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Addressing the Sugar Crisis Supply Chain Management Problem in the Philippines via a Mixed-Integer Linear Optimization Approach

Eunice Cristyl D. del Pilar [a] and Charlle L. Sy [b]
[ab] *Department of Industrial & Systems Engineering*
De La Salle University
ORCiD ID: Eunice Cristyl D. del Pilar https://orcid.org/0009-0009-6121-5244

Abstract. This paper seeks to address the sugar crisis supply chain management problem of the Philippines using a mixed-integer linear programming model. Despite the topic on resource scarcity being a widely taken subject in the literature, little to no research works have satisfactorily provided an objective means to allocate scarce resources. As such, the paper formulates a mixed-integer linear programming model to represent the allocation problem across multiple levels of echelons in the supply chain. Key results indicate that there may be a certain monopolistic characteristic of the allocation which happens as expected in reality.

Keywords. Sugar crisis problem, supply chain management, mixed-integer linear optimization approach

1. Introduction

Almost every part of the world has been poorly affected by the global COVID-19 pandemic. In specific, countries from marginalized regions have experienced the effects of the pandemic far worse than leading countries from an economic standpoint. Two years later, the Philippines is unfortunately still reeling in the effects of the pandemic, thus leading the public to have a brighter hope of finally having a better year than the preceding years. However, this year, the world has faced new challenges that are experienced across nations. These problems, to name a few are the following: the continuous rise of inflation rates, poverty, food insecurity, and health care fees, as well as climate change. While these problems are experienced by every nation, the Philippines has seemingly experienced an isolated scenario – that is, the 2022 Philippine sugar crisis. Recently, there has been a report of a shortage of supply of sugar in the domestic market in the Philippines which led to an increase in prices, shortages of byproducts having sugar as a prime ingredient, and the probability of business closured for industries involved in sugar-milling. In the current literature, the exact sugar shortage problem has never been addressed under any certain contexts. However, the greater scope of the resource shortage problem has been tackled using approaches such as performance measurement, social acceptability, and optimization of energy flow. It is, therefore, a very interesting and insightful avenue to explore how the specific sugar shortage problem can be addressed adequately by means of objective and mathematical tools that can establish the overall system including its boundaries, and, ultimately, aid in the decision-making process among stakeholders with diverse interests.

The current literature available addressing the problem revealed three major research gaps that serve as avenues for improvement and the solution to the problem at hand. For one, earlier research work addressing food scarcity typically revolves around the solution of a general food problem and not focusing on the scarcity of a specific food ingredient (i.e., sugar). This serves as a new direction for the scholastic community to look into in order to explore the root causes of the problem. Second, the previously published research articles fail to incorporate a broader method of addressing the problem by only taking into consideration the decision and solution approaches of a single decision-maker. This poses a problem for objectively, the decision-maker would lean towards the accomplishment of a single stakeholder's goal. Moreover, previous research works did not incorporate uncertainties in the model-building solutions to resource allocation. This signifies that the solution approaches that were prior developed rely on the stochasticity of the set parameters as well as an optimistic view of the research environment.

2. Review of Related Literature

2.1 Scarcity of Resources

When an imbalance between the resources available and the needs and aspirations of individuals, to the point of diminishing its value, occurs, scarcity of resources emerges [1]. The issue of scarcity of resources has long been listed as one of the threatening issues in the global context which brings forth a multitude of consequences due to the increasing forms of needs and aspirations with yet a limited and degrading amount of primary material requisites. The concept of scarce resources being an imbalance between the needs and availability of resources can also be evident in the wider spectrum of organizational structure. Following the notion that organizations collect and consume resources [2], organizations are structured and behave depending on the availability of their resources. When organizations are in a dilemma of failing to generate the complete quantity and quality of resources needed in order to thrive, it becomes a necessity to rely on external resources to provide whatever is lacking [3]. As such organizations refer to external resources with little to no access, the issue of mismatched organizational capacity resulting in unachieved organizational goals becomes evident [4].

To demonstrate the gravity of the issue of scarcity of resources, several instances of such can be noted across a wide array of domains including procurement [5], water [6], fuel [7], among many others. While the manifestation of scarcity is of a multitude and diverse forms, the idea is common – there are limited available resources and there is an increasing height of needs [8]. In specific, The United Nations refers to this phenomenon as evidence of competition over increasingly scarce renewable resources which can either be demand-induced or supply-induced [9]. As an illustration of this demand-induced scarcity, take for example the case of nutrition and environmental scarcity due to the recent COVID-19 pandemic [10]. Even in developed countries, such as the United Kingdom, food insecurity has increasingly emerged amidst the pandemic despite the fact that the level of agricultural production is considered to be adequate. For instance, consumers are found to seek substitutes or alternative food choices which are significantly nutritionally inadequate specifically during the lockdowns in the middle of the pandemic. As a result, risks of mineral deficiency and similar facets have become a concern. In a different case, demand-induced scarcity is also evident in the medical field and plays an even more critical role because the matter of life and death is already at hand [11]. Along that line, the priority of how life-saving medical interventions may be allocated has become a central concern in the extant literature. In fact, it has piqued further development to individuals of different ages following through interesting philosophical points of view about resource allocation. Aside from demand-induced scarcity, supply-induced scarcity has also been widely tackled. One case of such is taken from the views of environmental degradation in Somalia, a developing country [12]. Specifically, as the environmental value degrades, resource scarcity and the birth of civil conflict are investigated if an influence actually exists. It is found that an increase in population leads to the likelihood of civil conflicts by about one percent and that there is no direct relation between the rise of temperature, a manifestation of environmental degradation, to civil conflicts. Such findings are in complete contrast to an earlier work that attempted to explore whether supply-induced scarcity in general enables conflicts [13]. According to this work, civil violence on a global scale has greatly been driven by environmental degradation as seen in the desertification of drylands and other environmental factors in the least-developed countries in North Africa. However, while the temporary crisis in the local production systems become notable and prompts individuals to migrate to other countries which exposed them to revolutionary discourse, supply-induced scarcity is not entirely faulted for a such uprising.

2.2. A Case of the Supply-Induced Scarcity Problem

In a general view, the leading cause of supply-induced capacity points to the degradation of the environment due to natural disasters (e.g., typhoons, fire) and even poverty. Such events are very prominent and have significantly resulted in scarcity in developing countries like the Philippines. Recently, the Philippines faced one of the most pressing concerns of scarcity in sugar looming in 2016 and has been greatly highlighted in 2022 [14]. This issue has been increasingly persistent until it reached the point of exhaustion not only for the agricultural industries in the country but also for the major players in the manufacturing sector including Coca-Cola Bottlers Inc. among many others. While the pertinent root cause of this issue has not been clearly identified, several speculations pointed out factors in hoarding, agricultural damage due to the recent typhoons (i.e., Typhoon Rai in 2021), and unavailability of human workforce, especially during harvest seasons. Clearly, the sugar crisis experienced by the Philippines is a form of supply-induced scarcity. Despite the emergence of such an issue in the sugar crisis, there has been no concrete evidence of it being addressed at the national level, albeit at the primary industries level. Surprisingly, the issue of the sugar crisis has already occurred in the 1980s and was even investigated in the context of how it affected the international trading relations of the country among other countries. However, the recommendations put forward by this work have obviously been not considered, thus, prompting the eventual repeat of the same issue in 2022. While a descriptive account of the problem in the specific contexts of these countries cutting across various concerns in initiating a program, establishing policy changes to improve the global sugar crisis, investigating the rise of sugar in the global context, harnessing strategies to avoid bankruptcy due to the sugar crisis, and analyzing the performance of firms producing sugar, no research work has ever attempted to regulate the sugar crisis problem so as to allocate the remaining available supply to the end-consumers. By being able to allocate scarce resources, the equitable treatment of the stakeholder including the end-consumers will be accounted for and at the same time put forward the resources in a more efficient manner.

2.3. Recent Approached in the Literature that Aims to Address the Scarcity of Resources

To aid in the further analysis of addressing the sugar crisis in specific, recent frameworks and approaches developed in the literature designed to manage general scarcity issues have been looked into. For one, cost optimization and risk management models are developed by [15] to periodically distribute scarce renewable resources to different users in a water scarcity case. These models are intended to strike a balance between costs and risks in the planning of management of scarce resources subject to uncertain conditions. Numerical results showed the potential of these models which can not only be limited to its current application but may also be directed toward other similar scarcity problems involving management principles. For another, in a different case involving water resources, a multi-objective optimization model is developed by [16] to optimize the allocation of water resources while simultaneously considering the economic benefits and environmental impacts of water consumption. In this work, the model has satisfactorily identified the source of water to which the consumption of both urban and environment as well as the balance of supply and demand in water may be filled. At the larger scope of water consumption, an extended intuitionistic fuzzy interval two-stage stochastic programming model is formulated by [17] to aid in resource planning management with the integration of recourse penalty from resources scarcity and surplus. An actual case demonstration is carried out in an arid area to prepare a schedule on the agricultural cultivation scale with a basis on limited water resources. The model showed promising results in dealing with uncertainties and how they influence decision strategies as well as clarifying the physical implication of penalties from resource scarcity and surplus. Similarly, a water resources management scenario is focused on by [18] involving a multi-criteria decision analysis model to investigate the integrated water resources management in a lake basin. The model developed specifically employed an analytical hierarchy process (AHP) to evaluate the factors involved in increasing complexity in integrated water resources management in the case study considered. This work is able to identify the best solutions for conflicts pointed out and at the same time promote interaction among stakeholders and instruments to reach a more sustainable technique in water resources management. Another quantitative model being a stochastic simulation model is proposed by [19] to mimic more data on agricultural water supply and demand. Several parameters of the model are manipulated to obtain results that speak about the system being modeled as well as the security and reliability of the model.

Other than quantitative tools to address the scarcity of resources, a qualitative approachable has also emerged in the literature. For example, a more qualitative approach to managing scarce resources in the context of small enterprises by means of efficient use of resources including reducing formality, adjusting design processes, collaborating on the design and operational processes, implementing lead-user inventions, and managing design processes is formulated by [20]. Here, it has been concluded that scarcity on its own can be effectively managed based on its recognition and use of it to the advantage of firms. Also, a framework to address water scarcity in the agricultural production industry is developed with the integration of an agricultural water stress index by [21]. The emphasis of this work is more on the analysis of the provincial agricultural water footprint and water resources availability and its impact on the temporal and spatial patterns on the same index. Key results revealed that this index is more appropriate to reflect the scarcity problem along with the environmental impacts of agricultural production. It can be noted that these approaches involving optimization models, machine learning algorithms, and qualitative strategies to address the scarcity of resources, although excellently provided secure and reliable results, may be inadequate to resolve the issue of sugar crisis in the Philippines due to some characteristics of the previous approaches which cannot be directly transposed to the sugar crisis problem. Given the characteristics of the sugar scarcity problem involving multiple stakeholders, the uncertainty of demand and supply, and the unavailability of historical data to suggest an appropriate probability density function describing the problem, it can be highlighted further that the previous approaches presented in the literature using mathematical models, machine learning algorithms, and qualitative strategies may be deemed inadequate to frame the problem and effectively propose solutions accordingly. Such approaches will not be able to handle the diverse interests of stakeholders in the sugar crisis problem and provide a resolution that satisfies all of these interests. Furthermore, the uncertainty that arises in exceptional and prominent cases of the sugar crisis problem has only been looked into via penalty recourse which may not necessarily reflect the uncertainties in changes in demand or supply, or both, due to some reasons. Ultimately, since the sugar crisis problem in the Philippines has only been recorded to have emerged in the 1980s with no further developments until 2022, there are no quantitative representations of the problem making it difficult, if not impossible, to obtain an accurate representation of the trends in the demand and supply of sugar in the country.

Fortunately, a recent framework developed by [22] referred to as multiple-stakeholder-based target-oriented robust optimization (MS-TORO) provides promise as an application model for the sugar crisis problem. In context, the MS-TORO model is a multiple-criteria decision-making (MCDM) model that seeks to arrive at a decision that minimizes the deviation metric representing the levels of adjustments in interests that one stakeholder is willing to compromise to accommodate all the rest of the interests involved. For MS-TORO to be implemented, two general considerations are required: 1) for a decision problem to involve multiple stakeholders who have individual interests, and 2) for a decision problem to involve uncertainties in its parameters. These characteristics are exemplified by the sugar crisis problem at hand. Therefore, applicability-wise, MS-TORO can be analytically implemented. With the application of the MS-TORO model in the sugar crisis problem, the individual and diverse interests of multiple stakeholders can be taken into account in the allocation decision as well as the uncertainty in the demand and supply. Recently, the MS-TORO framework has been utilized to address the decision problem on aircraft rerouting [23,24] and location analysis in the microbusiness sector [25]. All of these problem applications formulated the MS-TORO framework according to an integer linear programming model based on a choice problem. In real-life applications of decision-making involving multiple stakeholders and uncertain parameters, there are certain cases of non-choice problems in the form of a mixed-integer linear programming model. However, this form of the MS-TORO framework has not yet been formulated in such a way despite the realistic application to actual decision problems. Therefore, the research gap advanced in this paper is the analysis of the sugar crisis problem in the Philippines with the use of a modified MS-TORO model. The direction of the research problem contributes to the literature and the body of knowledge in a multitude of ways: (a) the sugar crisis problem will be addressed by objectively allocating scarce resources, and (b) the traditional MS-

TORO model will be extended as a mixed-integer linear programming model to accommodate non-choice decision problems. These contributions are significant since the sugar crisis problem in the Philippines is not yet addressed in any analytic manner such that scarce resources can be effectively allocated. Furthermore, the extension of the traditional MS-TORO model can pave the way to further applications in a broader and more comprehensive context of decision problem analysis and modeling.

3. Research Methodology

3.1 Model Formulation

Decision variables. In this problem, the decision variables considered represent the level of allocation (i.e., for instance, in tons of sugar) for each echelon in the system. As an illustration, Figure 1 shows that there are y tons of available sugar in the entire country to be allocated to the regions requiring x tons of sugar. Correspondingly, cities in each region require some level of z tons of sugar for consumption. Therefore, the decision variables in the proposed model can be set as follows: x_i $where$ $\{x \in R \mid x \geq 0\}$; y_j $where$ $\{y \in R \mid y \geq 0\}$; and, z_k $where$ $\{z \in R \mid z \geq 0\}$.

Notations. The proposed mixed-integer MS-TORO model utilizes the following notations in formulating the model: $i \equiv$ set of sources where available sugar is from; $j \equiv$ set of region points from source i where an amount of x sugar shall be allocated; $k \equiv$ set of city points from region j where an amount of y sugar shall be allocated; $f \equiv$ farm crop yield; $c \equiv$ cost of allocation; $d \equiv$ total demand per city k; $s \equiv$ unit bid price of sugar for every region j;and, $r \equiv$ required demand by region j.

Objective function. In the sugar crisis problem, the proposed model aims to simultaneously consider the diverse interests of stakeholders in maximizing income due to the sales from sugar, maximizing demand satisfaction, and minimizing costs due to transportation from city level to its end-users. Specifically, the country level echelon aims to maximize income due to the sales from sugar allocation per region which is the sum-product of the total number of units allocated per region and its corresponding selling price. On the other hand, the region level aims to maximize the demand satisfaction to its level by acquiring as many tons as possible of sugar. Lastly, the city level echelon's goal is to minimize costs due to the transportation from the receiving hub down to its end-users considering the concept of economies of scale. Notice that the three individual objective functions are diverse and conflicting in goal, thus, needs to be reconciled by means of the proposed mixed-integer MS-TORO model. As such, the ultimate objective function of the model is presented as follows:

$$\min \theta \tag{1}$$

Constraints. The constraints in this model account for the individual objectives of stakeholders along with the system constraints represented by the following equations. Constraints (2) to (4) represent the individual interests of stakeholders in addressing sugar crisis problem. Constraint (2) reflects the preference of country-level stakeholders whose aim is to maximize the revenue earned from allocating x amount of sugar from source i to every j region. This constraint further involves the selling price s set for every *j* region and the *x* amount of sugar allocated by source *i*. Next, constraint (3) accounts for the interest of region-level stakeholders which intends to maximize the level of satisfaction of demand for every region *i*. Then, constraint (4) minimizes the costs due to the transport of *z* amount of sugar allocated for every city *k*. Also note that the first two constraints, constraint (2) and (3) are directed to maximize a certain goal, and thus should be both greater than or equal to the target function. Furthermore, since constraint (4) is directed to minimize a goal, then this constraint is set to be lesser than or equal to the target function. On the other hand, constraint (5) sets the total number of *z* amount of sugar for every city *k* to be greater than or equal to a *y* amount of sugar representing the available supply of region *j*. Constraint (6) states that the total amount of sugar in the sources should not exceed the crop yield *a*. Then, constraint (7) sets the *z* amount of sugar in city *k* to be lesser than or equal to the demand *d*. Similarly, constraint (8) restricts the model to allocate *y* amount of sugar in region *j* that is equal to or lesser than the supply *r* in region *j*. Then, constraint (9) forces the model to allocate an amount of sugar that is less than what can be allocated by a source *i* and region *j*. Finally, constraint (10) implies that the deviation metric should be a member of the closed interval 0 to 1 and constraint (11) implies non-negativity constraint of each decision variable.

$$\sum (s_j \cdot y_i) \geq \tau_i/(1+\theta) \qquad \forall ij \qquad (2)$$

$$y_j \geq \tau_j/(1+\theta) \qquad \forall j \qquad (3)$$

$$\sum (z_k \cdot c_k) \leq \tau_k \cdot (1+\theta) \qquad \forall k \qquad (4)$$

$$\sum_{k=1}^{k=5} z_k \geq y_j \qquad \forall j \qquad (5)$$

$$\sum_{k=1}^{k=5} x_i \leq a \qquad \forall j \qquad (6)$$

$$z_k \leq d_k \qquad \forall k \qquad (7)$$

$$y_j \leq r_j \qquad \forall j \qquad (8)$$

$$\sum y_j \leq \sum x_i \qquad \forall j \qquad (9)$$

$$\theta \in \{0,1\} \qquad (10)$$

$$x_i, y_j, z_k \geq 0 \qquad (11)$$

4. Research Methodology

In order to carry out the proposed mixed-integer linear programming model, an Apple MacBook Air M1 laptop with macOS Monterey version 12.4 and 8GB memory is used to run the model. A Demo Lingo/Mac64 Release 19.0.46 version is further used to solve the model involving 24 variables and 65 system constraints. A hypothetical sugar crisis problem is established as a baseline scenario. The model begins with an initial volume of resources from various points which is set to be allocated to multi-leveled echelon (i.e., regions and cities) representing the system. To further developed the baseline scenario, five sources with three regions, each region consisting of five cities, are considered in the model. Suppose that this baseline scenario has the following characteristics as shown in Table I-II. In addition to these data indicated in Table I to Table III, it is assumed that the farm crop yield, is equal to 50,000 metric tons. After running the model, the decision variables based on the number of units allocated to each source, region, and city as displayed on the number of units above each node of Fig. 1. In a general perspective, the model generated a deviation metric, of 0.79 ~0.8 which

Table 1. Bid price and demand requirement of regions to available resources (s)

Region (j)	*Bid Price (Php per metric ton)*	*Demand requirement (in metric ton)*
1	100,000	70,000
2	89,500	50,000
3	120,000	50,000

Table 2. Demand requirement per city (r)z

Region (j)	*City (k)*	*Demand (in metric tons)*	*Costs (in PhP)*
1	1	5	100,000
	2	7	200,000
	3	15	500,000
	4	2.2	50,000
	5	5	100,000
2	6	2.9	70,000
	7	3	75,000
	8	2	50,000
	9	9.7	700,000
3	10	10	750,000
	11	6	300,000
	12	7	350,000
	13	30	1,500,000
	14	25	1,000,000
	15	2.7	50,000

Table 3. Target amount of each stakeholder

Stakeholder	*Target*
1	Php 900,00
2	30,000 metric tons
3	Php 500,000,000

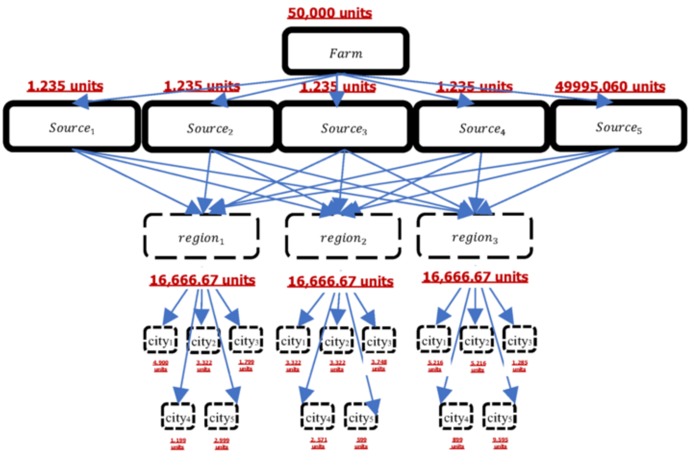

Figure 1. Results of the proposed mixed-integer MS-TORO model for sugar crisis problem

reflects the adjustments needed to be achieved by each stakeholder in order to achieve an equitable allocation of resources (i.e., sugar). Due to the relatively high index of the deviation metric, it can also be noted that the stakeholders are more to take risks by adjusting their goals to as much as 80% from the original setup. Such adjustment can make certain that the interests of other stakeholders can also be satisfactorily achieved, alongside the other system constraints. The allocation of resources during an ongoing crisis has been explored whilst bearing in mind the inherent goals and interests of the different stakeholders across different echelons involved in the resource allocation– that is to maximize sales, maximize demand satisfaction, and minimize the transportation cost. The model generated an optimal value of 0.80 as the target deviation metric of the resource allocation. This optimal deviation metric indicates that the stakeholders can adjust to as high as 80% from what was their original target sets in order to meet a fair level of satisfaction across all interests. Take, for instance, sources are distribution centers (DC), regions are the resellers, and cities are end-consumers. Say the target sales projection is Php 900,000 across five DCs of sugar.

While all five DCs basically accommodate the same quantity of sugar, the sales generated from each DC however, deviate due to the local demand and the cost of transportation. Therefore, DC A although has the same capacity and stock availability as DC B, may not be as efficient and profitable in the aspect of resource allocation. Moreover, the results of the optimization model suggest that the preferred allocation model is to impose a centralized distribution system to ensure the achievement of a level of satisfaction alongside other constraints in the system. This insight coincidentally may pose an apparent solution to the current 2022 sugar crisis in the Philippines, where initial investigations performed by government bodies suggest traders and distributors of sugar in the local setting are taking advantage of the shortage of sugar in the domestic market by hoarding. While the most cited cause of food crises is attributed to a tight supply, the government and policymakers in the Philippines rebuff this and claim the current crisis is artificial and point the blame toward the traders and the DCs of apparent hoarding in order to increase the prices of the commodity. While the model proposes insights into addressing the current sugar crisis of the Philippines, it is worth noting that further analysis of the sugar crisis should be considered for future studies.

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