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# Wine Supply Chain Network Configuration under a Water Footprint Cap

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**Abstract:** As agriculture and industry exploit more than 90% of the global freshwater resources, water overuse and degradation have emerged as critical socio-environmental challenges for both nations and corporations. In this context, the water footprint concept was introduced in order to quantify the freshwater consumption and pollution of a territory or across a product's life cycle. As research on water management in supply chains is growing, this work aims to integrate the perspective of freshwater resources into supply network configuration. Focusing on the agrifood sector, we have developed a mixed-integer linear programming model that can be used to minimize the operational costs under a water footprint cap in a wine supply chain network by selecting the optimal suppliers (vine growers), manufacturing sites (winemakers), and transportation modes (fuel-powered trucks). The optimization outcomes unveil that the wine network's configurations (structure and fuel type) vary significantly depending on the values of the water footprint cap so as to balance the trade-off between economic and water-related environmental efficiency. Beyond the viticulture sector, the proposed model is anticipated to act as a paradigm for setting joint sustainable targets or caps to limit water use across supply chains.

**Keywords:** supply chain network configuration; sustainability; water footprint; viticulture; wine industry; mixed-integer linear programming; e-constraint method



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## 1. Introduction

As freshwater resources are depleting at an alarming rate, projections caution that more than 40% of the world's population will be living in regions that are facing severe water scarcity by 2050 [1]. In fact, growing population, climate change, intensive agriculture, and continuing industrialization considerably stress the availability of freshwater supplies [2,3]. In particular, the agricultural sector consumes and pollutes about 70% of the global supply of freshwater, while the industrial sector accounts for 22% of worldwide freshwater appropriation [4]. As freshwater overexploitation and degradation have been emerging as crucial socio-environmental concerns that affect both consumers' and companies' awareness [5,6], an increasing number of leading corporations have launched water disclosure and management initiatives within their social responsibility agendas [7]. This is in line with the United Nations' Sustainable Development Goals (SDGs) that set, among other goals, specific targets for universal and equitable clean water access (SDG#6) [8] and the responsible use of natural resources, including freshwater (SDG#12) [9], by 2030.

In this context, the concept of water footprint (WF) has been introduced as a key performance indicator for quantifying water use at national, business, or product levels [10]. From a product's life cycle perspective, the WF is defined as the total volume of freshwater that is consumed and polluted, directly or indirectly, across a product's full supply chain [11].

As a multidimensional indicator, the WF consists of three components, i.e., green, blue, and grey water [10]. Specifically, green water addresses the absorption of rainwater by plants, blue water constitutes the consumption of surface or groundwater, and grey water refers to the freshwater quantity that is required for assimilating pollutants under specific water quality standards. Beyond the WF assessment approach, the life cycle analysis (LCA) community has developed alternative methodologies for evaluating freshwater consumption and pollution [12]; for example, assessment that is based on local water stress [13]. At the same time, *ISO 14046* can be used to specify the principles, requirements, and guidelines for the quantification, impact assessment, and reporting of the WF of products, processes, and organizations [14]. Overall, although several research efforts propose updated WF calculations (e.g., regarding grey water), it is crucial that all of the related data inventories, thresholds, and approaches regarding the quantification process should be transparent in order to support robust decision-making [15,16].

Given that WF analysis has become an established research field along with carbon footprinting [17], scientific publications on WF accounting and management across entire supply chains, particularly those of the agrifood sector, have been emerging [18–20]. As water scarcity will become the major climate-related threat to corporate assets within the next decades [21], agriculture should be also adapted by: (i) shifting operations to less water-stressed regions, (ii) cultivating adequate water-efficient crops, and (iii) using innovative farming technologies [22,23]. In this light, this work proposes that agribusinesses should integrate the WF aspect into their supply chain network configuration (SCNC) by selecting the optimal suppliers/farmers, manufacturing/processing sites, and transportation modes in terms of both the operational cost and water use. Hence, we pose the following research questions (RQs):

- *RQ#1: Which is the optimal design of an agrifood supply chain in terms of its economic performance and, further, considering its water use efficiency?*
- *RQ#2: How could a supply chain WF cap act as a shared target to limit water use beyond the boundaries of a single stakeholder?*

To respond to RQ#1, we developed a multi-objective mixed-integer programming (MILP) model to configure an agrifood supply chain network by minimizing the operational costs and WFs. In order to optimize the operations research (OR) model, an implementation case of wine supply in Greece, including different vine growers, winemaking locations, fuel-powered truck modes, and markets, was used. Notably, several research efforts focus on assessing the WF of wine [24–27]; wine is considered to be a premium product within the Greek economy, thus its sustainability should be safeguarded [28,29]. To tackle RQ#2, we utilized the e-constraint approach, through which the cost-related objective function was optimized by using the water-oriented objective function as an additional problem constraint [30]. By shifting the right-hand side of the constrained function, we explored diverse sustainable wine supply chain structures under different WF caps (e-values).

Overall, as green SCNC is a precondition for ensuring corporate sustainability [31], this research contributes to strategic decision-making for (re)configuring agrifood supply chain networks by enhancing both their financial performance and the freshwater resources' efficiency. The remainder of the paper is structured as follows. In Section 2, we provide a brief literature background on water-related supply network design efforts. In Section 3, the multi-objective MILP model for SCNC under a WF cap is explained. In Section 4, a realistic numerical experimentation of a wine supply chain in Greece is reported, while the obtained optimization results are discussed. In Section 5, we conclude with managerial insights and recommendations for future research.

## 2. Literature Background

In order to integrate the WF concept into agrifood SCNC, a brief description of the major freshwater requirements of each supply chain echelon is essential. Particularly, the suppliers (i.e., farmers) are responsible for the green WF with respect to the climatic and geographical conditions of their location [32], the blue WF that is related to the irrigation techniques (e.g., conventional, drip, or deficit) that are applied during cultivation [33], and the grey WF that results from the fertilizers that are used [34]. Manufacturers account for the blue WF that is associated with the water-related efficiency of the technological equipment (e.g., conventional systems, water recycling, and reuse) that is used during industrial processing [24], as well as the water that is consumed for cleaning packages and machines [17] and the grey WF that is linked to the direct or indirect industrial water pollution, for example that which is due to energy consumption [26]. Finally, transportation relates to the green, blue, and grey WF that is related to the production of the different types of fuels (e.g., fossil fuels or biofuels) that are used for powering the transporting vehicles [35].

Within the extant scientific literature, the scientific efforts in the field of SCNC incorporating the freshwater resources perspective are growing rapidly, particularly during the last years (Figure 1). In the agrifood sector, Vujanović et al. [36] built a multi-objective MILP model that aims to maximize corporate profits and evaluate the environmental impact of the energy, carbon, nitrogen, and water footprints in a poultry-meat supply chain network. At the same time, Fragoso and Figueira [37] developed a multi-objective MILP model that aims to maximize profitability, minimize carbon emissions and water use, and maximize employment and supplier numbers in a wine supply chain. Using a non-linear programming methodology, Motevalli-Taher et al. [38] formulated a multi-objective mixed-integer non-linear programming (MINLP) model that aims to minimize network costs and water consumption, while maximizing employment opportunities in a wheat supply chain. Dealing with uncertainty, Baghizadeh et al. [39] proposed a stochastic multi-objective MINLP model that aims to maximize profitability and minimize water and energy consumption, as well as the waiting and transportation times, in an agrifood supply chain. By implementing diverse approaches, Park et al. [40] developed a novel comprehensive framework that combines LCA, ReCiPe, and linear programming-based modeling in order to minimize environmental impacts (including water use) so as to produce a certain economic output in various agrifood supply chains.

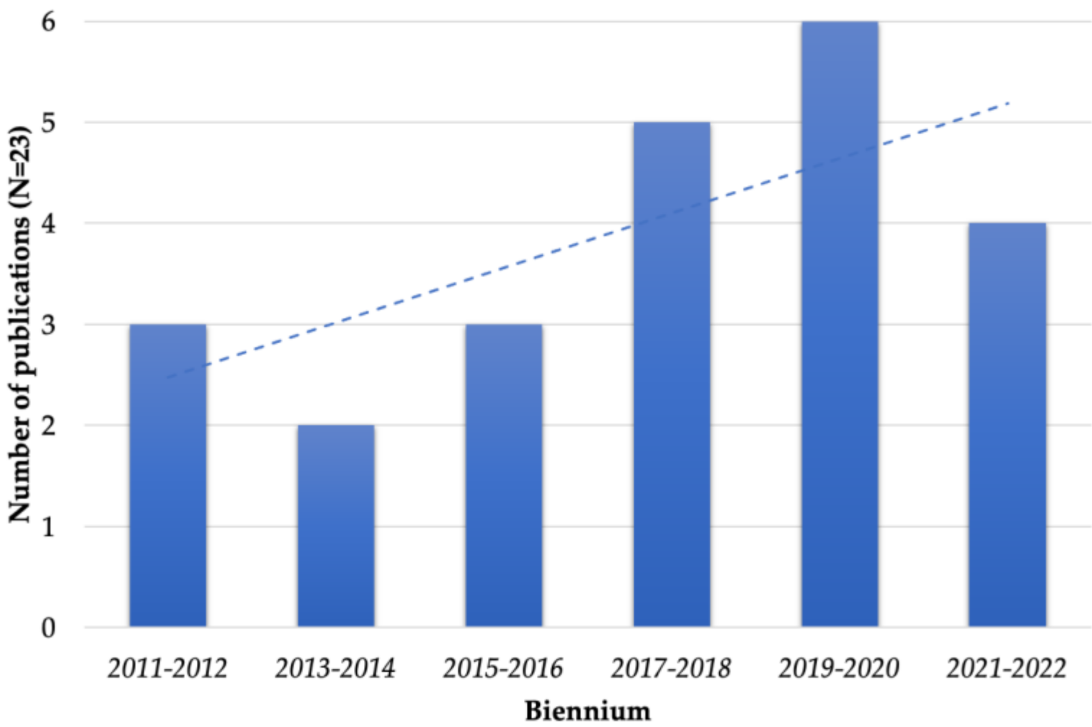


**Figure 1.** Distribution of publications by two-year period (Dotted line: linear trend).

Regarding the bioenergy and biofuels industry, Papapostolou et al. [41] developed an MILP model to optimize the economic performance of a biofuel supply chain network under environmental constraints that limit land use and freshwater consumption. Through a multi-objective perspective, Bernardi et al. [42,43] provided a multi-objective MILP model to maximize profitability and minimize both carbon and water footprints in a bioethanol supply chain network. Moreover, Nodooshan et al. [44] built a multi-objective MILP model to minimize the operational costs and carbon emissions of a biofuel supply chain network while considering freshwater consumption, while Abdali et al. [45] formulated a multi-objective MILP model to maximize the profits and minimize the carbon emissions and water use in a sugarcane-to-bioenergy supply chain. In order to incorporate uncertainty into their efforts, Abdali et al. [46] proposed a stochastic MILP model so as to minimize the operational costs, including the energy and water consumption costs, in a sugarcane-to-bioenergy supply chain, whereas Gonela et al. [47] developed a stochastic MILP to examine different supply chain configurations in a bioethanol industry under various sustainability standards (including those regarding water consumption). Furthermore, López-Díaz et al. [48] built a stochastic multi-objective MILP model that aims to design a sustainable (in terms of profits, emissions, and water requirements) biofuel supply chain while considering the production and distribution of feedstocks, grains, and biofuels that are under water and land constraints. Through a multi-method lens, Azadeh and Arani [49] developed a hybrid approach, including a system dynamics model and a stochastic MINLP model, in order to simulate the key parameters of the biodiesel supply chain (e.g., water consumption) and maximize the profits. In addition, Mahjoub and Sahebi [50] proposed a combination of GIS modeling and MINMAX goal programming to minimize the total costs, maximize the energy production, and minimize the water consumption in a bioenergy supply chain. Finally, Aviso et al. [51] formulated a fuzzy input–output model for supply chains considering WF constraints and they demonstrated it on the ceramic tile industry and biofuel production.

Within heavy industry, Hwangbo et al. [52] developed an MILP model to minimize the total annual costs of a biogas supply chain (including wastewater treatment) and simultaneously satisfy hydrogen demand, while Hwangbo et al. [53] built a stochastic MILP model to minimize the total cost while further considering the demand uncertainty of the water, electricity, steam, and hydrogen that are consumed in global hydrogen supply networks. Moreover, Chen et al. [54] provided an inexact multi-criteria decision-making framework that aims to optimize the economic and environmental (including freshwater supply) performance of a shale gas supply chain under uncertainty. Notably, Pourmehdi et al. [55] formulated a stochastic multi-objective MILP to optimize profitability, energy and water consumption, carbon emissions, employment opportunities, and lost working days in a closed-loop steel supply chain by determining the optimal production technology. With respect to light industry, Sherafati e al. [56] proposed a multi-objective MINLP model that aims to maximize profitability and social responsibility while taking into consideration environmental impacts, such the carbon and water footprints, in a cable supply chain. Finally, in a more generic context, Guo et al. [57] built a multi-objective MILP model for designing a sustainable supply chain network by minimizing the operational costs, carbon emissions, and water consumption, whereas Das et al. [58] developed a chance–constraint programming model for supply network design by addressing carbon and water footprints, waste, social indicators, service levels, transportation modes, and inventories under uncertainty.

Table 1 summarizes the abovementioned literature efforts on water-related SCNC, highlighting the sector that is under study, the methods that have been used, and the WF focus in the model that has been developed. Regarding the industrial sector, the majority of the articles fit within the bioenergy and biofuels field (48%), followed by those belonging to the agrifood industry (22%). In terms of the methodological approach that has been used, 61% of the research efforts developed MILP models, most of which propose a multi-objective perspective, while some papers provide non-linear programming models. In addition, several publications deal with stochastic models under uncertain environments, whereas others employ a combination of methodologies. With respect to the focus of the developed SCNC models for WF, 48% of the articles utilize parameters that are related to water consumption or pollution (along with the related enviro–economic impacts) in order to build the objective function, 22% of the papers refer to water use as a problem constraint, while 30% of the publications emphasize freshwater resources in both the objective function and the constraints. It should be noted that this review is not a rigid literature collection of water-oriented SCNC research, but that it rather acts as a guide map of the most pertinent scientific efforts in the field.

**Table 1.** Literature taxonomy (in author names' alphabetical order).

| Author | Year | Sector | Method | WF Focus |
|---|---|---|---|---|
| Abdali et al. [45] | 2021 | Bioenergy and biofuels | Multi-objective MILP | Objective |
| Abdali et al. [46] | 2022 | Bioenergy and biofuels | Stochastic MILP | Objective |
| Aviso et al. [51] | 2011 | Ceramics, bioenergy and biofuels | Fuzzy input-output model | Constraint |
| Azadeh and Arani [49] | 2016 | Bioenergy and biofuels | System dynamics, stochastic MINLP | Objective |
| Baghizadeh et al. [39] | 2021 | Agrifood | Stochastic multi-objective MINLP, G/M/S/M queuing system | Objective |
| Bernardi et al. [42] | 2012 | Bioenergy and biofuels | Multi-objective MILP | Objective |
| Bernardi et al. [43] | 2013 | Bioenergy and biofuels | Multi-objective MILP | Objective |
| Chen et al. [54] | 2018 | Shale gas and hydrogen | LCA, interval linear programming, multi-objective programming, multi-criteria decision analysis | Objective, constraint |
| Das et al. [58] | 2020 | Not applicable | Chance-constrained programming | Constraint |
| Fragoso and Figueira [37] | 2021 | Agrifood | Multi-objective MILP | Objective |
| Gonela et al. [47] | 2015 | Bioenergy and biofuels | Stochastic MILP | Constraint |
| Guo et al. [57] | 2019 | Not applicable | Multi-objective MILP | Objective |
| Hwangbo et al. [52] | 2017 | Shale gas and hydrogen | MILP | Objective, constraint |
| Hwangbo et al. [53] | 2017 | Shale gas and hydrogen | Stochastic MILP | Objective, constraint |
| Lopez-Diaz et al. [48] | 2018 | Bioenergy and biofuels | Stochastic multi-objective MILP | Objective, constraint |
| Mahjoub and Sahebi [50] | 2020 | Bioenergy and biofuels | GIS, MINMAX goal programming | Objective, constraint |
| Motevalli-Taher et al. [38] | 2020 | Agrifood | Multi-objective MINLP | Objective, constraint |
| Nodooshan et al. [44] | 2018 | Bioenergy and biofuels | Multi-objective MILP | Objective, constraint |
| Papapostolou et al. [41] | 2011 | Bioenergy and biofuels | MILP | Constraint |
| Park et al. [40] | 2016 | Agrifood | LCA, ReCiPe, data envelopment analysis | Objective |
| Pourmehdi e al. [55] | 2020 | Steel and metal | Stochastic multi-objective MILP | Objective |
| Sherafati e al. [56] | 2019 | Electronics | Multi-objective MINLP | Constraint |
| Vujanovic et al. [36] | 2014 | Agrifood | Multi-objective MILP | Objective |

## 3. Model Development

An SCNC model for minimizing the operational costs and the WF of an agrifood supply chain network, through selecting the optimal suppliers, manufacturing sites, and transportation modes, is proposed in this paper. In order to showcase a more realistic case study of the agrifood sector, we have considered a wine supply chain network. Although a typical wine supply chain may consist of suppliers, wineries, bottling plants, distribution centers, and demand points [59], this strategic study includes three discrete echelons: (i) suppliers (i.e., vine growers), (ii) manufacturing sites, where wine making/ageing and bottling are taking place, and (iii) markets, in which regional warehousing/distribution centers fulfil the bottled wine demand of nearby points (Figure 2). In order to build the OR model, a multi-objective MILP methodology was employed, including both continuous (i.e., quantity-related) and binary (i.e., location- or mode-related) variables [60].

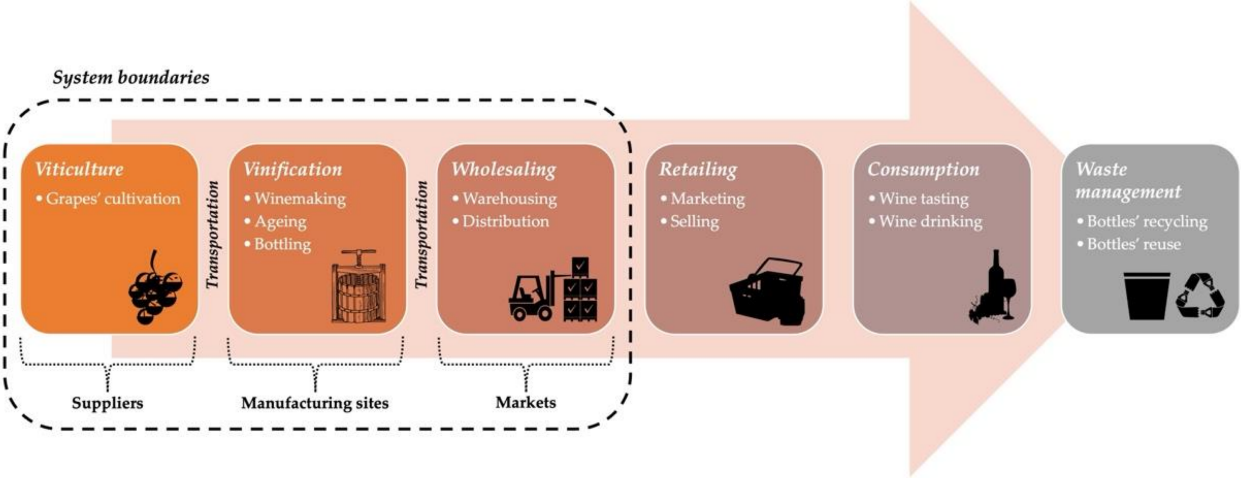


**Figure 2.** Wine supply chain network boundaries (Adapted from Aivazidou and Tsolakis [61]).

We further assumed the requirement of a single raw material type (i.e., a specific grape variety), which is sourced from different suppliers, and a unique product type (i.e., 0.75 L bottled wine), which is produced in different manufacturing sites of the winemaker. Each supplier and manufacturing site demonstrate diverse cost and water coefficients depending on the various technologies that are applied in the viticulture and winemaking stages, respectively. In addition, the transportation of the grapes from the suppliers to the manufacturing sites, as well as that of the bottled wine from the manufacturing sites to markets, can be performed by different types of trucks which can be discriminated based on the economic and water-related efficiencies of the fuels that are used. In order to facilitate the model's development, we used the following indices: i for suppliers, j for manufacturing sites, k for markets, and m for transportation modes. Given that wine is produced once a year, an annual time horizon is set, thus all of the continuous variables are expressed on a yearly basis. Tables 2 and 3 present the model's decision variables and parameters, respectively.

**Table 2.** SCNC model decision variables.

| Variable | Definition | Unit |
|---|---|---|
| $M_i$ | Mass of grapes sourced from supplier i | kg |
| $Q_j$ | Quantity of wine produced in manufacturing site j | bottle |
| $M_{ijm}$ | Mass of grapes transported from supplier i to manufacturing site j using transportation mode m | kg |
| $Q_{jkm}$ | Quantity of wine transported from manufacturing site j to market k using transportation mode m | bottle |
| $x_i$ | 1 if grapes are sourced from supplier i and 0 if not | {0,1} |
| $y_j$ | 1 if wine is produced in manufacturing site j and 0 if not | {0,1} |
| $x_{ijm}$ | 1 if grapes are transported from supplier i to manufacturing site j using transportation mode m and 0 if not | {0,1} |
| $y_{jkm}$ | 1 if wine is transported from manufacturing site j to market k using transportation mode m and 0 if not | {0,1} |

In order to optimize the economic and environmental sustainability of the system that is under study, the MILP model's objective functions were developed so as to quantify the total annual cost and WF of the wine supply chain network. More specifically, Equation (1) includes the fixed (i.e., first and third terms) and variable (i.e., second and fourth terms) costs of the grapes' procurement and wine production, as well as the transportation cost (i.e., fifth and sixth terms) of both the grapes and the wine. Equation (2) comprises the WF of the grapes' cultivation (i.e., first term), winemaking (i.e., second term), and transportation (i.e., third and fourth terms), depending on the type of fuel that is consumed.

$$\mathrm{Cost} = \sum_{i} f_i^g \cdot x_i + \sum_{i} v_i^g \cdot M_i + \sum_{j} f_j^w \cdot y_j + \sum_{j} v_j^w \cdot Q_j + \sum_{i,j,m} c_m \cdot d_{ij} \cdot M_{ijm} + \sum_{j,k,m} c_m \cdot h_{jk} \cdot b \cdot Q_{jkm} \tag{1}$$

$$WF = \sum_{i} w_i^g \cdot M_i + \sum_{j} w_j^w \cdot Q_j + \sum_{i,j,m} w_m \cdot t_m \cdot d_{ij} \cdot M_{ijm} + \sum_{j,k,m} w_m \cdot t_m \cdot h_{jk} \cdot b \cdot Q_{jkm} \quad (2)$$

**Table 3.** SCNC model parameters.

| Parameter | Definition | Unit |
|---|---|---|
| $f_i^g$ | Fixed cost of grapes' procurement from supplier i | € |
| $v_i^g$ | Variable cost of grapes' procurement from supplier i | €/kg |
| $f_j^w$ | Fixed cost of wine production in manufacturing site j | € |
| $v_j^w$ | Variable cost of wine production in manufacturing site j | €/bottle |
| $c_m$ | Transportation cost per mass unit of grapes/wine and distance using transportation mode m | €/kg/km |
| $d_{ij}$ | Distance between supplier i and manufacturing site j | km |
| $h_{jk}$ | Distance between manufacturing site j and market k | km |
| b | Bottle's gross weight | kg/bottle |
| $w_i^g$ | Water footprint of grapes' procurement from supplier i per mass unit of grapes | L/kg |
| $w_j^w$ | Water footprint of wine production in manufacturing site j per quantity unit of wine | L/bottle |
| $w_m$ | Water footprint of fuel consumption using transportation mode m per volume unit of fuel | L/L |
| $t_m$ | Fuel consumption per mass unit of grapes/wine and distance using transportation mode m | L/kg/km |
| L | Considerably large positive number | - |
| r | Conversion ratio of mass of grapes per quantity of wine | kg/bottle |
| $D_k$ | Wine demand of market k | bottle |

Notably, there are three methodological approaches for solving multi-objective programming problems according to the phase in which the decision-maker expresses their preferences, namely: (i) the a priori, (ii) the interactive, and (iii) the a posteriori methods [62]. In the a posteriori method, the efficient solutions are calculated and then the decision-maker selects the most preferred one. In order to solve the proposed SCNC problem, the e-constraint method was employed. This is considered to be the most appropriate a posteriori method for bi-objective MILP problems [30]. More specifically, following the e-constraint approach, the cost-related objective function was optimized using the water-oriented objective function as an additional problem constraint (Inequation (3)). By parametrically shifting the right-hand side (e-value) of the constrained function, we obtained several feasible solutions to the problem. However, the calculation of the right-hand side range was not a trivial process. In fact, although the best (lower) cap of the e-range was easily attainable as the optimal value of the individual minimization of the WF function, the worst (higher) cap was not. Thus, Mavrotas [30] proposed the use of lexicographic optimization. Following this method, first the cost function was individually minimized. Then, the higher cap of the e-range was obtained by minimizing the WF function under an additional constraint, expressing that the cost function equals its optimal value based on the prior individual minimization.

*Min*

$$\sum_{i} f_i^g \cdot x_i + \sum_{i} v_i^g \cdot M_i + \sum_{j} f_j^w \cdot y_j + \sum_{j} v_j^w \cdot Q_j + \sum_{i,j,m} c_m \cdot d_{ij} \cdot M_{ijm} + \sum_{j,k,m} c_m \cdot h_{jk} \cdot b \cdot Q_{jkm}$$

*Subject to:*

$$\sum_{i} w_i^g \cdot M_i + \sum_{j} w_j^w \cdot Q_j + \sum_{i,j,m} w_m \cdot t_m \cdot d_{ij} \cdot M_{ijm} + \sum_{j,k,m} w_m \cdot t_m \cdot h_{jk} \cdot b \cdot Q_{jkm} \leq e \; \forall \, i, j, k \quad (3)$$

$$M_i = \sum_{j,m} M_{ijm} \; \forall \, i \quad (4)$$

$$Q_j = \sum_{k,m} Q_{jkm} \; \forall \, j \quad (5)$$

$$M_i \leq L \cdot x_i \; \forall \, i \quad (6)$$

$$Q_j \leq L \cdot y_j \; \forall \, j \quad (7)$$

$$\sum_{i,m} M_{ijm} = r \cdot \sum_{j} Q_j \ \forall\, j \tag{8}$$

$$\sum_{j,m} Q_{jkm} = D_k \ \forall\, k \tag{9}$$

$$\sum_{m} x_{ijm} \ \leq \ 1 \ \forall\, i, j \tag{10}$$

$$\sum_{m} y_{jkm} \ \leq \ 1 \ \forall\, j, k \tag{11}$$

$$M_{ijm} \ \leq \ L \cdot x_{ijm} \ \forall\, i, j, m \tag{12}$$

$$Q_{jkm} \ \leq \ L \cdot y_{jkm} \ \forall\, j, k, m \tag{13}$$

$$M_i, Q_j, M_{ijm}, Q_{jkm} \ \geq \ 0 \tag{14}$$

$$x_i, y_j, x_{ijm}, y_{jkm} \ \in \ \{0, 1\} \tag{15}$$

Formulas (4) to (13) constitute the rest of the problem constraints of the MILP model. Particularly, the total mass of the grapes that are sourced from supplier i should be equal to the sum of the masses of the grapes that are transported from supplier i to all of the manufacturing sites j, regardless of the transportation mode m (Equation (4)). The total quantity of wine that is produced in manufacturing site j should be equal to the sum of the quantities of the wine that is transported from manufacturing site j to all of the markets k, regardless of the transportation mode m (Equation (5)). A mass of grapes is sourced from supplier i only if supplier i is selected for procurement (Inequation (6)), whereas a quantity of wine is produced in manufacturing site j only if manufacturing site j is selected for production (Inequation (7)). In addition, the total mass of the grapes that are transported from all of the suppliers i to the manufacturing site j, regardless of the transportation mode m, should cover the total quantity of the wine that is produced in manufacturing site j (Equation (8)). The total quantity of wine that is transported from all of the manufacturing sites j to market k, regardless of the transportation mode m, should cover the demand for wine of market k (Equation (9)). If a mass of grapes is transported from supplier i to the manufacturing site j (Inequation (10)) or a quantity of wine is transported from the manufacturing site j to market k (Inequation (11)), only one transportation mode m can be used at a time. Finally, a mass of grapes is transported from supplier i to manufacturing site j using transportation mode m (Inequation (12)) or a quantity of wine is transported from manufacturing site j to market k using transportation mode m (Inequation (13)) only if the related decisions are made. Formulas (14) and (15) constitute the non-negativity constraints of the model.

## 4. Numerical Experimentation

In order to test the applicability of the MILP model, a realistic case study in the Greek territory is presented, including data acquisition and assumptions. Thereafter, a brief discussion of the obtained optimization results is provided.

### *4.1. Case Study Description*

Three different suppliers in Chalkidiki, Larissa, and Korinthia were considered. The average local agricultural WF was retrieved from the WaterStat database [63], based on the calculations of Mekonnen and Hoekstra [64] and according to the WF assessment methodology [10]. Given that the supplier in Chalkidiki demonstrates the lowest blue WF (i.e., 70 L/kg compared to 125 and 103 L/kg in Larissa and Korinthia, respectively), potentially due to the utilization of water-friendly irrigation techniques, we assumed that this supplier offers the highest variable cost. The total WFs, along with rational estimations of the fixed and variable costs of procurement, are presented in Table 4. In addition, we considered two manufacturing sites in Thessaloniki and Attiki. The average industrial WF is based on the approximations of Ene et al. [24]. Assuming that the manufacturing site in

Thessaloniki utilizes water recycling and reuse equipment, we considered that it exhibits a lower WF, yet higher costs. The total WFs, along with rational estimations of the fixed and variable costs of winemaking, are illustrated in Table 5. Finally, we considered three indicative markets in Ioannina, Larissa, and Achaia. According to the proposed model, we assumed that the total demand can be covered by the capacity of the manufacturing plants. Table 6 depicts the expected demand for bottled wine at each respective market.

**Table 4.** Supplier-related parameter values.

| Supplier i | Location | $f_i^g$ (€) | $v_i^g$ (€/kg) | $w_i^g$ (L/kg) |
|---|---|---|---|---|
| 1 | Chalkidiki | 1800 | 1.2 | 526 |
| 2 | Larissa | 1500 | 0.8 | 531 |
| 3 | Korinthia | 1200 | 1.0 | 566 |

**Table 5.** Manufacturing site-related parameter values.

| Manufacturing Site j | Location | $f_j^w$ (€) | $V_j^w$ (€/bottle) | $W_j^w$ (L/bottle) |
|---|---|---|---|---|
| 1 | Thessaloniki | 2000 | 2.4 | 2 |
| 2 | Attiki | 1000 | 1.8 | 5 |

**Table 6.** Market-related parameter values.

| Market k | Location | $D_k$ (bottle) |
|---|---|---|
| 1 | Ioannina | 30,000 |
| 2 | Larissa | 60,000 |
| 3 | Achaia | 45,000 |

We further considered two different transportation modes, depending on the type of fuel (i.e., petrol or bioethanol) that is consumed by the trucks. Notably, the use of bioethanol E85 as a transportation fuel, which is a fuel blend of 85% bioethanol and 15% petrol by volume, is not allowed by the Greek legislation unless for experimentation reasons [65]. However, for comparison reasons, it was included in the analysis given its increasing demand in the US market [66] and its emergence in some EU countries, such as France and Finland [67]. In fact, bioethanol constitutes a cheaper and lower-emission alternative to petrol, albeit less water-friendly considering the high irrigation requirements for the cultivation of biofuel crops [35]. The WFs, along with rational estimations of the transportation cost and fuel consumption of each mode, are presented in Table 7. The distances between the various nodes of the wine supply chain network (i.e., the suppliers, manufacturing sites, and markets) were calculated based on average estimates (Table 8). Finally, the bottle's gross weight and the conversion ratio from grapes to wine were set to equal 1.35 and 0.975 kg per bottle of wine, respectively.

**Table 7.** Transportation mode-related parameter values.

| Transportation Mode m | Type of Fuel | $c_m$ (€/kg/km) | $w_m$ (L/L) | $t_m$ (L/kg/km) |
|---|---|---|---|---|
| 1 | Petrol | 0.00050 | 0.33 | 0.000020 |
| 2 | Bioethanol E85 | 0.00044 | 0.90 | 0.000025 |

**Table 8.** Distances between the network nodes.

| Distance (km) | Chalkidiki | Larissa | Korinthia | Ioannina | Achaia |
|---|---|---|---|---|---|
| Thessaloniki | 100 | 150 | 610 | 260 | 470 |
| Attiki | 600 | 350 | 120 | 420 | 210 |

### *4.2. Results and Discussion*

By employing the LINGO 17.0 software, we initially calculated the right-hand side values of the e-constraint. The lowest cap of the e-range was estimated at 69,505,090 L of freshwater through the individual minimization of the WF function. Following the lexicographic optimization [30], the highest cap of the e-range was estimated at 70,568,474 L of freshwater through the minimization of the WF function under the additional constraint referring to the equality of the cost function to its optimal value (399,363.5 €) based on prior individual minimization. In order to perform sensitivity analyses, the e-range was divided into four equal intervals and the five grid points were used as individual e-values. Table 9 presents a summary of the optimization results, while Figure 3 depicts the different configurations of the wine supply chain network across the e-range of the WF constraint.

**Table 9.** Summary of optimization results.

| WF Cap (e-Value, L) | Supplier | Manufacturing Site | Transportation Mode | Mass of Grapes (kg) | Quantity of Wine (Bottle) | Operational Costs (€) |
|---|---|---|---|---|---|---|
| $e_1$ = 69,505,090 | Chalkidiki | Thessaloniki | Petrol, bioethanol | $M_1$ = 131,625<br>$M_{112}$ = 131,625 | $Q_1$ = 135,000<br>$Q_{111}$ = 30,000<br>$Q_{121}$ = 60,000<br>$Q_{131}$ = 45,000 | 517,157.8 |
| $e_2$ = 69,770,936 | Chalkidiki, Larissa | Thessaloniki, Attiki | Bioethanol | $M_1$ = 105,547.27<br>$M_2$ = 26,077.73<br>$M_{112}$ = 87,750<br>$M_{122}$ = 17,797.27<br>$M_{222}$ = 26,077.73 | $Q_1$ = 90,000<br>$Q_2$ = 45,000<br>$Q_{112}$ = 30,000<br>$Q_{122}$ = 60,000<br>$Q_{232}$ = 45,000 | 478,986.9 |
| $e_3$ = 70,036,782 | Chalkidiki, Larissa | Thessaloniki, Attiki | Petrol, bioethanol | $M_1$ = 65,841.53<br>$M_2$ = 65,783.47<br>$M_{112}$ = 65,841.53<br>$M_{222}$ = 65,783.47 | $Q_1$ = 67,530<br>$Q_2$ = 67,470<br>$Q_{112}$ = 7530<br>$Q_{122}$ = 60,000<br>$Q_{211}$ = 22,470<br>$Q_{232}$ = 45,000 | 452,974.7 |
| $e_4$ = 70,302,628 | Chalkidiki, Larissa | Thessaloniki, Attiki | Petrol, bioethanol | $M_1$ = 32,919.35<br>$M_2$ = 98,705.65<br>$M_{112}$ = 32,919.35<br>$M_{222}$ = 98,705.65 | $Q_1$ = 33,763<br>$Q_2$ = 101,237<br>$Q_{122}$ = 33,763<br>$Q_{211}$ = 30,000<br>$Q_{221}$ = 26,237<br>$Q_{232}$ = 45,000 | 427,999.9 |
| $e_5$ = 70,568,474 | Larissa | Attiki | Petrol, bioethanol | $M_2$ = 131,625<br>$M_{222}$ = 131,625 | $Q_2$ = 135,000<br>$Q_{211}$ = 30,000<br>$Q_{221}$ = 60,000<br>$Q_{232}$ = 45,000 | 399,363.5 |

In general, each e-value (or else "WF cap") leads to: (i) a different structure of the wine supply chain network regarding the optimal suppliers, manufacturing sites, and transportation modes, and (ii) diverse optimal production and transportation volumes of the grapes or bottled wine in order to balance the trade-off between the operational costs and freshwater use. More specifically, in the case of a strict WF cap (the lowest $e_1$-value), the optimal solution selects the production of grapes and bottled wine in Chalkidiki and Thessaloniki, respectively, as the most water-friendly options. The transportation of grapes from Chalkidiki to Thessaloniki (a short distance) is conducted by bioethanol-powered trucks. However, in order to keep costs at a rationally low level, the transportation of bottled wine from Thessaloniki to all three of the markets is performed by petrol-powered trucks. In contrast, in the case of a lenient WF cap (the highest $e_5$-value), the optimal solution selects the production in Larissa and Attiki as the most cost-efficient, yet less water-friendly, options. Furthermore, the transportation of the grapes from Larissa to Attiki and bottled wine from Attiki to Achaia (a short distance) is conducted by bioethanol-powered trucks, whereas the rest of the routes are performed by petrol-powered trucks.

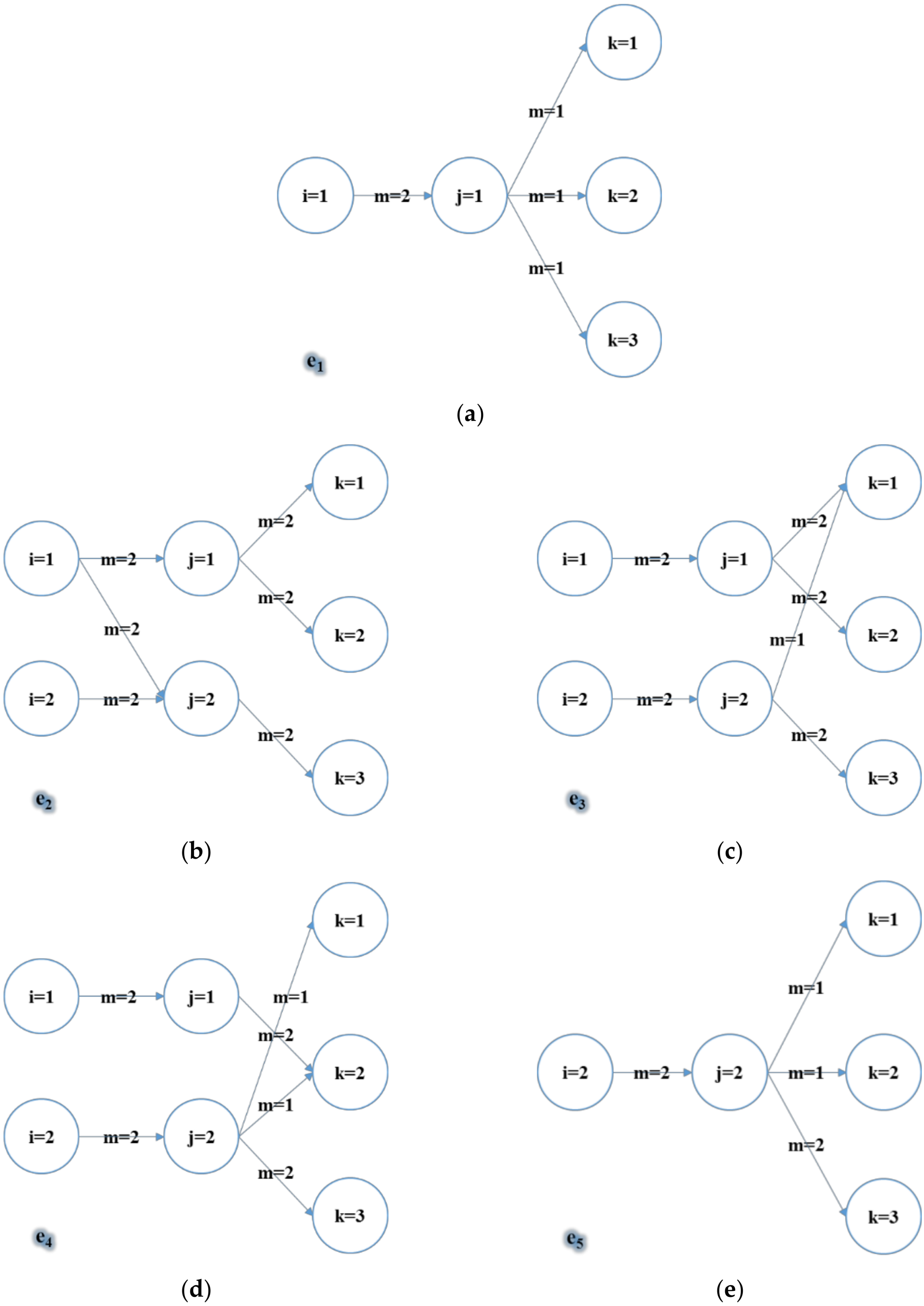


**Figure 3.** Wine supply chain network configurations: (**a**) $e_1$-value (lowest cap); (**b**) $e_2$-value; (**c**) $e_3$-value; (**d**) $e_4$-value; (**e**) $e_5$-value (highest cap).

In the cases of all of the intermediate e-values, the optimal solutions opt for both suppliers in Chalkidiki and Larissa, as well as both manufacturing sites in Thessaloniki and Attiki. Evidently, a lower e-value favors the production of greater volumes of grapes and bottled wine in Chalkidiki and Thessaloniki, respectively, while a higher e-value promotes production in Larissa and Attiki. Concerning transportation, the various e-values generate differentiated node connections and diverse transportation mode combinations. Particularly, in case of a rather strict WF cap ($e_2$-value), the grapes are also transported from Chalkidiki (a water-friendly supplier) to Attiki despite the long distance, increasing the costs. The bottled wine is transported from Thessaloniki to Larissa and Ioannina, as well as from Attiki to Achaia, following the shortest paths. Notably, all of the routes are performed solely by bioethanol-powered trucks in order to keep the WF within the target. In the rest of the cases (the $e_3$- and $e_4$-values), the grapes are transported exclusively from the suppliers to their closest manufacturing sites using bioethanol-powered trucks so as to balance the network's economic and water-related performance. With respect to the delivery of the bottled wine, the products are transported from Thessaloniki to Ioannina and Larissa and from Attiki to Ioannina and Achaia in the case of the $e_3$-value, as well as from Thessaloniki to Larissa and from Attiki to Ioannina, Larissa and Achaia in case of the $e_4$-value. In both cases, bioethanol-powered trucks are used for shorter distances and, conversely, petrol-powered trucks are used for longer distances.

Finally, none of the optimal solutions selected the supplier in Korinthia. In fact, as the proposed model was tested on a realistic case study, any changes in the WF indices, cost parameters or markets' demand may lead to different structural and numerical outcomes. However, given the model's consistency, the qualitative findings in terms of the interrelation between the cost efficiency and freshwater resources' preservation would move in the same direction as the presented outcomes. In this vein, as the WF has be proven to be a critical indicator that could affect supply chain sustainability and further considering that the water use impact varies among regions with different water stress indices [68], the respective stakeholders are encouraged to set joint WF targets and caps across their global networks. It should also be mentioned that the proposed strategic MILP model is by no means a rigid methodology for water-oriented SCNC, but it rather acts as a first-effort decision-making tool for assisting agrifood corporations in configuring sustainable supply chain networks with WF consideration. Additional OR methodologies and models may be applied in order to compare the obtained results with the current ones. Prospective real-world cases studies are expected to reinforce quantitative research in the field of supply chain water management and offer practical policy recommendations and targeted managerial insights.

## 5. Conclusions

As freshwater constitutes a vital resource for both agricultural and industrial activities worldwide [4], the incorporation of water stewardship initiatives into supply chain management is imperative. In order to integrate the water-related aspect into sustainable SCNC, we have developed an MILP model for cost minimization under a WF cap. From an operational perspective, this paper contributes towards focusing on the WF concept as a pivotal key performance indicator for evaluating the sustainability performance of an entire supply chain. In this vein, we propose that corporations should work jointly with their stakeholders towards setting a shared WF target across their global supply chains. From an academic viewpoint, this work adds value to the OR field by combining water stewardship and supply chain management by means of MILP. For an indicative wine supply chain network, the findings highlight that the structure of the network, along with the production and transportation volumes, varies significantly depending on the values of the WF cap so as to balance the trade-off between economic and freshwater use efficiency. Overall, our model is a first effort to support both decision-makers and researchers in strategically designing and planning supply chain networks by optimizing the operational costs while considering freshwater resources' preservation.

Regarding future research directions, we propose the investigation of additional modelling issues, either separately or in combination with each other, in order to reinforce the practicality of the model. Specifically, we suggest: (i) the integration of multiple raw materials and products into the model (e.g., different types of grape varieties and wines), (ii) the development of a multi-period model considering inventories, (iii) the implementation of alternative multi-objective optimization methods for comparing effectiveness, and (iv) the examination of the system under uncertainty. These proposals may further support the analysis of the spatio-temporal variability of the agrifood production that affects WF outcomes [69]. Notably, as the developed model can be applied to diverse agricultural or industrial products after appropriate modification, we suggest that this research should be extended across additional production sectors. Upcoming research efforts should focus on real-world case studies, beyond numerical experimentation, in order to provide targeted policy implications and recommendations. Finally, the inclusion of further environmental indicators (e.g., emissions, energy, or waste) [17], either in the objective functions or in the constraints, could offer a holistic perspective for sustainable SCNC to extensively cover the United Nations' SDGs [70].

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