1.1.2 Colombian dairy sector

As pointed out by Tordecilla-Madera et al. (2017), the Colombian dairy sector faces a series of challenges regarding its successful entry to the international market and consolidation within the internal market. Colombian National Council for Economic Policy (CONPES) has introduced policies for improving this sector's competitiveness (CONPES, 2010), through CONPES document No. 3675 that is aimed at improving the Colombian dairy sector's competitiveness by developing strategies whose goal is to reduce production costs, increasing productivity, promoting collaborative schemes, and strengthening the sector's institutional administration. Such policy also sought to improve sanitary and safety measures for strengthening competitiveness, improving public health, and gaining access to national and international markets; analysis has thus been undertaken at each level in the production chain, including associations representing the production, storage, transportation, manufacturing, and commercialization sectors, as well as those entities responsible for inspecting production, overseeing and controlling the processes so involved, and the sale of milk and other dairy products. In this project, the information and data are inspired from the case studies of Moreno-Camacho et al. (2022) regarding a regional dairy supply chain network in the central region of Colombia.

1.1.3 Additional background, gaps between current research and previous studies

Traditional research focused on the economic aspect of supply chain design until the release of Sustainable Development Goals (SDGs) by the United Nations, moving the supply chain design research toward addressing sustainability.

Early sustainability research ditched the environmental issue of supply chain design models. But as time passed, they found new approaches to the sustainability problem: to consider not just the environmental aspect, but also economic and social factors, which is also our way of approaching the topic.

As a result, the number of publications addressing environmental and social assessments of the supply chain design problem has rapidly increased over the last several years. However, these studies were proved to lack societal factor evaluation into the design of sustainable supply chains. In other words, the published studies assessed one or two dimensions of the theoretical sustainability model, while the model contains three. The lack of societal factors and of case studies, the need of conceptual model, and metrics for sustainable evaluation are the main gaps identified in the literature review below.

1.2 Problem Statement

In developing countries, the dairy industry is recognized as a number of small and medium-sized milk suppliers and records a limited number of purchasers in the processing level, leading to a substantial imbalance in the sector. Simultaneously, the dearth of cohesive farmer associations exacerbates this disparity, leaving individual producers at a significant disadvantage when engaging in negotiations with larger entities.

Specifically in Colombia, the situation has been exacerbated following the infiltration of imported milk into the local market subsequent to the Free Trade Agreement. In 2021, milk imported from the US constituted a staggering 69% of the total imported milk volume, further challenging the viability of domestic producers. Besides, the current capacity of Colombian factories only processes 48% of the total milk produced on farms, intensifying competition among smallholders. Those farmers unable to secure processing opportunities are compelled to resort to informal collectors, subjecting them to increased risks and accepting prices below the market rate for their milk. As a result, wages paid for workers also get lower, aggravating the income imbalance between rural and urban areas. The ramifications of these challenges extend beyond the economic sphere, permeating into the social fabric of Colombian society, and acting as a social factor hindering the overall development of Colombia.

In terms of sustainability, because the components as farms and factories are not well organized and not well equipped, the whole system has not reached its optimal capacity. Consequently, the number of facilities increases, coupled with construction activities devoid of careful considerations regarding location and scale factors, exacerbates environmental pollution, consequently impacting the well-being of individuals within affected communities. Simultaneously, distribution planning also has effects on returnability and profitability of enterprises.

1.3 Objectives of the study

Our project aims to identify the optimal placement and capacity of processing and distribution facilities, as well as select suppliers from a pool of potential candidates, determine transportation modes between suppliers and plants, plants and distribution centers, distribution centers and retailers. Then, we continue to define the quantity of product transferred between facilities to meet the demand for dairy products across various regions. Our model considers economic, environmental, and social factors. Economically, the objective is to minimize total network costs, encompassing facility location costs, processing costs, and transportation expenditures. The environmental dimension is assessed by quantifying CO2e emissions stemming from production and transportation activities. Social objectives aim to maximize the positive social impact generated by employing individuals at processing facilities and sourcing milk from local farms.

1.4 Scope and Limitations

1.4.1 Scope

- Consider the design of a single-period, four-tier supply chain, consist of suppliers (collecting centers and farmers), processing plants, distribution centers and retailers.
- Evaluate original data including 29 suppliers, 10 retailers, 4 processing plants, 6 distribution centers, and 3 types of trucks (light, medium and heavy). Variations in data sets will be used to comprehensively assess each scenario.
- Distances: suppliers to plants > plants to distribution centers > distribution centers to retailers.

- Consider only plant and distribution center opening costs, raw material costs, and processing costs.
- Unemployment rate based on the global percentage of unemployed individuals.

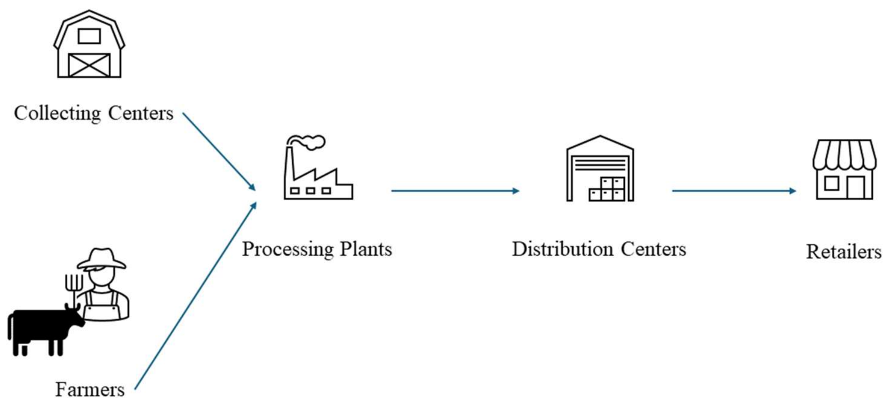


Figure 1-1. Dairy supply chain network

1.4.2 Limitations

- The data source was inaccessible, preventing us from validating the results presented in the paper.
- The accessibility of different transportation modes to vendors or retailers was random.
- Inaccurate constraints in the original paper led to skewed results.
- Due to a lack of knowledge in solving multi-objective problems using the original paper's method, we applied an alternative method learned during our studies.
- The performance of this model is only reliable within the specific dataset considered below.

1.5 Assumptions

- Inventory status at each location over time is not evaluated.
- Suppliers are given equal priority when receiving orders.
- All customer demand is fully met.
- The added value factor is always equal to 1.

1.6 Project planning

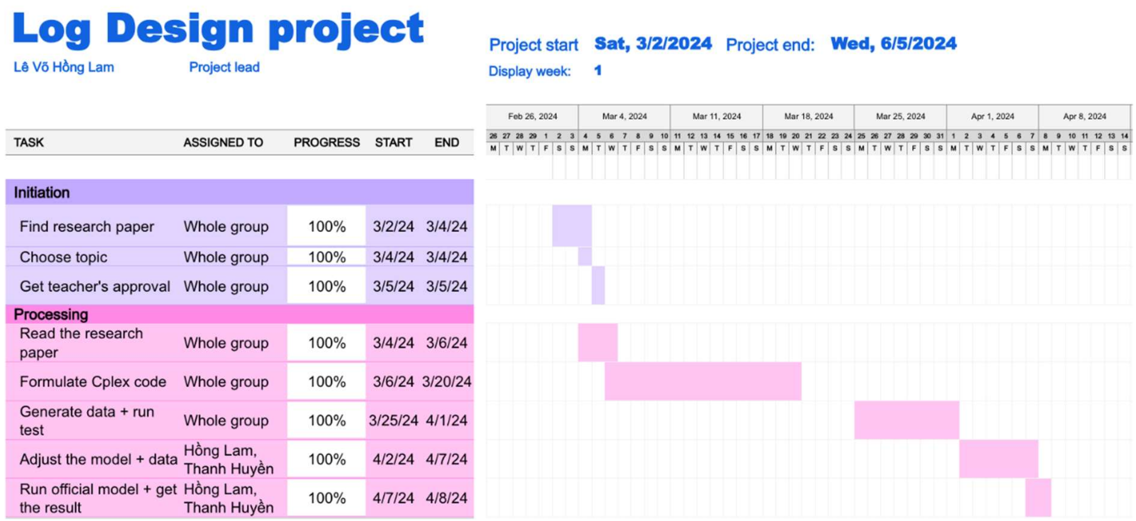


Figure 1-2. Gantt Chart - Initialization and Processing phases

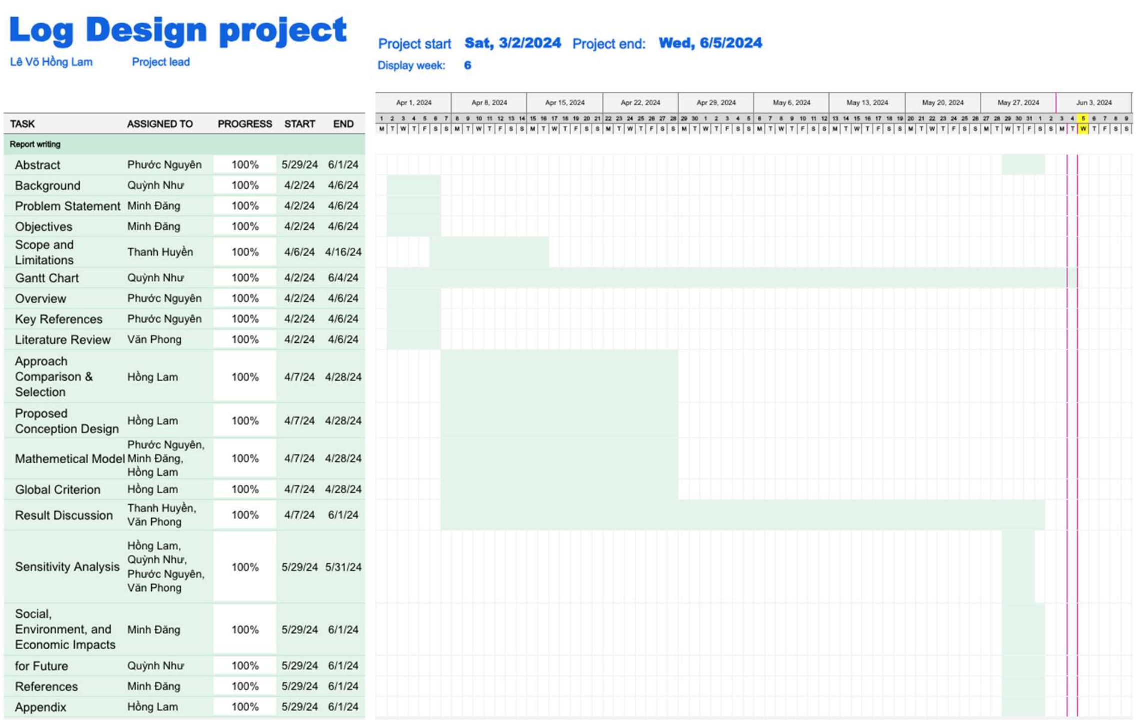


Figure 1-3. Gantt Chart - Report Writing phase

CHAPTER 2 RELATED WORK

2.1 Overview

In recent years, the word "sustainability" has become increasingly popular. However, it is difficult to implement and satisfy three criteria: economic, environmental, and social. In order to accomplish all goals, everything should be researched in detail by some related works. Therefore, the data required for the paper was also looked for and thoroughly evaluated for inclusion in the research. The information needed for the article was also searched and carefully considered for inclusion in the study. Information taken from research will ensure the accuracy and depth of the problem because research articles often focus on a certain subject or problem and the conclusions from there will be applied to research to clarify the problems or suggest solutions. Each stage of the project is completed depending on the information found in the papers. Research indicates that the dairy industry is understudied and needs to be explored. In addition, other research was also absorbed from scientific articles, contributing to the feasibility of the project. At the stage of modeling and finding solutions, research articles have also proposed solutions with many different perspectives. Each reference used allows readers to evaluate the development of ideas, verify states, and explore deeper into the discussion, thereby increasing the overall quality and reliability of the project. Their collective contribution not only broadens the discussion in academia but also guides the process. Well-researched reference materials are essential to the problem-solving process from the first discovery to the actual application of the solution.

2.2 Literature Review

One of the biggest contributors to greenhouse gas emissions in industrialized nations is the dairy industry, which is a part of agriculture, releasing a plenty of toxic gasses, harming wastes and tiny substances. However, this is especially true in emerging nations, where low productivity poses a threat to natural ecosystems because of factors including rising food demand.

Sustainable supply chain network design (SSCND) was introduced by Chardine-Baumann & Botta-Genoulaz (2014) to indicate the evaluation of environmental and social factors, concerning supplier selection, facilities location, production processes, technological choices, and transportation. Chardine et al(2014) showed the criteria to be classified in the terms of use of resources, pollution, biodiversity threats, work conditions, human rights actions compliance with child labor, gender equity, among others (Chardine-Baumann & Botta-Genoulaz, 2014). Awere to environmental factors, based on available criteria, they developed into the Multi-Objective Optimization Problem (MOOP) (Mota et al., 2018). Focusing on hybrid-objective models considering economic and environmental performance assessment, researchers show the math model to analyze deeper about sustainable supply chain design. For instance, some paper such as a novel linear programming formulation with a multi-objective optimization (cost and environmental objectives) Rohmer et al. (2019), problems with complex interrelations between process dynamics, capacity evolution, and dynamic setups require further investigation by Dolgui et al. (2019).

While the previous paper was just dedicated to life cycle analysis and considered food production and consumption decisions, some factors are currently added in the system, that is environmental factors. A three stage production–distribution model by Cuong et al. (2021). There are several factors such as a land-use assessment for the location of crops, processing facilities, warehouses, forests, and renewable energy production fields and the use of renewable energies or calculates the equivalent CO2 emissions generated by the orchard production, pasteurization process, bottling, and transportation activities. To fulfill the model, from Multi-Objective Optimization Problem (MOOP) (2018) made into a nonlinear multi-objective model or a Genetic Algorithm and Multi-criteria Decision-Making to make multiple choices and flexible scenarios. They analyzed weighted matrices to find the closest feasible solution to a reference point in some factor in CO2, transportation, worth values and labor cost and the biorefinery supply chain network design to consider social aspects.

These papers contributed significantly to the sustainable supply chain design network. While papers during the middle of 2010-2020 just focused on economy and supply chain factors, environmental factors have added in the network to make a three-stage supply chain in ten years recently. Besides, the model from MOOP made into a specific model using non-linear matrix, it allows the flexible scale for multiple objectives. In this paper, the author based on previous contributions, they used an augmented ε-constraint method to solve the problem and the social benefit is estimated as a weighted sum of the different social impacts of different types of jobs created in different locations. A multi-objective model is made using the method of weighted metrics and develops the design of a closed-loop supply chain, including the saved costs by the recovery activities and the cost of CO2e emissions are accounted for in the environmental dimension. In the model, the minimization of costs and impacts via CO2e emission are considered to the performance in the economic and the environmental dimension, respectively observed the forest mill, biorefinery operation, biomass and biofuel 123 Annals of Operations Research transportation, and energy generation are considered to calculate CO2 equivalent emissions (CO2e) and the social benefit to solve sustainable supply chain design based on previous contributions.

However, in the context of sustainability at supply chain level, there are some inherent inconveniences related to the application of a priori and a posteriori method. There is a difficulty of selecting the weights to cope with problems of scale, since the objectives have different magnitudes. Moreover, it is expected from the decision maker to have some knowledge about the interdependencies of the objectives and the feasible objectives values. However, sustainability encompasses a broad set of requirements, many of them outside of the focus of classic business decisions, and the expected results coming from the appropriation of sustainable practices might be difficult to estimate. Therefore, there is no certainty in the accurate selection of weights by the decision maker. Third, the visualization of the set of Pareto optimal solutions is not easy when the problem considers three or more objectives.Therefore, there is no certainty in the accurate selection of weights by the decision maker. Furthermore, considering the rise in the definition of national and continental plans to the reduction of GHG emissions and the improvement of social health and living conditions, it makes sense to establish expected values to the sustainability objectives considering information from outside the company in the future research.

2.3 Key References

To finalize the project, numerous sources were researched and utilized, with each document contributing uniquely to the research work. The most important instance is the article "Sustainable supply chain network design: a study of the Colombian dairy sector" that was released in January 2022 by the Annals of Operations Research. This specific article is crucial to the project and is a primary source of information. It served as a "magnetic needle" for the concept of the project as well as a guide for the rest of the assignment. It provides a deep understanding into the severity and present real stage of the problem, provides specific information essential for recognizing the issue, and makes recommendations for potential solutions. The article serves as an important foundation in resolving problems. Making use of the information and mathematical models provided in the article, programming operations were executed to derive the optimal solution. The key references have played an indispensable role in developing the ongoing assignment.

CHAPTER 3 METHODOLOGY

3.1 Approach Comparison and Selection

Table 3-1. Advantages and disadvantages of considered approaches

Approaches	Advantages	Disadvantages
Mixed Integer Linear Programming	Providing a global optimal solution and the possibility of solving large scale problems. Allowing for modeling complex decision-making scenarios involving both discrete and continuous variables	High mathematical complexity in their formulation and the linearization of non-linear problems, as well as the high computational time required in mid- and large-scale applications
Non-linear Programming	Handling complex, real-world relationships between variables that are not easily expressed as linear functions.	Interactions between objectives can be highly nonlinear, complicating the optimization process. Requiring intensive coding techniques to solve such as Python
Global Criterion	Straightforward and easy to implement. Requiring less time and effort to evaluate alternatives and reach a decision	Global criterion decision-making can oversimplify complex decision problems by reducing them to a single dimension. This oversimplification may obscure important nuances or interactions among different criteria, leading to inadequate understanding and analysis of the decision problem.

Chebyshev Goal Programming	Establishing a good balance between the accomplishment of multiple goals. Do not consider bias or preferences among the objectives	Not be well-suited for highly complex, multi-dimensional problems with numerous interrelated objectives and constraints
Genetic Algorithm	Very flexible, more efficient for large-size problems and being able to use non-linear constraints in models closer to the real functioning	The achieved optimal solution cannot be the global optimum. All the levels of optimization (economic, environment, social) cannot be integrated and optimized together. Time-consuming running.

According to the analytic table above, it is obvious that Mixed Integer Linear Programming is a powerful mathematical optimization technique used to model and solve decision-making problems with discrete variables. By integrating Mixed Integer Linear Programming into the solution framework, we can accurately capture the complexities of supply chain design, including facility locations, transportation modes, and product flows. In addition, sustainable supply chain network design involves conflicting objectives, including minimizing costs, reducing environmental impact, and enhancing social benefits. The Global Criterion approach enables the simultaneous consideration of these objectives by aggregating them into a single composite measure or utility function. This allows us to explore trade-offs and identify Pareto-optimal solutions that represent the best compromise between conflicting goals.

In conclusion, this work decided to select the final approach is combining Mixed Integer Linear Programming and Global Criterion. This strategy aims to address the multi-objectives problem in sustainable supply chain network design considering economic, environment, and social dimensions simultaneously.

3.2 Proposed Conception Design

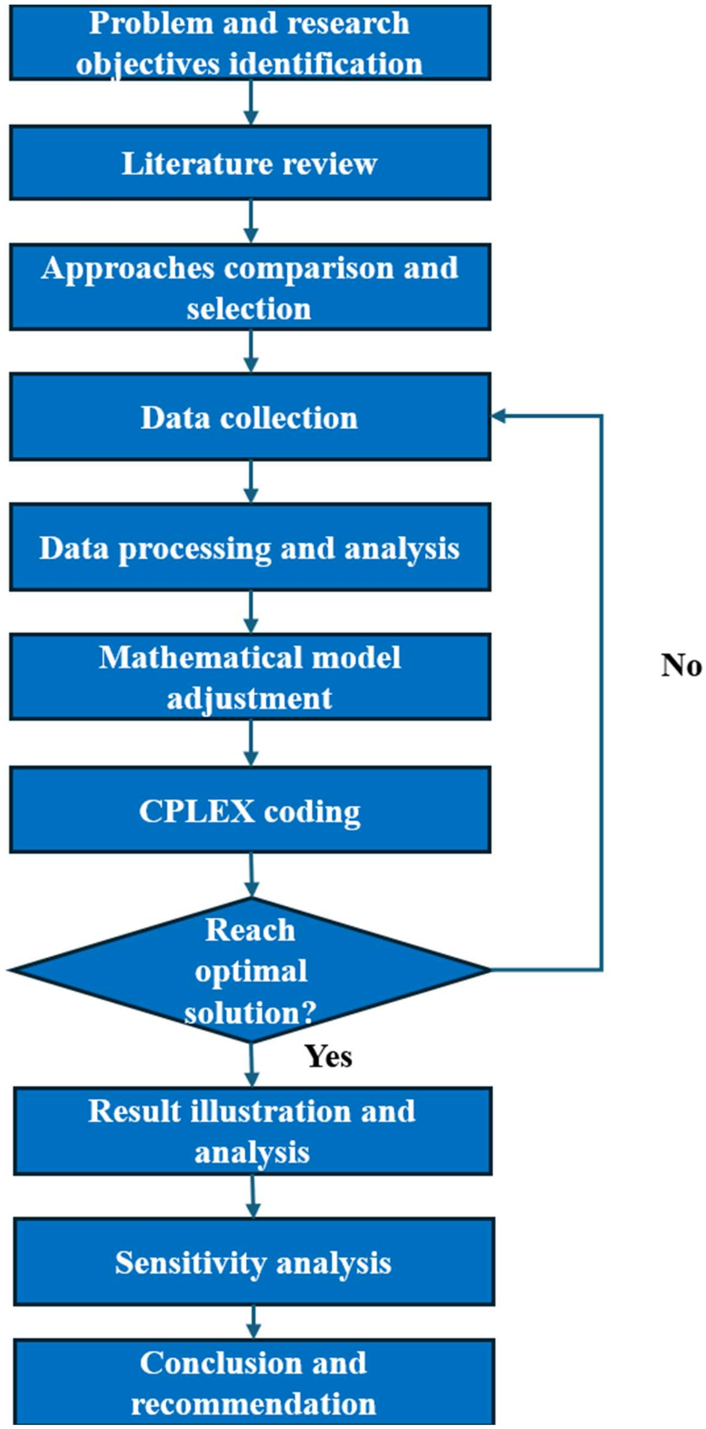


Figure 3-1. Flowchart of proposed concept design

The flowchart outlines a structured research and analysis process with several main steps. Initially, the problem is defined, and clear research objectives are established within the field of sustainable supply chain network design. Subsequently, we conducted a comprehensive search for the key reference which aligns closely with our research problem and synthesize numerous relevant research for literature review using academic databases such as Google Scholar and ResearchGate. In the approaches comparison and selection step, various methodologies are evaluated and selected based on criteria including feasibility, suitability and expected outcomes. Following that, necessary data is gathered through different reliable sources from the key reference and relevant research papers. During this process, an issue was identified in the mathematical model from the key reference, where all suppliers ship a quantity of zero to the destination. Consequently, we modify the mathematical model to ensure that any supplier delivering raw milk to processing plants or collecting centers must have a corresponding shipped quantity. The CPLEX coding step involves implementing the mathematical model using IBM ILOG CPLEX 12.9 to solve the optimization problem. The expected outcomes in this step include the total cost, CO2 emissions, social benefits, number of suppliers utilized and the corresponding shipment quantities, the locations of opened processing plants and distribution centers. At the decision point, the results are assessed to determine whether they meet the predefined criteria. If not, data adjustments are made and the process iterates. Upon achieving the optimal solution, results are illustrated and analyzed, and a sensitivity analysis is conducted to examine the impact of changing facility costs (fixed cost of opening processing plants and distribution centers). Finally, the conclusion and recommendation are proposed by summarizing the key research findings, providing actionable insights, and suggesting directions for future works.

CHAPTER 4 SOLUTION DEVELOPMENT

4.1 Mathematical model formulation

4.1.1 Notations

4.1.1.1 Set of indices

S = F ∪ C: set of suppliers, including both farmers (F) and collecting centers (C)

P: set of potential locations to install processing plants

D: set of potential zones to locate distribution centers

R: set of retailers

M: set of available transportation types from farmers to processing plants

T: set of available transportation types from processing plants to distribution centers and retailers

CP: set of capacity options for processing plants P

CD: set of capacity options for distribution centers D

4.1.1.2 Parameters

LC_{cp}: fixed cost of opening a processing plant with capacity cp ∈ CP

LC_{cd}: fixed cost of opening a distribution center with capacity cd ∈ CD

Pr_s: Price of raw milk per ton at supplier s ∈ S

PC: processing cost per aggregated unit at processing plants

$Dist1_{sp}$: Distance in km between the supplier s ∈ S and the processing plant p ∈ P

$Dist2_{pd}$: Distance in km between the processing plant p ∈ P and the distribution center d ∈ D

$Dist3_{dr}$: Distance in km between the distribution center d ∈ D and the retailer r ∈ R

TC_t: transportation cost per ton of milk in transport t ∈ T

CS_s: maximum supply capacity of supplier s ∈ S

CM_{cp}: production capacity of a processing plant with capacity cp ∈ CP

Mop: maximum desired occupation rate of processing facilities

Mup: minimum allowed operation rate for processing facilities

CDC_{cd}: storage capacity at distribution center with capacity cd ∈ CD

$Mudc$: minimum allowed operation rate for distribution center

Dem_r: Demand of retailer r ∈ R

Trv_{sm}: equal to 1 if vehicle type m ∈ M have access to supplier s ∈ S

Trv_{rt}: equal to 1 if transport type t ∈ T have access to retailer r ∈ R

$Fcons_m$: Fuel efficiency of vehicle type m ∈ M kilometers per gallon

$Fcons_t$: Fuel efficiency of vehicle type t ∈ T kilometers per gallon

Cap_m: Capacity in tons of milk of vehicle type m ∈ M

Cap_t: Capacity in tons of milk of vehicle type t ∈ T

Emfc: CO2e emission produced per consumed gallon of fuel

Empr: CO2e emissions produced per ton of milk processed at the plant

Ur_p: Employment rate at the potential location of processing plant p ∈ P

φ_s: Added value factor of the region of supplier s ∈ S

4.1.1.3 Decision variables

x_{spm}: quantity of litters of raw milk shipped from supplier s ∈ S to processing plant p ∈ P delivered in vehicle type m ∈ M

x_{pdt}: quantity of aggregated units of processing milk delivered from processing plant p ∈ P to distribution center d ∈ D by vehicle type t ∈ T

x_{drt}: quantity of aggregated units of processing milk sent from distribution center d ∈ D to retailer r ∈ R by vehicle type t ∈ T

y_s: equal to 1 if supplier s ∈ S is ready to supply any quantity of raw milk to processing plants or collecting centers, 0 otherwise

y_{pcp}: equal to 1 if a processing plant is in potential zone p ∈ P with capacity cp ∈ CP

y_{dcd}: equal to 1 if a distribution center is open in potential zone d ∈ D with capacity cd ∈ CD

4.1.2 Mathematical Model

There are three objectives functions that need to be achieved

Minimize

$$Z_1 = \sum_{p\in P, cp\in CP} LC_{cp} * y_{pcp} + \sum_{d\in D.cd\in CD} LC_{cd} * y_{dcd} + \sum_{s\in S, p\in P, m\in M} Pr_s * x_{spm} + \sum_{p\in P, d\in D, t\in T} PC * x_{pdt} + \sum_{p\in P, d\in D, t\in T} TC_t * x_{pdt} + \sum_{d\in D, r\in R, t\in T} TC_t * x_{drt} \quad (1)$$

The first objective function is to minimize the total cost (Z_1), which is the sum of total cost of opening processing plants and distribution centers, total cost of purchasing raw milk, total processing costs, total transportation cost of processing milk delivered from processing plant to distribution center and transportation cost of processing milk sent from distribution center to retailer.

Minimize

$$Z_2 = \sum_{s\in S, p\in P, m\in M} \frac{Emfc * Dist1_{sp} * x_{spm}}{Cap_t * Fcons_t} + \sum_{d\in D, p\in P, t\in T} \frac{Emfc * Dist2_{pd} * x_{pdt}}{Cap_t * Fcons_t} + \sum_{d\in D, r\in R} \frac{Emfc * Dist3_{dr} * x_{drt}}{Cap_t * Fcons_t} + \sum_{d\in D, p\in P, t\in T} Empr * x_{pdt} \quad (2)$$

The second objective function is to minimize emissions emitted from the production and transportation activities (Z_2). It is the sum of total CO2 emission produced when transport between suppliers and processing plants, between processing plants and distribution centers, between distribution centers and retailers and total CO2e emissions produced of milk processed at the plant.

Maximize

$$Z_3 = \frac{\sum_{p \in P, cp \in CP} Ur_p * y_{pcp}}{\sum_{p \in P} Ur_p} + \frac{\sum_{s \in S} \varphi_s * y_s}{\sum_{s \in S} \varphi_s} \tag{3}$$

The third objective function aims to maximize the social advantage associated with job opportunities in located processing facilities and selecting a farmer as a supplier.

Demand and flow conservation constraints

$$\sum_{d \in D, t \in T} x_{drt} = Dem_r \quad r \in R \tag{4}$$

Constraint (4) makes sure the total quantity of aggregated units of processing milk sent from distribution centers to retailers by vehicle type t ∈ T is equal to demand of retailers.

$$\sum_{s \in S, m \in M} x_{spm} = \sum_{d \in D, t \in T} x_{pdt} \quad p \in P \tag{5}$$

Constraint (5) makes sure total quantity of litters of raw milk shipped from suppliers to processing plants delivered in vehicle type m ∈ M is equal to total quantity of aggregated units of processing milk sent from processing plants to distribution centers by vehicle type t ∈ T.

$$\sum_{r \in R, t \in T} x_{drt} = \sum_{p \in P, t \in T} x_{pdt} \quad d \in D \tag{6}$$

Constraint (6) makes to total quantity of aggregated units of processing milk sent from distribution centers to retailers by vehicle type t ∈ T is equal to quantity of aggregated units of processing milk delivered from processing plants to distribution centers by vehicle type t ∈ T.

Facilities capacity constraints

Constraints (7) to (13) are adjusted to give an accurate result when the binary decision variables show whether any quantities shipped and opened plants and DCs.

$$BigM(y_s - 1) + \sum_{p \in P, m \in M} x_{spm} \le CS_s \qquad s \in S \tag{7}$$

Constraint (7) ensures the total amount of raw milk shipped from suppliers to processing plants does not exceed the maximum capacity of suppliers if suppliers deliver any products.

$$BigM\left(y_{pcp} - 1\right) + \sum_{d \in D, t \in T} x_{pdt} \le CM_{cp} * Mop \qquad p \in P, cp \in CP \tag{8}$$

Constraint (8) ensures the total amount of processing milk shipped from processing plants to distribution centers less than or equal to maximum capacity and maximum occupation rate of processing plants.

$$BigM(y_{dcd} - 1) + \sum_{p \in P, t \in T} x_{pdt} \le CDC_{cd} \qquad d \in D, cd \in CD \tag{9}$$

Constraint (9) prevents the total amount of processing milk shipped from processing plants to distribution centers from being over the maximum capacity of distribution center.

Transport availability constraints

$$BigM(y_s - 1) + \sum_{p \in P} x_{spm} \le CS_s * Trv_{sm} \qquad s \in S, m \in M \tag{10}$$

Constraint (10) ensures the total amount of raw milk shipped from suppliers to processing plants less than or equal to maximum capacity of suppliers and vehicle m ∈ M.

$$BigM(y_{dcd} - 1) + \sum_{d \in D} x_{drt} \le \ CDC_{cd} * Trv_{rt} \quad d \in D, cd\ \in CD, r \in R, t \in T \tag{11}$$

Constraint (11) ensures the total amount of processing milk shipped from distribution centers to retailers less than or equal to maximum capacity of distribution centers and vehicle t ∈ T.

Operational constraints

$$BigM\left(y_{pcp} - 1\right) + \sum_{cp \in CP} CM_{cp} * Mup \ \le \sum_{d \in D, t \in T} x_{pdt} \qquad p \in P, cp \in CP \tag{12}$$

Constraint (12) ensures when a processing plant is opened, it is used at least 80% of its capacity.

$$BigM(y_{dcd} - 1) + \sum_{cd \in CD} CDC_{cd} * Mudc \leq \sum_{p \in P, t \in T} x_{pdt} \quad d \in D, cd \in CD \tag{13}$$

Constraint (13) ensures when a distribution center is opened, it is used more than or equal to 80% of its capacity.

$$\sum_{cp \in CP} y_{pcp} \leq 1 \qquad p \in P \tag{14}$$

Constraint (14) limits one processing plant is opened at each selected region, and one processing plant only has one size.

$$\sum_{cd \in CD} y_{dcd} \leq 1 \qquad d \in D \tag{15}$$

Constraint (15) limits one distribution center is opened at each selected region, and one distribution center only has one size.

Constraints (16) to (19) must be added to make sure that binary decision variables have a value of zero while the key reference lacks them leading to the y_s is always 1 regardless of no shipments.

$$BigM * y_s \geq \sum_{p \in P, m \in M} x_{spm} \quad s \in S \tag{16}$$

$$BigM * \sum_{cp \in CP} y_{pcp} \geq \sum_{d \in D, t \in T} x_{pdt} \quad p \in P \tag{17}$$

$$BigM * \sum_{cd \in CD} y_{dcd} \geq \sum_{p \in P, t \in T} x_{pdt} \quad d \in D \tag{18}$$

$$BigM * \sum_{cd \in CD} y_{dcd} \geq \sum_{r \in R, t \in T} x_{drt} \quad d \in D \tag{19}$$

From constraint (16) to (19), this model is expected that three binary variables will be zeros if there are not any quantities shipped through each location.

4.2 Global Criterion

To solve our multiple-objectives optimization problem, we utilize the Global Criterion approach considering economic, environmental, and social simultaneously.

In this project, Global Criterion is adopted instead of Chebyshev Goal Programming in the key reference. The main advantages of this approach are its simplicity and effectiveness because it does not require the Pareto ranking procedure (Sadeghian et al., 2019). The Global Criterion method addresses the issue by adapting an appropriate compromise function among problem functions. This approach is used to solve the multi-objective problem by considering all objective functions to find the best compromise solution. In this case, the global criterion approach searches for the lowest total cost, the minimum amount of CO2 emissions by manufacturing and transportation activities and provides the maximum social benefits. To achieve this, the Global Criterion method first identifies the compromise function that considers all the individual goals. Then, the sum of the obtained compromise solutions is combined into a comprehensive function as follows (considering p = 1):

$$\boldsymbol{Minimize\ Z} = \left(\frac{\boldsymbol{Z_1} - \boldsymbol{Z_1}^*}{\boldsymbol{Z_1}^*}\right)^{\boldsymbol{p}} + \left(\frac{\boldsymbol{Z_2} - \boldsymbol{Z_2}^*}{\boldsymbol{Z_2}^*}\right)^{\boldsymbol{p}} + \left(\frac{\boldsymbol{Z_3}^* - \boldsymbol{Z_3}}{\boldsymbol{Z_3}^*}\right)^{\boldsymbol{p}}$$

where Z_i^* indicates the value of Z_i in case of single-objective optimization

$\left(\frac{Z_i - Z_i^*}{Z_i^*}\right)^p$ aim (Z_i): minimization and $\left(\frac{Z_i^* - Z_i}{Z_i^*}\right)^p$ aim (Z_i): maximization

CHAPTER 5 RESULTS

5.1 Experimental Design

5.1.1 Input data

Table 5-1. Dataset of low demand

Low Demand						
Data ID	Supplier	Processing plant	Distribution center	Retailer	Demand of retailer	Maximum supply capacity of supplier
1	29	4	6	10	Uniform (40,120)	Uniform (20,35)
2	29	2	6	10	Uniform (40,120)	Uniform (20,35)
3	29	2	5	10	Uniform (40,120)	Uniform (20,35)
4	29	4	5	10	Uniform (40,120)	Uniform (20,35)
5	29	3	6	10	Uniform (40,120)	Uniform (20,35)
6	29	3	5	10	Uniform (40,120)	Uniform (20,35)
7	29	4	7	10	Uniform (40,120)	Uniform (20,35)
8	29	5	6	10	Uniform (40,120)	Uniform (20,35)
9	29	5	7	10	Uniform (40,120)	Uniform (20,35)
10	29	3	7	10	Uniform (40,120)	Uniform (20,35)

We construct the dataset consisting of 29 suppliers in the rural areas, 4 locations for processing plants, 6 locations for distribution centers and 10 retailers located in the capital city, which is inspired from the case studies of Moreno-Camacho et al. (2022) regarding a regional dairy supply chain network in the central region of Colombia. We consider two cases of low demand and high demand. In the case of low demand, customer demands at retailers are generated from a uniform distribution of [40, 120] (Park et al., 2016). The maximum supply capacity of supplier follows uniform distribution of [20, 35]. In terms of high demand, customer demand from retailers is generated from a uniform distribution of [80, 120]. The maximum supply capacity of supplier follows uniform distribution of [30, 50]. After running the first data ID, we adjusted the number of processing plant and distribution center locations based on the utilization of suppliers and the number of locations opened.

For instance, Dataset 2 exhibits a 50% reduction in the number of processing plants, attributable to the underutilization observed in Dataset 1. In a similar vein, Datasets 3 through 10 adjust the number of processing plants and distribution centers, either increasing or decreasing, based on the outcomes derived from the preceding datasets.

Table 5-2. Dataset of high demand

High Demand						
Data ID	**Supplier**	**Processing plant**	**Distribution center**	**Retailer**	**Demand of retailer**	**Maximum supply capacity of supplier**
1	29	4	6	10	Uniform (80,120)	Uniform (30,50)
2	29	2	6	10	Uniform (80,120)	Uniform (30,50)
3	29	2	5	10	Uniform (80,120)	Uniform (30,50)
4	29	4	5	10	Uniform (80,120)	Uniform (30,50)
5	29	3	6	10	Uniform (80,120)	Uniform (30,50)
6	29	3	5	10	Uniform (80,120)	Uniform (30,50)
7	29	4	7	10	Uniform (80,120)	Uniform (30,50)
8	29	5	6	10	Uniform (80,120)	Uniform (30,50)
9	29	5	7	10	Uniform (80,120)	Uniform (30,50)
10	29	3	7	10	Uniform (80,120)	Uniform (30,50)

5.1.2 Procedure

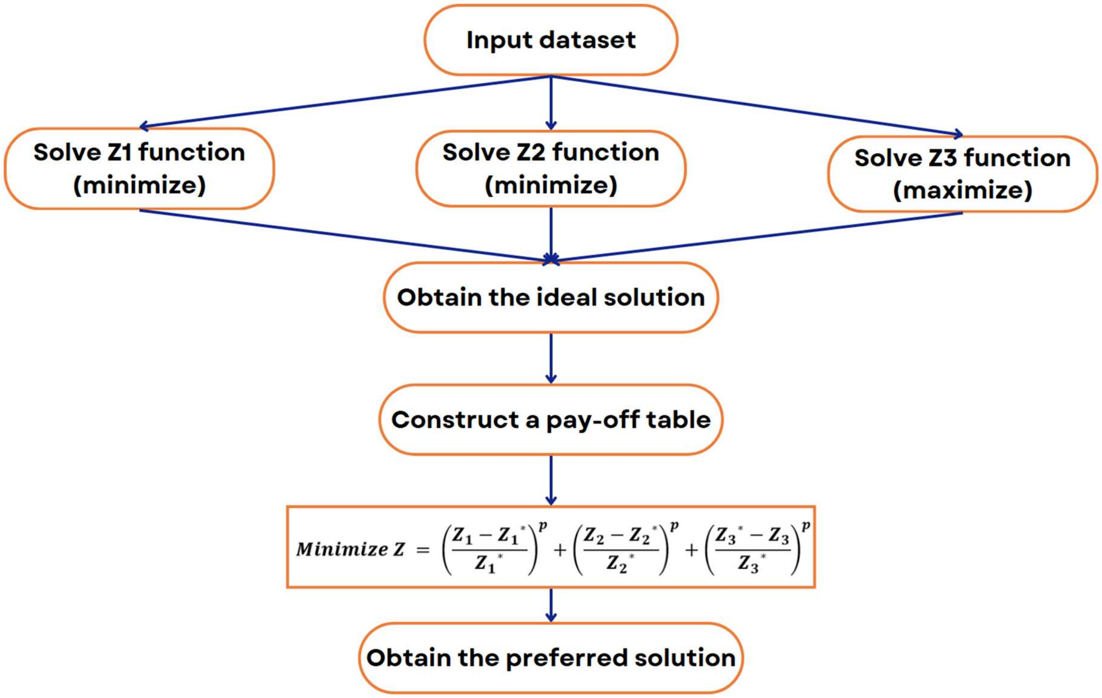


Figure 5-1. Running the mathematical model with multi-objective functions procedure

With 20 datasets representing both low and high demand levels, the process begins by determining the optimal solution for each objective function individually. Next, for each dataset, the minimum values of Z1 and Z2 and the maximum value of Z3 are identified after three iterations. These extreme values are then substituted into the Global Criterion equation to integrate the results. This integration yields the efficient solution, which is referred to as the final solution of the model. This approach ensures that the solution is optimized across all objectives, providing a balanced and effective outcome for the given demand levels.

5.2 Results Illustration and Explanation

This section presents three efficient solutions of triple objectives including total cost, environmental effect and social benefits in terms of low and high demand. In addition, we also consider the total number of suppliers who continuously cooperate with the potential plants in the future and the number of potential plants and distribution centers.

Table 5-3. Result of low demand case for 10 datasets

Low demand Uniform (40, 120) and supply capacity Uniform (20, 35)

Data set	S	P	DC	Z1	Z2	Z3	Utilized supplier	Utilized plants	Utilized DCs	Shipped Quantities
1	29	5	7	121,320	13,194	1.0162	22	1L	2M+1L	515
2	29	5	6	130,450	13,799	1.0094	24	1L	3S+1L	530
3	29	4	7	116,310	19,209	0.9408	22	1L	2M+1L	573
4	29	4	6	181,270	18,634	1.4272	26	1M+1L	1S+2M +2L	745
5	29	4	5	163,500	14,174	1.067	29	1M+1L	3L	771
6	29	3	7	112,480	12,244	1.2	21	1L	1M+2L	603
7	29	3	6	138,230	14,174	1.067	21	1L	1S+1M +2L	645
8	29	3	5	131,460	12,188	0.9754	20	1L	1S+1M +2L	485
9	29	2	6	176,580	18,151	1.8966	26	2L	2M+2L	745
10	29	2	5	186,360	19,101	2	29	1M+1L	1S+2M +2L	774

From table 5-1, the result would be better if there were four plants opened, illustrating through the total quantity of shipment is over 700 units. Probably, the increase in production flow is the reason why total cost, environmental factors and social benefits go up.

As would be expected, the number of distribution centers is too high, some of them cannot utilized well.

In conclusion, datasets 6 and 9 give the balance in cost, environmental, and social benefits. Depending on the tolerance of entrepreneurs in cost and level of strict environment, they can consider one of two scenarios with different served demand.

Table 5-4. Result of high demand case for 10 datasets

High demand Uniform (80, 120) and supply capacity Uniform (30, 50)										
Data set	**S**	**P**	**DC**	**Z1**	**Z2**	**Z3**	**Utilized suppliers**	**Utilized plants**	**Utilized DCs**	**Shipped Quantities**
1	29	5	7	205,200	24,974	1.245	26	2L	1M+3L	1055
2	29	5	6	213,910	23,506	1.1954	25	2L	2S+3L	974
3	29	4	7	200,150	25,207	1.4272	26	2L	4L	977
4	29	4	6	221,690	24,611	1.3378	24	2L	1M+4L	960
5	29	4	5	202,020	23,371	1.3371	25	2L	2M+2L	935
6	29	3	7	221,910	23,785	1.5251	26	2L	2S+3L	960
7	29	3	6	225,750	24,168	1.5764	25	2L	3S+1M +2L	990
8	29	3	5	210,940	24,422	1.4906	25	2L	2S+1M +2L	960
9	29	2	6	203,160	24,658	1.8276	24	2L	4L	960
10	29	2	5	208,630	23,930	1.8276	24	2L	4L	960

According to table 5-2, dataset 1 shows the highest quantities, but the social benefits is not competitive to the others. However, if companies would like to adjust the total cost and social efficiency in balance, dataset 4 could be considered with the lower sold products.

5.3 Sensitivity Analysis

In this section, the changes of fixed cost for installing processing plants and distribution center are evaluated. We try to test and give comments for each objective in the interval 20% decrease to 20% increase.

Table 5-5. Value variation of the objective to different fixed cost of plants in Low Demand level

Changing LC[cp] in Low Demand case				
Facility cost	**Z1**	**Z2**	**Z3**	**S**
Decrease 20%	107,280	12,298	1.0266	29
Decrease 15%	182,770	18,736	1.6978	27
Decrease 10%	101,580	12,103	0.99083	27
Decrease 5%	132,480	12,356	0.95764	27
Unchange	112,480	12,244	1.2	29
Increase 5%	121,450	11,971	0.96355	18
Increase 10%	177,520	18,862	1.7143	29
Increase 15%	202,240	19,679	1.6798	28
Increase 20%	175,550	19,325	1.6571	29

When the cost of opening plants changes, three important factors also fluctuate. The graph shows that the lowest total cost occurs when this specific cost is reduced by 10%. However, the social and environmental objectives are better achieved when the cost is increased by 10%.

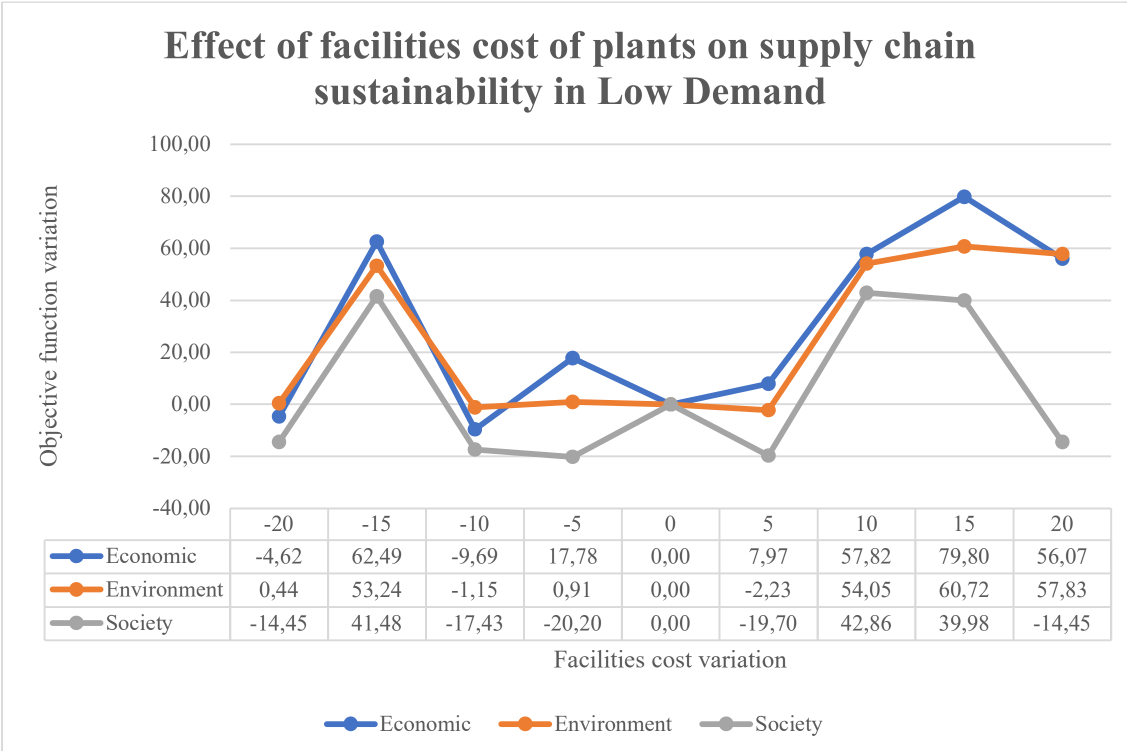


Figure 5-2. Effect of facilities cost of plants on supply chain sustainability in Low Demand case

Table 5-6. Value variation of the objective to different fixed cost of plants in High Demand level

Changing LC[cp] in High Demand case				
Facility cost	**Z1**	**Z2**	**Z3**	**S**
Decrease 20%	184,580	23,894	1.2753	26
Decrease 15%	208,010	25,528	1.3098	27
Decrease 10%	204,570	24,560	1.3511	26
Decrease 5%	227,310	24,868	1.2409	25
Unchange	205,200	24,974	1.245	26
Increase 5%	207,970	24,004	1.2064	24
Increase 10%	198,360	23,856	1.2367	24
Increase 15%	119,345	23,863	1.2409	25
Increase 20%	231,570	23,135	1.2409	25

With the fixed cost variation of plants at a high demand level, the total cost still follows the same pattern as in the previous case. The cost objective drops significantly by 41.84% when the fixed cost of plants decreases by 15%. However, social benefits peak with a 10% reduction in fixed costs, while environmental benefits are maximized with a 20% reduction in fixed costs.

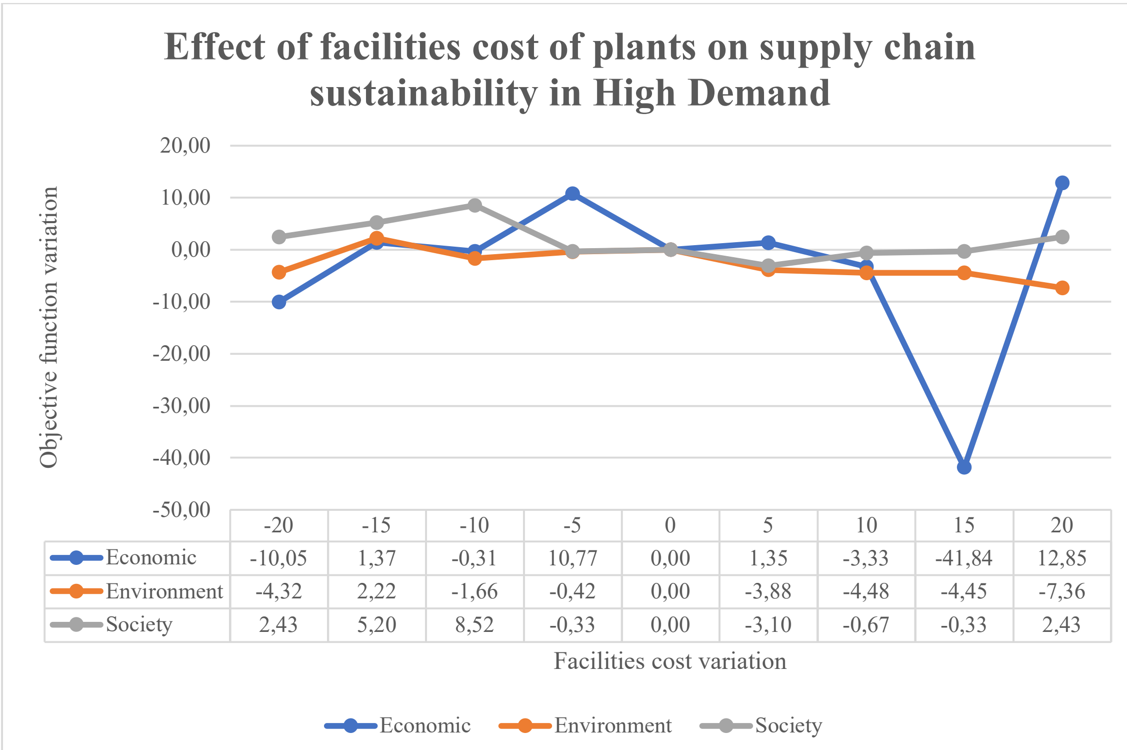


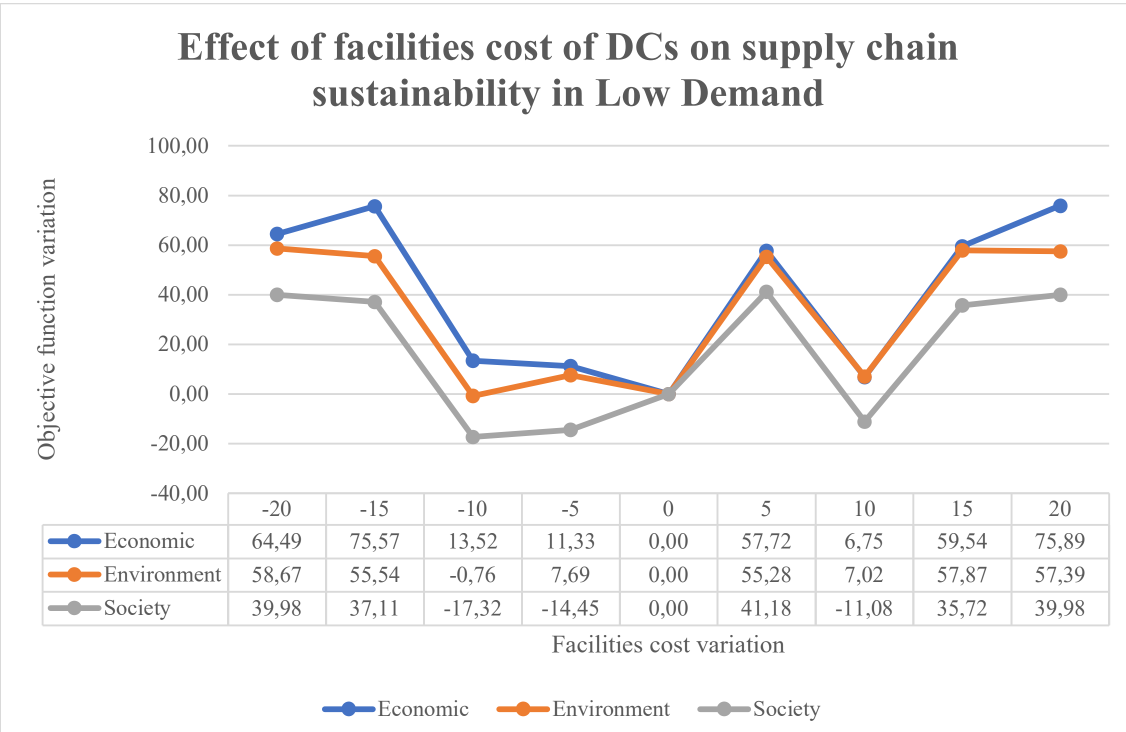
Figure 5-3. Effect of facilities cost of plants on supply chain sustainability in High Demand case

Table 5-7. Value variation of the objective to different fixed cost of DC in Low Demand level

Changing LC[cd] in Low Demand case				
Facility cost	**Z1**	**Z2**	**Z3**	**S**
Deacrease 20%	185,020	19,428	1.6798	28
Decrease 15%	197,480	19,044	1.6453	27
Decrease 10%	127,690	12,151	0.99212	18
Decrease 5%	125,220	13,186	1.0266	19
Unchange	112,480	12,244	1.2	21
Increase 5%	177,400	19,013	1.5941	28

Increase 10%	120,070	13,103	1.067	21
Increase 15%	179,450	19,329	1.6286	27
Increase 20%	197,840	19,271	1.6571	29

The results show that within the range of a 20% increase to a 20% reduction in the fixed costs of DCs, both the total cost and environmental impact increase. Unlike the variation in fixed costs of plants, the environmental factor achieves higher results when the facility cost either decreases or increases by 20%.



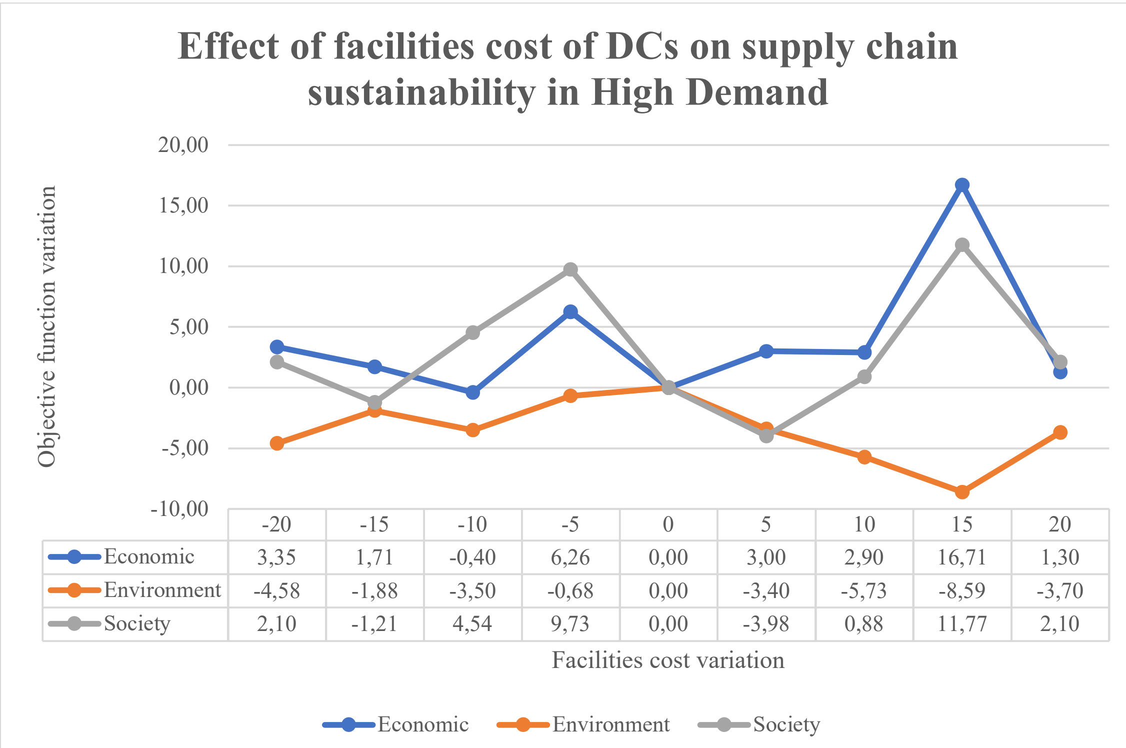
	-20	-15	-10	-5	0	5	10	15	20
Economic	64,49	75,57	13,52	11,33	0,00	57,72	6,75	59,54	75,89
Environment	58,67	55,54	-0,76	7,69	0,00	55,28	7,02	57,87	57,39
Society	39,98	37,11	-17,32	-14,45	0,00	41,18	-11,08	35,72	39,98

Figure 5-4. Effect of facilities cost of DCs on supply chain sustainability in Low Demand case

Table 5-8. Value variation of the objective to different fixed cost of DC in High Demand level

Changing LC[cd] in High Demand case				
Facility cost	**Z1**	**Z2**	**Z3**	**S**
Deacrease 20%	212,070	23,831	1.2712	25
Decrease 15%	208,700	24,505	1.2299	26

Decrease 10%	204,380	24,100	1.3015	24
Decrease 5%	218,040	24,804	1.3662	26
Unchange	205,200	24,974	1.245	26
Increase 5%	211,360	24,126	1.1954	25
Increase 10%	211,150	23,542	1.256	25
Increase 15%	239,490	22,828	1.3015	25
Increase 20%	207,870	24,049	1.3056	26



	-20	-15	-10	-5	0	5	10	15	20
Economic	3,35	1,71	-0,40	6,26	0,00	3,00	2,90	16,71	1,30
Environment	-4,58	-1,88	-3,50	-0,68	0,00	-3,40	-5,73	-8,59	-3,70
Society	2,10	-1,21	4,54	9,73	0,00	-3,98	0,88	11,77	2,10

Figure 5-5. Effect of facilities cost of DCs on supply chain sustainability in High Demand

In this scenario, reducing the fixed costs of DCs leads to a decrease in the first and second objectives. However, the social impact fluctuates dramatically within a 15% change, reaching its peak when the cost increases by 15%.

CHAPTER 6 CONCLUSIONS

6.1 Result Discussion and Implications

It can be seen that, through sensitivity analysis with decreasing and increasing facilities costs, we can see a linear change between three factors: Economic, Environment and Society. In other words, changes in business costs will have an accompanying impact on the environment and social values. This is understandable as cost factors will greatly impact the environment in terms of infrastructure and environmental treatment machinery. It would be terrible if businesses ignored environmental factors to cut costs. That would cause great harm and cause losses in both the whole environment and the business's risk costs. Similarly, cost factors will also have an indirect impact on society such as employee issues, salaries, etc.

However, in reality, there must be a trade-off between the above factors. It would be difficult to force all businesses to balance and maintain stability in all three components. Therefore, there needs to be cooperation from participating units and support from the government. An example of this model is Vinamilk dairy company in Vietnam, along with a roadmap called "Reducing Carbon Footprint, Aiming for Net Zero" implemented from 2010 to 2050. In particular, special emphasis is placed on this model to four aspects "Sustainable livestock farming - Green production - Environmentally friendly logistics - Sustainable consumption". To achieve that goal, Vinamilk has entered into joint ventures with government organizations to ensure green supply in their operating model.

Obviously, for the supply chain network problems of the dairy consumer industry which is considered a set of data based on the origin data of Columbian diary sector in the key reference, more careful research and evaluation of new problems are needed to further improve the model. However, this model can be considered a good example for strategists, who can see the internal factors of the problem, and from there will rely on and plan the supply chain here appropriately. most comprehensive and sustainable.

6.2 Social, Environment, and Economic Impacts

This paper illustrated the new approach of sustainability of one supply chain network design. Compared to most traditional designs that only aim to one aspect, the paper introduced a multi-objective optimization model incorporating the three dimensions. A case-study research in Colombian dairy sector was taken as an exemplary application, aiming to optimize the supply chain's impact on economy, society, and environment aspects. Particularly, the purpose of the model is to minimize total cost, simultaneously, minimize CO2e emissions at both production and transportation activities (environmental dimension), and two factors associated with the generation of employment and societal development (social dimension).

It can be seen that the difference in priority of each dimension affected the final results. Depending on business strategy, different alternatives would be applied, in this case, our project decided to balance three aspects. In which, in terms of society, utilization of employers and local suppliers results in shortening differences between cities and countries, hence leading to a more stable society. In addition, having a sustainable relationship with a supplier also shows trust and promotes both development (economic factor). At the same time, facility optimization also reduces the excess emission during manufacturing and transportation stages (environmental side). These three aspects are interconnected. Protecting the environment safeguards people's lives, which is a social factor. A stable society is linked to economic development, and a strong economy, in turn, supports environmental protection and enhances social well-being.

6.3 Recommendation for Future Research

In the running of our project, we noticed a lack of capacity binary parameters (Trv_{rt}, Trv_{sm}). However, there might be a possibility some other flaws that affect the result were not indicated by us in the research. Besides, there are not any opening restrictions for using vehicles, therefore some light trucks deliver 40 units while the heavy trucks transport just 20 units. As a result, the capacity of the truck does not utilize well compared to real life.

In future studies, researchers could explore models that span multiple time periods to illustrate how activities unfold over the long term, ultimately leading to stable sustainability indicators within the supply chain. Additionally, given the growing emphasis on national and continental plans to reduce greenhouse gas emissions and enhance social well-being, it is logical to establish expected sustainability targets by incorporating external information and recognizing supply chains as integral to community development.

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APPENDIX

A. File mod

```
/*********************************************
 * OPL 22.1.0.0 Model
 * Author: Admin
 * Creation Date: 31 thg 3, 2024 at 22:46:22
 *********************************************/
 int S=...;
 int P=...;
 int DC=...;
 int R=...;
 {string} Cp=...;
 {string} Cd=...;
 {string} M=...;
 {string} T=...;

 range s = 1..S;
 range p = 1..P;
 range dc= 1..DC;
 range r = 1..R;

execute{
  var now = new Date();
    Opl.srand(Math.round(now.getTime()/1000));
}
 float LC1[Cp]=...;
 float LC2[Cd]=...;
 float Pr[s]=...;
 float PC=...;
 float Dist1[s][p]=...;
 float Dist2[p][dc]=...;
 float Dist3[dc][r]=...;
 float TC[T]=...;
 int scale1=15;
 float CS[i in s]=20+rand(scale1)/scale1*(35-20);
 int CM[Cp]=...;
 float Mop=...;
 float Mup=...;
 float Mudc=...;
 int CDC[Cd]=...;
 int scale=80;
 float Dem[i in r]=40+rand(scale)/scale*(120-40);

 int Trv1[s][M]=...;
 int Trv2[r][T]=...;
 float Fcons1[M]=...;
 float Fcons2[T]=...;
 int Cap1[M]=...;
 int Cap2[T]=...;
 float Emfc=...;
 float Empr=...;
 float Ur[p]=...;
 int phi[s]=...;
 int BigM = 999999;
```

```
 //Decision variables
 dvar int+ x1[s][p][M];
 dvar int+ x2[p][dc][T];
 dvar int+ x3[dc][r][T];
 dvar boolean y[s];
 dvar boolean y1[p][Cp];
 dvar boolean y2[dc][Cd];

 //Objective functions
 dexpr float Z1=sum(p in p, Cp in Cp)(LC1[Cp]*y1[p][Cp]) + sum(dc in dc, Cd in
Cd)(LC2[Cd]*y2[dc][Cd]) + sum(s in s, p in p, m in M)(Pr[s]*x1[s][p][m])+ sum(p in p,
dc in dc, t in T)(PC*x2[p][dc][t]) + sum(p in p, dc in dc, t in
T)(TC[t]*x2[p][dc][t])+ sum(dc in dc, r in r, t in T)(TC[t]*x3[dc][r][t]);
 dexpr float Z2=sum(s in s, p in p, m in
M)(Emfc*Dist1[s][p]*x1[s][p][m]/(Cap1[m]*Fcons1[m]))+sum(p in p,t in T,d in
dc)(Emfc*Dist2[p][d]*x2[p][d][t]/(Cap2[t]*Fcons2[t]))+sum(r in r, t in T, d in
dc)(Emfc*Dist3[d][r]*x3[d][r][t]/(Cap2[t]*Fcons2[t]))+sum(p in p, d in dc, t in
T)Empr*x2[p][d][t];
 dexpr float Z3=(sum(p in p, cp in Cp)Ur[p]*y1[p][cp])/(sum(p in p)(Ur[p]))+(sum(s in
s)phi[s]*y[s])/(sum(s in s)phi[s]);

//minimize Z1;
//minimize Z2;
//maximize Z3;
minimize ((Z1-116310)/116310)+((Z2-19209)/19209)+((0.94089-Z3)/0.94089);


 //Constraints
 subject to{
c4: forall (r in r)
  sum(d in dc, t in T)x3[d][r][t]==Dem[r];


c5:         forall(p in p)
      sum(s in s, m in M)x1[s][p][m]==sum(d in dc, t in T)x2[p][d][t];
c6:         forall(d in dc)
      sum(r in r, t in T)x3[d][r][t]==sum(p in p, t in T)x2[p][d][t];



c7:
      forall(s in s)BigM*(y[s]-1)+sum(p in p, m in M)x1[s][p][m]<=CS[s];

c8:
      forall(p in p, cp in Cp)
        BigM*(y1[p][cp]-1)+sum(d in dc, t in T)x2[p][d][t]<=CM[cp]*Mop;

c9:
      forall(d in dc, cd in Cd)
        BigM*(y2[d][cd]-1)+sum(p in p, t in T)x2[p][d][t]<=CDC[cd];

c10:
      forall(s in s, m in M)
        BigM*(y[s]-1)+sum(p in p)x1[s][p][m]<=CS[s]*Trv1[s][m];

c11:
      forall(d in dc, cd in Cd, r in r, t in T)
        BigM*(y2[d][cd]-1)+sum(d in dc)x3[d][r][t]<= CDC[cd]*Trv2[r][t];
```

6.B

```
c12:
      forall(p in p, cp in Cp)
        BigM*(y1[p][cp]-1)+sum(cp in Cp)CM[cp]*Mup<=sum(d1 in dc, t in
T)x2[p][d1][t];

c13:
      forall(d in dc, cd in Cd)
      BigM*(y2[d][cd]-1)+CDC[cd]*Mudc<=sum(p in p, t in T)x2[p][d][t];


c14: forall(p in p)
      sum(cp in Cp)y1[p][cp]<=1;


c15: forall(d in dc)
      sum(cd in Cd)y2[d][cd]<=1;


c16: forall(s in s)
        BigM*y[s]>=sum(p in p, m in M)x1[s][p][m];

c17: forall(p in p)
        BigM*sum(cp in Cp)y1[p][cp]>=sum(d in dc, t in T)x2[p][d][t];

c18: forall(d in dc)
        BigM*sum(cd in Cd)y2[d][cd]>=sum(p in p, t in T)x2[p][d][t];

c19: forall(d in dc)
        BigM*sum(cd in Cd)y2[d][cd]>=sum(r in r, t in T)x3[d][r][t];
}


execute{
  writeln("z1,",Z1);
  writeln("z2,",Z2);
  writeln("z3",Z3);
}
```

B. File dat

```
/*********************************************
 * OPL 22.1.0.0 Data
 * Author: Admin
 * Creation Date: 31 thg 3, 2024 at 22:46:22
 *********************************************/
SheetConnection excelsheet("C:\\Users\\Admin\\Downloads\\Data Logdes.xlsx");
S from SheetRead(excelsheet,"Set!B3");
P from SheetRead(excelsheet,"Set!B4");
DC from SheetRead(excelsheet,"Set!B5");
R from SheetRead(excelsheet,"Set!B6");
Cp from SheetRead(excelsheet,"Data!A2:C2");
Cd from SheetRead(excelsheet,"Data!A6:C6");
M from SheetRead(excelsheet,"Data!X31:Z31");
T from SheetRead(excelsheet,"Data!X34:Z34");
LC1 from SheetRead(excelsheet,"Data!A3:C3");
```

```
LC2 from SheetRead(excelsheet,"Data!A7:C7");
Pr from SheetRead(excelsheet,"Data!B10:B38");
PC from SheetRead(excelsheet,"Data!F1");
Dist1 from SheetRead(excelsheet,"Data!F4:H32");
Dist2 from SheetRead(excelsheet,"Data!L4:R6");
Dist3 from SheetRead(excelsheet,"Data!V4:AE10");
TC from SheetRead(excelsheet,"Data!M17:O17");
CM from SheetRead(excelsheet,"Data!N20:P20");
Mop from SheetRead(excelsheet,"Set!G1");
Mup from SheetRead(excelsheet,"Set!G2");
Mudc from SheetRead(excelsheet,"Set!G3");
CDC from SheetRead(excelsheet,"Data!N24:P24");
Trv1 from SheetRead(excelsheet,"Data!O32:Q60");
Trv2 from SheetRead(excelsheet,"Data!T32:V41");
Fcons1 from SheetRead(excelsheet,"Data!X32:Z32");
Fcons2 from SheetRead(excelsheet,"Data!X35:Z35");
Cap1 from SheetRead(excelsheet,"Data!X39:Z39");
Cap2 from SheetRead(excelsheet,"Data!X42:Z42");
Emfc from SheetRead(excelsheet,"Data!T44");
Empr from SheetRead(excelsheet,"Data!T45");
Ur from SheetRead(excelsheet,"Data!T47:V47");
phi from SheetRead(excelsheet,"Data!M20:M48");
```

C. Data input in Excel file

Notation	Explanation	Value
Cp	Capacity options for processing plants	small, medium, large
Cd	Capacity options for distribution centers	small, medium, large
S	Set of suppliers	29
P	Set of potential locations to install processing plants	4
DC	Set of potential zones to locate distribution centers	6
R	Set of retailers	10
M	Transportation types from farmers to processing plants	light truck, medium truck, heavy truck
T	Transportation types from processing plants to distribution centers and retailers	light truck, medium truck, heavy truck
Mop	Maximum desired occupation rate of processing facilities	0.9
Mup	Minimum allowed operation rate for processing facilities	0.4
Mudc	minimum allowed operation rate for distribution centers	0.5
Emfc	CO2e emission produced per consumed gallon of fuel (unit: pounds)	249
Empr	CO2e emissions produced per ton of milk processed at the plant (unit: pounds)	22.38

- *Fixed cost of opening a processing plant with capacity cp ∈ CP*

LC of cp ($)

Small	Medium	Large
7500	8000	9000

- *Fixed cost of opening a distribution center with capacity $cd \in CD$*

LC of cd ($)		
Small	Medium	Large
12000	14000	15000

- *Price of raw milk per ton at supplier Pr_s*

Supplier	Price ($)
1	64
2	91
3	65.2
4	73.6
5	68.5
6	72.2
7	50.7
8	55.8
9	96.7
10	61.8
11	92.8
12	38
13	91.7
14	44.3
15	94.4
16	74.5
17	58.1
18	75
19	76.8
20	37.1
21	75.4
22	67.8
23	64.4
24	51.2
25	95.8
26	60.5
27	69.4
28	44
29	60.1

- *Distance in km between the supplier s and the processing plant p*

$Dist1_{sp}$	p				
s	1	2	3	4	5
1	35	68	74	73	81
2	60	43	48	57	78
3	76	69	64	62	35

4	44	46	85	44	64
5	80	87	82	62	43
6	76	38	90	50	94
7	70	81	52	81	87
8	65	72	49	52	35
9	49	40	59	76	31
10	55	40	43	49	91
11	96	33	81	44	84
12	65	51	76	76	77
13	33	98	41	87	58
14	57	92	53	94	30
15	46	88	32	39	63
16	41	38	37	60	83
17	93	64	58	43	85
18	99	44	45	74	46
19	49	86	70	49	77
20	86	75	40	31	33
21	71	74	85	42	32
22	78	47	66	63	72
23	32	61	40	56	61
24	89	54	35	92	54
25	94	93	80	67	73
26	62	71	39	82	36
27	85	90	79	84	46
28	85	37	96	68	95
29	60	82	78	69	90

- *Distance in km between the processing plant p and the distribution center d*

$\mathbf{Dist2_{pd}}$	**d**							
p	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	44	24	32	32	34	42	40	36
2	28	30	49	41	35	45	20	27
3	36	34	43	35	25	33	31	46
4	35	47	49	20	35	24	29	48
5	36	33	32	40	35	31	37	42

- *Distance in km between the distribution center d and the retailer r*

$\mathbf{Dist3_{dr}}$	**r**									
d	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	11	18	20	8	12	14	20	14	16	17
2	18	8	7	5	11	12	19	13	10	10
3	16	18	13	13	15	19	19	20	12	6
4	5	7	16	16	16	8	15	15	9	9
5	6	11	8	14	12	7	9	9	17	14
6	7	6	11	6	11	16	13	18	10	12
7	19	14	19	7	13	10	11	10	11	15

8	14	12	6	17	10	10	8	19	18	19

- *Transportation cost per ton of milk in transport type t*

TC[t] ($)		
Light truck	**Medium truck**	**Heavy truck**
10	18	22

- *Production capacity of a processing plant with capacity cp*

CM of cp (tons)		
Small	**Medium**	**Large**
300	400	500

- *Storage capacity at distribution center with capacity cd*

CDC of cd (tons)		
Small	**Medium**	**Large**
120	180	300

- *Fuel efficiency of vehicle type m kilometers per gallon*

Fcons[m]		
Light truck	**Medium truck**	**Heavy truck**
58	45	30

- *Fuel efficiency of vehicle type t kilometers per gallon*

Fcons[t]		
Light truck	**Medium truck**	**Heavy truck**
60	50	40

- *Capacity in tons of milk of vehicle type m*

Cap[m]		
Light truck	**Medium truck**	**Heavy truck**
160	400	650

- *Capacity in tons of milk of vehicle type t*

Cap[t]		
Light truck	**Medium truck**	**Heavy truck**
100	250	450

- *Employment rate at the potential location of processing plant p*

p	**1**	**2**	**3**	**4**	**5**
Ur[p]	0.6	0.5	0.65	0.7	0.85

- *Accessibility of vehicle type m to supplier s (equal to 1 if m have access to s, 0 otherwise)*

Trv[s][m]	**m**		
s	**Light truck**	**Medium truck**	**Heavy truck**
1	1	1	1

2	1	1	1
3	1	0	1
4	1	1	1
5	1	1	1
6	1	1	0
7	1	1	1
8	0	1	1
9	1	1	1
10	1	1	1
11	1	1	1
12	1	0	1
13	1	1	0
14	1	1	1
15	1	1	1
16	0	1	1
17	1	1	1
18	1	1	1
19	1	1	1
20	1	0	1
21	1	1	1
22	0	1	1
23	1	1	1
24	1	0	1
25	1	1	1
26	0	1	1
27	1	1	0
28	1	1	1
29	1	1	1

- *Accessibility of vehicle type t to retailer r (equal to 1 if t have access to r, 0 otherwise)*

Trv[r][t]	**t**		
r	**Light truck**	**Medium truck**	**Heavy truck**
1	1	1	1
2	1	1	1
3	1	1	1
4	1	0	1
5	0	1	1
6	1	1	1
7	1	1	1
8	1	1	0
9	1	1	1
10	1	0	1

- *Added value factor of the region of supplier*

s	**1**	**2**	**3**	**4**	**5**	**….**	**27**	**28**	**29**
φ_s	1	1	1	1	1	1	1	1	1

6.I