A Supply Chain Optimization Model Considering Cost and Water Footprint

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Identifying an appropriate scheme in utilizing water in any industrial system is an essential response to alleviate the effects of climate change. Water footprint (WFP) is a method of measuring freshwater appropriation on different levels – national, corporate, activity, or product. It allows a company to measure its direct and indirect freshwater consumption to identify possible interventions to reduce water consumption. Existing studies on water footprint mainly focused on the assessment but failed to use it for prescriptive modelling in the supply chain where the decisions are affected by the WFP assessments. In this study, we develop an optimization model for supplier selection in a supply chain to minimize both the costs and water footprints to produce a product. The model considers sourcing raw materials with differences in prices and water footprints depending on the source. The model is demonstrated on a case study adapted from industry data. The results of the analysis show the that the water footprint of the raw materials can affect the company's decisions on procuring their materials when the level of priority for the water footprint is set to at least 40 %. The study proves that consideration of the water footprint in a supply chain model can balance the effect of choosing the lowest cost.

1. Introduction

Many firms consider water as an essential component in their operations (Aviso et al., 2021). Water is being utilized to ensure continuous production of goods. The agricultural industry, for instance, accounts for largest of the world's freshwater consumption (Balsom, 2020). The manufacturing sector, which uses the products of the agricultural sector, further contributes to the consumption of water to process their products (Hoekstra, 2015). The escalating activities from these agricultural and industrial sectors coupled with the climate change are causing water stress (Manzardo et al., 2014). Also, Drofenik et al. (2021) suggested the need to have a balance between food production and lowering environment impact. Depletion of the available freshwater resources is being experienced because of the increasing production outputs of the different economic sectors and growing spending of people (Wang et al., 2021a). It is expected that the world's demand for water will increase by 55 % between 2000 and 2050 (Whitmee et al., 2015). Efficient use of water in industrial systems is an important climate change adaptation strategy (IPCC, 2022).

Socio-economic development and securing necessities of life are now threated by water scarcity (Liu et al., 2017). Because of the current and possible future states of water availability, efforts on mitigating the impact of water scarcity have been introduced. Water footprint is a concept that is align with water conservation. Water footprint is an extent of freshwater consumption related to product or activity (Hoekstra, 2015). This concept measures the total amount of freshwater needed to manufacture the product along the supply chain (Hoekstra et al., 2011). It covers the accounting of water consumption of the raw materials and of the processes needed to produce the products. According to Hoekstra et al. (2011), the three components of water footprint of a product or activity are blue, green, and gray water footprint. The blue water footprint component pertains to the volume of ground water or surface water consumed in producing the product. The green water footprint component pertains to the volume of rainwater consumed in producing the product. The gray water footprint component pertains to the volume of water needed to absorb a load of pollutants to comply with the ambient water quality standards (Hoekstra et al., 2011). Water footprint (WF) can offer a good approach in assessing and addressing environment related problems (Wang et al., 2018). According to Wang et al. (2018), there is an increasing trend

on studies linking WFP to energy, carbon emission, and nitrogen emission. Given these efforts, model-based cost-benefit analysis is necessary for any industrial water conservation initiative (Wang et al., 2021b)

There have been studies that attempted to account for the water footprint of a certain product or activity. Water footprint becomes embedded in products and can be transferred through international trade (Yang et al., 2020). The work of Rivas Ibáñez et al. (2017) accessed and computed for the water footprint of Gazpacho, a chilled vegetable soup, produced by a company in Spain. In the accounting of the water footprint of Gazpacho, the water footprints associated to the seven ingredients and packaging materials were considered. Also included are the water footprint contributions of the processes to produce the finished product.

Elbeltagi et al. (2020) made a study that aimed to estimate the water footprint, particularly the blue and green water footprint, in producing maize. They used Artificial Neural Network in estimating the water footprints based on temperature, precipitation, solar radiation, soil moisture, wind speed, and vapor pressure deficit from three different production sites. Madaka et al. (2022) made a study that analyzes the water footprint associated with the extraction and production of metals used for consumer electronics products using life cycle analysis methodology. The goal of the study is to determine materials that have major contribution to the water footprint. Madaka et al. (2022) attempted to use the assessment as guides in making decisions related to the supply chain. Handayani et al. (2020) made a study that assessed the water footprint in producing the Indonesian batik. The blue and gray water footprint components were considered in the study.

In a supply chain where the raw materials and the manufacturing process are water dependent, the consideration of water footprint is appropriate. None of above-mentioned studies took advantage of using water footprint data as input parameters in quantifying decisions along the supply chain. According to Vlachos and Aivazidou (2018), there are limited studies that integrate water footprint in the supply chain operations. Aivazidou et al. (2016) suggested to integrate WFP in all industrial and supply chain operations. The knowledge on the WFP assessments of materials and processes should be used as basis to make important decisions in the supply chain. Integrating water footprint into supply chain management can mitigate regional water stress (Wang, et al., 2020). Despite these developments and suggestions in the existing literatures, there is still a research gap in advancing the applicability of the WFP and this is to use it as quantifiable basis in supply chain decisions.

To address the research gap, this study incorporates water footprint as an objective function in an agro-industrial supply chain optimization model. This study will formulate a mathematical model that will determine the optimal mix of raw materials to use that minimizes total cost and total water footprint. According to Kuo and Lee (2019), footprint metrics should be integrated into green supply chain models based on multi-objective formulations. This study uses the cost and WFP information related to the raw materials from different sources in producing a product. Aside from extending the relevance of WFP assessments for future research, the results of the study can serve as basis for collaboration with the suppliers to improve performance of the supply chain. According to Tseng et al (2019), existing studies on green supply chain practices is lacking with theoretical evidence to assess the connection between the actions and performance of the supply chain. Tseng et al (2019) suggested to use the evidence whenever studies on designing a framework between green supply chain practices and performance are to be done. This study can justify the need to strengthen the collaboration with suppliers to minimize procurement cost and water footprint of the supply chain. The rest of the paper is organized as follows. Section 2 provides the problem statement. Section 3 presents the mathematical model. Section 4 shows the results and discussions. Finally, section 5 shows the conclusions.

2. Problem statement

A set of suppliers that can supply all raw materials needed to produce the final product. Each raw material j coming from supplier i has a corresponding purchase cost, c_{ij}. Further, each raw material j has an associated water footprints in terms of blue (b_{ij}), green (g_{ij}), and gray (r_{ij}) components. The aim is to determine the amount of raw materials to purchase from the set suppliers that will minimize cost and water footprint. Figure 1 shows the system being considered.

3. Methodology/ Model formulation

The following are the assumptions employed in the model: (1) each supplier has unique processes and production efficiency that led to varying production costs and water footprints per raw material; (2) each supplier has two levels of capacities – collective capacity and individual capacity per raw material; (3) a unit of final product requires j number of raw materials; (4) the demand of the final product is known; and (5) every raw material j requires a fixed amount to produce a unit of the final product.

The model has two objective functions. The first objective function, Z_1, is total cost per unit of the final product produced as shown in Eq(1). The total cost consists of the procurement costs of the raw materials needed to

produce the final product. The second objective function, Z_2, is total water footprints per unit of the final product as shown in Eq(2). It is the sum of the water footprint of the individual raw material used to produce a unit of the final product.
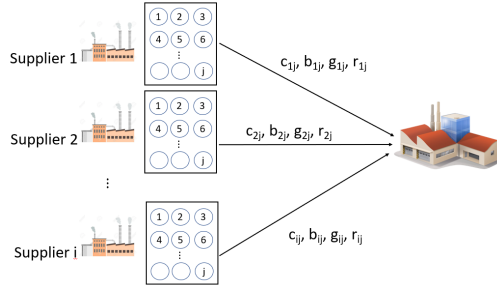

Figure 1: System in consideration

$$Min\ Z_1 = \sum_j \sum_i \frac{c_{ij} x_{ij}}{DEM} \tag{1}$$

$$Min\ Z_2 = \sum_j f_j \tag{2}$$

The water footprint of raw material j has three components as shown in Eq(3). These are the blue, green, and gray water footprint components. Eq(4) to Eq(6) represent the blue, green, gray components of the water footprint. The water footprint contributions of all the raw materials are divided by the total demand or target production of the final product. Hence, the second objective function represents the total water footprint per unit of final product produced.

$$f_j = B_j + G_j + R_j \qquad \forall j \tag{3}$$

$$B_j = \frac{\sum_i b_{ij} x_{ij}}{DEM} \qquad \forall j \tag{4}$$

$$G_j = \frac{\sum_i g_{ij} x_{ij}}{DEM} \qquad \forall j \tag{5}$$

$$R_j = \frac{\sum_i r_{ij} x_{ij}}{DEM} \qquad \forall j \tag{6}$$

There are two sets of constraints for the model. These are the capacity constraints and the demand constraint. Eq(7) is the collective capacity of supplier i. Each supplier has a lower collective capacity compared to individual capacity for raw materials. Eq(8) is the individual raw material capacity for supplier i.

$$\sum_j x_{ij} \le CAP_i \qquad \forall i \tag{7}$$

$$x_{ij} \le RMCAP_{ij} \qquad \forall i,j \tag{8}$$

The demand constraint for each raw material j is shown in Eq(9). The demand for each raw material j is a function of the total demand or target production for the final product and the fixed amount of the raw material to produce a unit of the final product. Eq(10) represents the non-negative constraint.

$$\sum_i x_{ij} = \propto_j DEM \qquad \forall j \tag{9}$$

$$x_{ij} \ge 0 \qquad \forall i,j \tag{10}$$

To integrate the total cost (Z_1) and water footprint (Z_2) objective functions into a single equation, the concept on a weighted Goal Programming is used. Each objective function is converted into a goal constraint as shown in Eq(11) and Eq(12). The deviation from best solution, Z1min and Z2min, are to be minimized in the Goal

Programming objective function. This is similar to the method used by Tiu and Cruz (2017). Eq(13) shows the Goal Programming objective function. The decision-maker will assign values to the weights, cweight and WFPweight, that will serve as the level of priority. The value of the weights is anywhere between 0 to 1. The sum of the weights should be equal to one.

$$Z_1 - u = Z1min \tag{11}$$

$$Z_2 - v = Z2min \tag{12}$$

$$Min\ Z = 100 \left(\frac{u}{Z1max - Z1min} cweight + \frac{v}{Z2max - Z2min} WFPweight \right) \tag{13}$$

The final model is reduced to a single objective that minimizes total weighted deviations. The size of the model is dependent on the number of suppliers that can supply the required materials to produce the final product.

4. Results and discussions

The model is illustrated here with a case study adapted from Rivas Ibáñez et al. (2017). Additional hypothetical data were provided since data from the case study are enough. In the validation process, the final product needs seven raw materials which can be sourced from three suppliers. Each supplier is assumed to be capable of providing all the raw materials with different selling prices and water footprints. The working model was implemented in Excel and solved using Excel Solver.

The conversion to Goal Programming objective function will require the identification of the maximum and minimum values of the total cost objective function and water footprint objective function before solving the Goal Programming model. These maximum values (Z1max and Z2max) and minimum values (Z1min and Z2min) can be derived by solving the model using one objective function at a time with the other objective function serving as system variable. The values of Z1max, Z2max, Z1min, and Z2min are additional inputs to the Goal Programming Model. In the validation process, the following are the weight ratios (cweight, WFPweight) considered in the – (0 %, 100 %), (20 %, 80 %), (40 %, 60 %), (50 %, 50 %), (60 %, 40 %), (80 %, 20 %), and (100 %, 0 %).

Figure 2a and 2b shows the results of the sensitivity done on the model. As shown in Figure 2a, as the level of priority for the total cost went down from 100 % to 50 %, the total cost per unit of production increases significantly and the water footprint per unit of production decreases significantly. It is best to set the weight of the total cost to anywhere between 40 % to 50 % if the decision maker prefers to achieve the impact of the WFP to the solution. The consolidation of the two objective functions using goal programming encompasses the different behaviours of decision-makers when two conflicting objective functions are present. This method can provide appropriate solutions depending on the level of preference of the decision-maker.
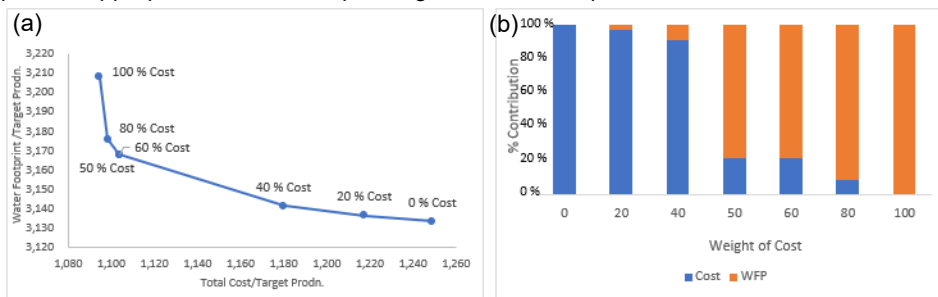

Figure 2: Sensitivity results for (a) total cost vs. water footprint relationship, (b) deviation contribution to the goal programming objective function

Figure 2b shows the percentage contribution of the deviations from the minimum value of the total cost per unit of production and from the minimum value of the water footprint. Based on the graph, it shows that at a weight of at most 40 % for the total cost, the total deviations are primarily comprised of deviations from the minimum total cost per unit of production. If the weight of the total cost increases at least 50 %, the composition of the total deviations is mostly contributed by the deviation from the water footprint.

Figure 3a and 3b show the sources of raw materials depending on the level of priority of the objective functions. When the water footprint is prioritized over the total cost, as shown in Figure 3a, the firm will have to source all raw materials from the first supplier. This means that the products of the first supplier have the lowest water footprints. On the other hand, the firm will try to distribute the sourcing of their raw materials among the available

suppliers when the priority shifted to the total cost as shown in Figure 3b. This is because the products of the first supplier having the lowest water footprints but more costly.

The results of the study are consistent with the study done by Tiu and Cruz (2017) where the economic and environmental impact were considered. There will be a point where environmental impact (or the water footprint) will give more significant impact over economic. Further, the result of the study proves that WFP assessments provided in the study of Rivas Ibáñez et al. (2017) can be used for prescriptive modelling.
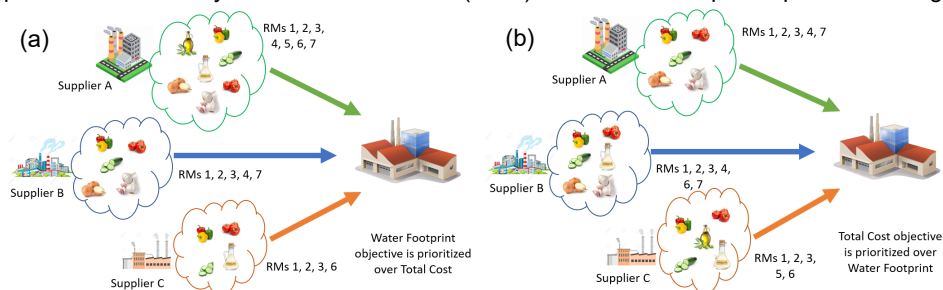

Figure 3: Sources of raw materials with (a) prioritized water footprint, and (b) prioritize total cost

5. Conclusions

An optimization model for supplier selection considering costs and water footprint was developed with capacity and demand constraints. The two objective functions were integrated into one using goal programming. The study was able to widen the relevance of water footprint assessments by using the data in supply chain decisions like supplier selection. Hence, studies on water footprint should not only focus on the assessment. The study shows that water footprint can become significant with a level of priority between 40 % to 50 %. Also, the consideration of water footprint allows the purchase of raw materials from supplier with a higher cost if it will reduce the total water footprint of the process. This study can be extended by considering other tactical and operational decisions in the supply chain. One of these is the selection of the processes or machines to use that can improve the direct water consumption in producing the products. Another direction for further study is to include the accounting of indirect water consumption in storing and delivery of products to the consumers. Activities related to collection of used products and recovery activities can also be considered. With these considerations, it would be appropriate to include the minimization of carbon footprint as another objective function.

Nomenclature

i – index for supplier i
j – index for raw material j
Z_1 – total cost per unit of production, peso/unit
Z_2 – total water footprint, m^3/unit
Z – total weighted deviation, percent
$Z1max$ – maximum total cost value, peso/unit
$Z1min$ – minimum total cost value, peso/unit
$Z2max$ – maximum total water footprint, m^3/unit
$Z2min$ – minimum total water footprint, m^3/unit
u – deviation from minimum total cost, peso/unit
v – deviation from minimum total water footprint, m^3/unit
cweight – weight assigned to total cost deviation
WFPweight – weight assigned to total water footprint deviation
c_{ij} – procurement cost from supplier i of raw material j, peso/unit
f_j – water footprint of raw material j used per unit of production, m^3/unit

B_j – blue water footprint component raw material j used per unit of production, m^3/unit
G_j – green water footprint component of raw material j used per unit of production, m^3/unit
R_j – gray water footprint component of raw material j used per unit of production, m^3/unit
b_{ij} – blue water footprint component of a unit of raw material j from supplier i, m^3/unit
g_{ij} – green water footprint component of a unit of raw material j from supplier i, m^3/unit
r_{ij} – gray water footprint component of a unit of raw material j from supplier i, m^3/unit
DEM – demand of the final product, units
CAP_i – total capacity of supplier i, units
$RMCAP_{ij}$ – capacity of supplier i for raw material j, units
$\propto_j$ – amount of raw material j needed to produce a unit of the final product, units
x_{ij} – amount of raw material j to purchase from supplier i, units

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