



**MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES
IN PURE AND APPLIED SCIENCES**



**WATER AND WASTEWATER
MINIMIZATION IN INDUSTRIAL
PROCESSES THROUGH MATHEMATICAL
PROGRAMMING**

TUBA BUDAK

PhD THESIS

Department of Engineering Management

Thesis Supervisor

Prof. Dr. Serol BULKAN

Thesis CO- Supervisor

Assist. Prof.Dr. Semih ÖZEL

ISTANBUL, 2024



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Tuba BUDAK



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ÖZET

MATEMATİKSEL PROGRAMLAMA YÖNTEMİYLE ENDÜSTRİYEL PROSELERDE SU VE ATIKSU AZALTIMI

2030 yılı itibarıyla şiddetli olarak yaşanacak su sıkıntısı sebebiyle hem evsel hem de endüstriyel kullanımda su temini konusunda oldukça zorlu süreçler bize beklemektedir. Su tüketiminin önemli bir kısmı tarımda gerçekleşmektedir. Tarım konusunda Devlet Su İşleri başta olmak üzere pek çok kurum damlama sulama ve su kullanımının azaltılmasına yönelik çiftçiyi bilinçlendirmeye çalışmaktadır. Diğer taraftan da endüstriyel kullanımdaki suyun azaltılması hem kaynakların verimli kullanılması açısından hem de firmaların su ayak izini azaltması açısından oldukça önemlidir.

Endüstride en fazla su tüketimi Tekstil sektöründe sonra Ana-metal sanayinde ve gıda sektöründe gerçekleşmektedir. Su kullanımının azaltılması amacıyla literatürde tanımlanan pek çok uygulama bulunmaktadır. Bunlardan ilki süreçlerin gözden geçirilerek su tüketiminin azaltılmasıdır. Bir diğeri uygulama ise su tüketimlerinin su ağı kapsamında incelenmesidir. Bu uygulama için genellikle Pinch analizi yöntemi kullanılmakta olup son dönemlerde daha karmaşık yapılar için matematiksel modelleme yöntemi seçilmektedir.

Bu çalışmada su yoğun sektörlerde kullanılmak üzere bir model geliştirilmiştir. Bu modelde suyun azaltılmasının yanı sıra oluşan atıksuyun arıtılarak yeniden kullanılması olanağı da irdelenmiştir. Geliştirilen model zeytinyağı üretim prosesinde denenmiştir. Zeytinyağı üretim prosesinde açığa çıkan atıksuların analizleri yapılarak endüstriyel boyutta farklı arıtma yöntemleri çalışılmıştır.

GENMBR ile kombine arıtma sistemi farklı senaryolar kapsamında incelenmiştir. Kombine sisteme ultrafiltrasyon, ters ozmoz ve ultraviyole sistemler entegre edilerek su azaltımı kapsamında en iyi sonuç elde edilmiştir. Senaryo 3'te su tüketimi yaklaşık %70 oranında azalırken, mevcut duruma kıyasla toplam yıllık maliyet 5 kat artmıştır.

Senaryolar maliyet açısından irdelendiğinde ise Senaryo 1 en iyi sonucu vermiştir. Su tüketimi %58 oranında azalırken aynı zamanda toplam yıllık maliyet de yaklaşık %50 oranında azalma göstermiştir.

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ABSTRACT

WATER AND WASTEWATER MINIMIZATION IN INDUSTRIAL PROCESSES THROUGH MATHEMATICAL PROGRAMMING

The extremely high water stress will cause severe problems in terms of water supply in both domestic and industrial usage. In Türkiye, a significant portion of water consumption takes place in agriculture. In agriculture, many institutions, especially the Devlet Su İşleri, are trying to raise awareness of the farmers for drip irrigation and reducing water use. On the other hand, reducing water in industrial usage is very important both in terms of efficient use of resources and reducing the water footprint of companies.

The highest water consumption in the industry is realized in the textile , followed by the iron and steel and the food. There are many applications defined in the literature to reduce water use. The first of these is to reduce water consumption by reviewing the processes. Another application is the examination of water consumption within the scope of the water network. Pinch analysis method is generally used for this application, and the mathematical modeling method has been chosen for more complex structures in recent years.

In this study, a model has been developed for use in water-intensive industries. In this model, besides the reduction of water, the possibility of reusing the wastewater generated by treatment is also discussed. The developed model was tested in the olive oil production process. Different treatment methods have been studied on an industrial scale by analyzing the wastewater released in the olive oil production process.

The developed model was operated with different scenarios by integrating the GENMBR and combined treatment system. According to the model, the best result was obtained with the integration of the Ultrafiltration, Reverse Osmosis and Ultraviolet systems (Scenario 3) into the combined system in terms of freshwater reduction. In this scenario, approximately 70% water reduction was achieved in the facility, however, the total annual cost was increased by 5 times.

When examined in terms of cost, Scenario 1 gave the best result. Freshwater consumption has decreased by 58%, while its current annual cost has decreased by 50%.

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CLAIM FOR ORIGINALITY

There are many studies in the literature to reduce water consumption in water-intensive industries. In these studies, water-energy integration is striking, and generally the reuse of treated water is not detailed. The characterization of the water used in the food industry is of great importance. For this reason, it is not possible to directly use the water from any process in another process. In order to purify and reuse the water used in the required characterization, wastewater analysis should be carried out in the production plant. Within the scope of this study, wastewater produced in olive oil production, which was selected as an example, was analyzed in detail, and treatment systems suitable for the current situation were studied and integrated into the model. Optimization has been made for the different scenarios.

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SYMBOLS

- f_{water} : Amount of water consumption (m^3)
- $f_{\text{wastewater}}$: Amount of wastewater generation (m^3)
- f_{washing} : Amount of water entering the washing process (m^3)
- $f_{\text{separation}}$: Amount of water entering the separation process (m^3)
- f_{malaxing} : Amount of water entering the malaxing process (m^3)
- f_{boiler} : Amount of water entering the boiler (m^3)
- f_{p}^{in} : Total amount of water entering the process (m^3)
- $f_{\text{s,p}}$: Amount of water from source to process (m^3)
- f_{ww} : Total amount of wastewater generated in the production system (m^3)
- f_{d} : Amount of wastewater to be discharged (m^3)
- $f_{\text{ww,p}}$: Amount of regenerated water from wastewater treatment unit to process (m^3)
- $f_{\text{p,ww}}$: Amount of water from process to wastewater treatment unit (m^3)
- $f_{\text{p',p}}$: Amount of water from process to process (m^3)
- $x_{\text{p,c}}^{\text{in}}$: Concentration of contaminant of water entering the process (kg/m^3)
- $x_{\text{s,c}}$: Concentration of contaminant of water from source to process (kg/m^3)
- $x_{\text{ww,c}}$: Concentration of contaminant of water from wastewater treatment unit to process (kg/m^3)
- $x_{\text{d,c}}$: Concentration of contaminant of wastewater to be discharged (kg/m^3)
- $x_{\text{p,c}}$: Concentration of contaminant of water from the process to the wastewater treatment unit (kg/m^3)
- $x_{\text{p',c}}$: Concentration of contaminant of water from process to process (kg/m^3)
- L_i : Amount of pollution from olive/olive oil (kg)
- r : Removal ratio of contaminant (%)
- C_{FW} : Freshwater cost (Euro/m^3)

C_{ww} : Wastewater treatment operating cost (Euro/m³)

C_D : Discharge cost (Euro/m³)

lb : Lower boundary

ub : Upper boundary

H : Plant operating hours per annum (h)



ABBREVIATIONS

COD	: Chemical Oxygen Demand
DAF	: Dissolved Air Floatation
GAMS	: General Algebraic Modeling System
HEN	: Heat Exchange Network
HIRAN	: Heat Integrated Resource Allocation Network
HIWAN	: Heat Integrated Water Allocation Network
HIWN	: Heat Integrated Water Network
HIWRN	: Heat-Integrated Water Regeneration Network
LP	: Linear Programming
MILP	: Mixed-Integer Linear Programming
MINLP	: Mixed Integer Nonlinear Programming
MP	: Mathematical Programming
NLP	: Nonlinear Programming
PA	: Pinch Analysis
PAC	: Polyaluminum Chloride
RO	: Reverse Osmos
SDG	: Sustainable Development Goals
TAC	: Total Annual Cost
TOC	: Total Organic Carbon
UF	: Ultra Filtration
VAT	: Value Added Tax
WEN	: Water Energy Network
WN	: Water Network



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1. INTRODUCTION

Water is essential for human health, agriculture, and industry. However, climate change, population growth, industrialization, and unsustainable management practices pose serious dangers to the world's water resources (Ana et al., 2023). A quarter of the world's population, (up to 4 billion people), are subjected to water stress conditions for at least one month per year; of these, 50% face extremely high water stress. By 2050, the population is expected to grow by 30%, the socioeconomic system will have developed, and consumption habits will have changed. Political unrest and conflicts over water are both on the rise. Additionally, the issue is getting worse due to climate change, which covers accelerating sea level rise, escalating floods and droughts, and changing precipitation patterns (UN-Water, 2019; Khah et al., 2023). Figure 1.1 shows the water stress of the European river basins in the years 2000 and 2030. Regions with a water exploitation index of 0-20% face low water stress, while regions with a water exploitation index above 40% experience severe water stress. It is predicted that water stress would grow in many regions of Türkiye, in 2030 compared to 2000.

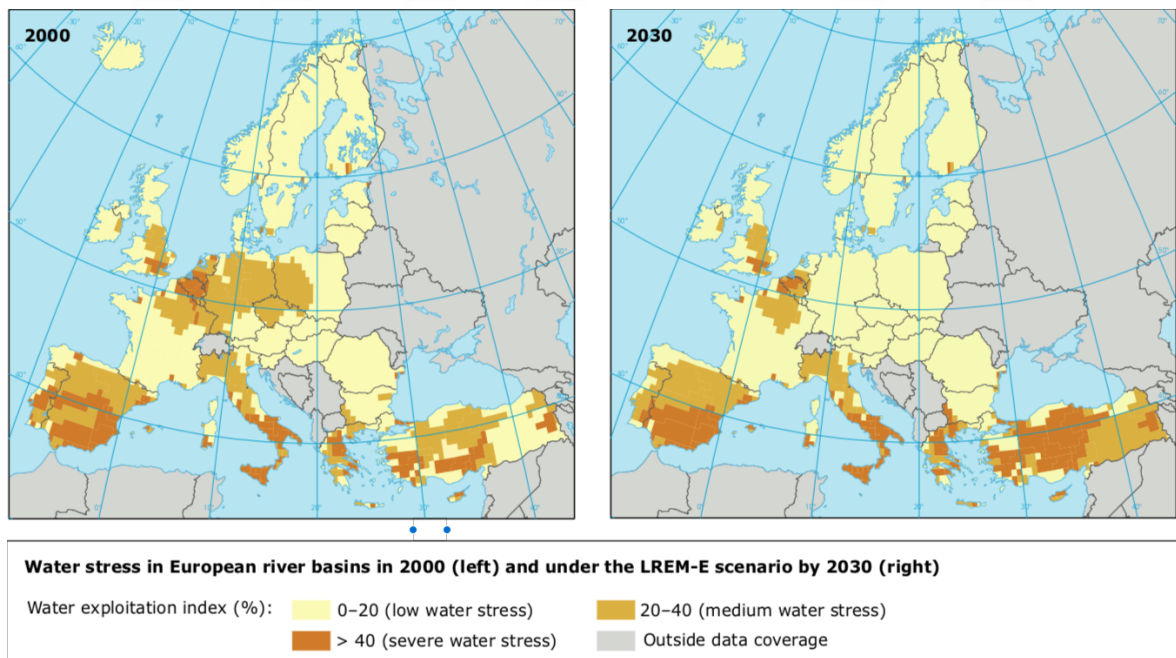


Figure 1.1. Water stress in Europe, 2000 and 2030 (EEA, 2017).

Due to drinking water being extremely rare in dry areas, and building human settlements being heavily dependent on both water and energy, the importance of freshwater is rising throughout the world. 19% of the freshwater withdrawals worldwide are used by industry and energy combined. According to regional distribution, industrial water withdrawal makes up only 2% of water use in low-income countries, compared to 17% in high-income ones. Companies in seven key industries - food, textile, energy, industrial, chemicals, pharmaceuticals, and mining - are responsible for almost 70% of the world's freshwater use and pollution (Koncagül and Connor, 2023).

The annual amount of usable water per capita in Türkiye was 1,652 m³ in 2000, 1,544 m³ in 2009, and 1,346 m³ in 2020. Considering the usable water potential per capita, Türkiye is among the countries experiencing water pressure. For this reason, it is important to use water optimally, and studies are carried out to evaluate the potential of water resources and to use it in a multi-purpose way by building storage facilities. In addition, it is aimed to bring renewal projects to the fore in order to prevent water losses in the irrigations that are in operation, to use water more effectively and efficiently, to eliminate drainage problems that affect the quality of the soil, and to popularize the use of modern closed irrigation systems instead of classical open system irrigation networks (DSİ, 2020).

In 2020, a total of 62.2 billion m³ of water was withdrawn from water resources. Of the water, 70.7% was used for irrigation, %13.3 by thermal power plants, 10.4% by municipalities, 4.5% by facilities in the manufacturing industry and OIZs, 0.7% by rural areas, and 0.4% by mining enterprises (Figure 1.2) (ÇŞİB, 2020).

Among the sub-sectors of the manufacturing industry, the sectors that use the most water are the manufacture of basic metals and fabricated metal products with 63%, the manufacture of chemicals and chemical products, basic pharmaceutical products, rubber and plastic products with 17%, manufacture of textiles, wearing apparel and leather products with 8%, and manufacture of food, beverage and tobacco products with 6%.

Efficient use of resources is important in order to increase competitiveness in the manufacturing industry and reduce environmental pollution. Resource consumption and waste generation in the manufacturing processes should be kept to a minimum and the principle of cleaner production should be widespread. The use of resources in the

manufacturing processes may differ for each sector, and due to limited resources, productivity practices are needed on a sectoral basis (Kavurucu et al., 2022).

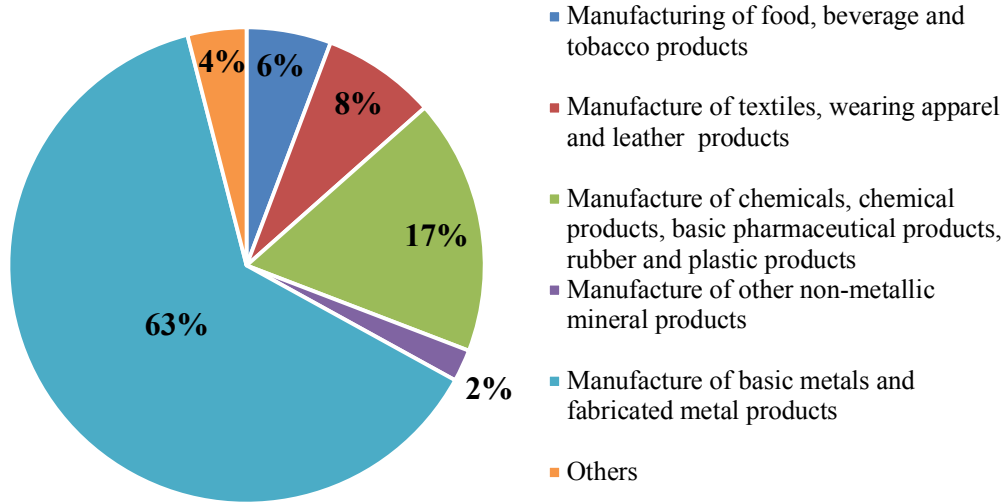


Figure 1.2. Water statistics of manufacturing industry sub-sectors, 2020 (TÜİK, 2020).

Cleaner production is an integrated strategy used in production processes and services, for preventing environmental pollution and increasing the company’s competitiveness through the efficient use of natural resources. The idea of cleaner production is to be generated maximum output with minimum resources and by-products (Chia and Hadibarata, 2021). With the use of cleaner production methodology, the hotspots of the process are determined by making measurements (flue gas, thermal leakage, energy loss, air leakage) and analyzing the some critical parameters of wastewater, and solid waste in the facility. The specific consumption of water, energy, and raw material, as well as the generation of wastes, are calculated and compared with the consumption of similar facilities in the literature. The improvement opportunities are defined with the findings from measurement and analysis.

The basic tools used to implement cleaner production, are brainstorming, flow analysis tools, ecomapping, quality tools, accounting analysis tools, and lean practices. The basic tools focus on monitoring and assessment of resource consumption. However, advanced tools such as process graphs, pinch analyses, computer-aided modeling, and artificial

intelligence, contribute to the optimization of resource consumption and promote sustainable resource management (Fan et al., 2020).

To utilize water more efficiently and prevent environmental pollution, a solution should be found for the minimization of water usage and wastewater generation. Sustainable water management can be achieved by applying advanced tools like pinch analysis (PA) and computer-aided modeling or mathematical programming (MP). Pinch Analysis is a graphical method that is based on physical understanding, knowledge, and heuristics; it is unable to deal with problems involving multiple contaminants. Though, the mathematical programming method is much more easily able to handle complex problems with nonlinear and nonconvex (B. Duhbaçı et al., 2021).

Generally, PA and MP methods are used in sectoral applications to reduce water consumption. Solving medium and large scale problems can become time-consuming as well as computationally expensive. To overcome this obstacle, the mathematical programming methods are developed. MP methods are commonly used to understand the current situation better. Additionally, mathematical programming enables sensitivity analysis that is related to how changes in model parameters affect the solution (Ibric et al., 2016).

Academic studies remark that Türkiye will experience severe water stress in 2030. It has been noted that there are some measures for managing water stress. The measures are the reduction of water demand and losses during the use and supply system, storage of water during water-abundant times, increasing water availability such as wastewater and saltwater reuse, and application of water-efficient technologies (EEA, 2021).

A huge amount (70.7%) of water consumption in Türkiye originates from agricultural activities. In order to reduce the water used in agricultural activities, systems such as drip irrigation and sprinkler have begun to be used (ÇŞİB, 2020). Due to wastewater discharge costs and wastewater treatment costs being higher than water supply costs, companies that carry out industrial activities mostly focus on the amount of wastewater and pollution load. The Green Deal Action Plan published in 2021 includes actions for water recovery, reuse of treated water, and reduction of water consumption (Ministry of Trade, 2021). In order to implement the actions, the first step is to optimize water consumption in industrial facilities by using optimization tools such as mathematical

modeling. The second step is to analyze the water quality needed in the process and determine the process that is able to use the treated water.

1.1. Aim of the Study

The goal of this study is to develop a mathematical model to reduce water consumption and wastewater generation in the water-intensive sectors and to investigate water and wastewater minimization options through this model. For this purpose, olive oil production, which is critical in terms of water use and wastewater generation, is discussed. This study, which will also form the basis for other water-intensive sectors, is also aimed to contribute to The United Nations Sustainable Development Goals (SDGs), especially Goal 6.

1.2. Literature Review

In this section, studies published in the literature on water and wastewater reduction are presented in detail. In the first part, information about water network synthesis problems is given, and in the second part, these problems are classified. In the last part, the solution approaches of these problems are examined.

1.2.1. Water network synthesis problem

Water network (WN) synthesis problems consist of only water integration. A few review papers on WN synthesis have been published in the previous two decades. Bagajewicz (2000) evaluated the methods used in water network design and water network retrofitting. The author described the challenges with freshwater/wastewater reuse and wastewater treatment in two stages of the water network synthesis problem. For the purpose of constructing the best industrial water networks, a review paper including mass and non-mass transfer mechanisms, has been published (Jezowski, 2008). While the water network synthesis issues were covered by both writers within the parameters of the mathematical modeling methods, Foo (2009) examined insight-based strategies including pinch analysis. The importance of water and heat integration has been underlined, even if the topic of heat integration has not been addressed in these studies.

The review paper related to the WN synthesis issues involving both isothermal WNs and also nonisothermal WNs has been presented by Jezowski (2010). While Klemes

(2012) solely covered the minimization of water and wastewater in manufacturing industries, Chen and Wang (2012) analyzed the networks connected to the utilities of operating units, including energy, water, and pressure. The water network synthesis challenges that reuse, and recycle solutions were taken into consideration were examined by Grossmann et al. in 2014. The use of mathematical programming techniques in biofuel production facilities was considered.

The books also contain summaries of the process integration and strategies for integrated process WNs. The concepts of design tools have been covered in the chapter of Savulescu and Kim's book titled "Novel methods for combined energy and water minimization in the food sector". The study has undertaken an analysis of the combined minimization of water and energy for the food processing sector. However, Savulescu and Alva-Argaez (2013)'s handbook of process integration offers a thorough overview of process integration applications for processors of food and drink, petrochemicals and electricity, pulp and paper, and steel.

It is important to note that there has been a rise in the literature associated with nonisothermal water networks over the last ten years. Ahmetovic et al. (2015) provided a thorough literature review on this topic. The authors present the most recent advancements in sectoral process integrated WN implementations in this study, as well as the thoroughness of mathematical modeling techniques in terms of restrictions. Fan et al. (2018) analyzed improvements made in the planning and focusing of water treatment system and regeneration units. The pinch analysis method as well as mathematical modeling techniques have both been looked at in this paper. Baleta et al. (2019), who just published a review paper, focused on the circular economy while summarizing the most current advancements in resources such as energy, and water, as well as environmental systems.

In order to find the best choices for wastewater regeneration and reuse in industrial parks, Alnouri et al. (2016) introduced an optimization methodology. To keep pipe networks from costing too much, the scientists took into account pipeline scenarios. The reuse and recycling options of water in industrial parks has been examined in a different study by Aguilar-Oropeza et al. (2019). The water requirements for each facility were met by a network that was created in this article at the lowest possible cost. Pan et al.

(2016) offered innovative multi-level ways for addressing the issues with ecoindustrial parks. Three symbiotic relationships—between energy, material, and water—and a four stage modeling concept make up the unique techniques. The unit, process, plant, and industrial network stages have all been taken into account when developing and testing the four-level model.

Tiu and Cruz (2017) also created a Mixed-Integer Linear Programming (MILP) model to minimize both freshwater use and wastewater generation in eco-industrial parks in addition to the sequential method. In addition to other research, they took into account environmental aspects (which include the quality and quantity of the water) and economic costs (which cover piping, operating, and treatment costs) as a functional objective. Leong et al. (2017) combined the multi-objective optimization method with the analytical hierarchy process to optimize the design requirements for creating an eco-industrial park.

Liu et al. (2018) created a heat integrated water allocation network (HIWAN) for EIPs, in contrast to earlier research, and optimized the HIWAN by modeling the network using nonlinear programming. Both simultaneous and sequential optimization routes have been created for this synthesis. Sequential design had a lesser demand, but it was found that the simultaneous design produced results that satisfy all constraints.

Kamat et al. (2023) developed a novel algorithm for water network synthesis problems with multiple contaminants. The Greedy Search Algorithm uses the theory of concentration potential to find the feasible solution at each iteration. Every iteration's solution is disturbed and reused as the starting point for the subsequent iteration. It has been observed that improving the solution's perturbation to get the starting point for the following iteration leads to better solutions.

1.2.2. Categorization of water network synthesis problems

The two types of water network synthesis issues are isothermal and nonisothermal. In isothermal WNs, it is assumed that all streams have a constant temperature, whereas in nonisothermal WNs, this assumption is not made. In process units and regeneration units or integrated systems incorporating both units, isothermal WNs are synthesized and designed. To reduce freshwater use and wastewater generation, integrated WNs include

regeneration recycling, regeneration reuse, and water reuse. Nonisothermal WNs are typically used in process units, heating and cooling units, and treatment units to concurrently reduce water and energy consumption (B. Duhbaci et al., 2021).

Designing an integrated water network and heat exchange network (HEN) for a specific purpose function is the goal for nonisothermal WN issues. Finding connections between freshwater sources, process units, treatment units, wastewater discharge points, and heating-cooling units is another goal of nonisothermal WNs (Ahmetovic et al., 2015). But Ghazouani et al. (2015) have suggested a linear strategy to reduce the overall running cost of a heat integrated resource allocation network (HIRAN). The annual operational cost of the HIRAN was reduced using the MILP model during the problem's solution phase after allocation limitations and the minimum freshwater flow rate were established.

A nonisothermal WN problem covers water usage, cooling and heating stages, and wastewater treatment units. The heat exchanges are caused by nonisothermal mixing or by heat exchangers (Ibric et al., 2016). Hong et al. (2016) modeled the issue using the General Algebraic Modeling System (GAMS) and provided a method for simultaneous optimization of the HIWAN integrating water allocation networks and parallel HEN systems. Since the economic performance of a parallel heat exchanger is worse than the series in this study, a model might be developed by taking serial heat exchangers into account. To conserve freshwater, the authors of a different study (Hosnar and Kralj, 2016) concentrated solely on the distribution of utilized wastewater and condensate. Mixed integer nonlinear programming (MINLP) was used in this study to achieve the highest annual profit.

When published articles about the nonisothermal water network were examined, it was found that all of the studies' main objectives were to reduce the network's total annual cost (TAC). TAC typically includes investment expenses for heat exchangers as well as operational costs for utilities, freshwater, and wastewater treatment.

In their analysis, Hong et al. (2017) took into account the area cost of the heat exchanger in addition to the investment cost. To address the issue, the authors suggested a MILP technique that used a unique transshipment type HEN model with isothermal mixing and nonisothermal mixing, stream bypassing, and stream splitting. A model for the

synthesis of single and interplant nonisothermal water networks was created by Ibric et al. in 2017. They identified the WNs among the various plants in their model using binary parameters. The linkages between the various facilities required that the model include the cost of installing piping.

Alnouri et al. (2018) expanded their analysis by include the costs of waste disposal, and zero liquid discharge while the WN synthesis issues that have the objective function of TAC minimization already cover the cost of freshwater, wastewater treatment, and piping. A MINLP was utilized to design the problem, which centered on the water integration and included brine management within the context of zero liquid discharge.

In non-isothermal situations, requirements like temperature and pollutant concentration become more significant in order to decrease freshwater usage while minimizing energy consumption. Thus, there are nonlinear restrictions and a lot of variables in the mathematical models utilized to solve the heat integrated water network problems. Therefore, it is exceedingly challenging to find solutions to such issues. Wang et al. (2017) created eight criteria to limit the amount of nonlinear terms and variables and make the issues easier to solve. Maximum concentration of output flow, nonisothermal mixing, and pinch standards for water and heat exchanger networks have all been taken into account when developing these guidelines.

The objective function of the suggested model for isothermal water network issues included the running costs of freshwater and utility, regeneration costs, treatment costs for wastewater treatment systems, and investment costs for pipes. In order to define intra-plant and inter-plant integration, a case study was presented for the steel industry in which the cost of piping as well as the cost of pumping (Zhang et al., 2018).

A study on the optimal scheduling of several freshwater resources was published by Chaturvedi et al. (2016), despite the fact that WN studies focused on a single freshwater source are common in literature. By utilizing the MILP model in this study, the authors were able to reduce the operational costs for batch water networks with variable schedules and different resources. Although wastewater treatment systems were not addressed in this article, manufacturing line reactions and water resources were. The batch water network synthesis of Dong et al.'s (2016) study included numerous

wastewater regeneration modules, in contrast to the prior study's single module approach. To reduce the overall cost annually, the authors suggested a MINLP model.

Regeneration systems are regarded as a vital component of water management since they assist in lowering freshwater use and wastewater generation. The impact of regenerated concentrations on regenerated stream utilization was examined by Li et al. in 2015. The authors separated the issue into simple and complex contamination systems. Only networks with fixed mass load operations were discovered to be eligible for the analysis, but its outcomes were not completely ideal. In a different study on regeneration systems, a stepwise design was put forth to create the best regeneration reuse water network and reduce freshwater use (Li and Guan, 2016).

Water-using processes are divided into two groups: fixed flowrate and fixed contaminant load. While the processes for fixed pollutant loads involve mass transfer equipment like extraction, scrubbing, and washing, the processes for fixed flowrates consist of reactors, boilers, and cooling towers which lack mass transfer equipment. In water and energy minimization issues, this distinction is frequently missed. But in their research, Xie et al. (2016) paid close attention to fixed flowrate systems. In order to jointly optimize the water allocation network and the heat exchange network, they presented a heuristic approach for fixed flowrate systems. The suggested method incorporates two design steps: heat exchange network and water allocation, as well as it is based on a single temperature peak design (a form of pinch analysis method).

In another paper, Sujak et al. (2017) suggested a comprehensive strategy for creating the Cost Optimal Water Network by taking economics into account. The method includes two steps: an economical mode and a freshwater-saving mode. Annual savings were greatest in the suggested model when all water minimization methods and budget constraints were taken into account concurrently. In non-isothermal networks, this method might be used.

It has been noted that, throughout the literature, mainly isothermal WN problems have been researched. WN problems were examined in two groups, such as isothermal and nonisothermal. In isothermal WN problems, heat exchange networks and wastewater treatment were also not included. It was underlined that non-isothermal WN problems are more difficult to solve than isothermal ones.

1.2.3. Mathematical Programming of WN Problems

Pinch analysis and mathematical techniques based on mathematical programming are used to synthesize water networks. The objective functions and/or restrictions of the water network optimization problems are nonlinear. The applications of industrial processes typically make use of nonlinear programming (NLP) and mixed integer nonlinear programming (MINLP). When the issue is resolved using NLP or MINLP, substantial computer resources and a thorough first estimation of the answer are required to begin the optimization process. Because of this, some research, like those by Kamat et al. (2019), Zhao et al. (2016), and Xu et al. (2015), use linear programming to simplify their problems.

GAMS software is typically used to solve optimization problems, including nonlinear programming, mixed integer linear programming, and mixed integer nonlinear programming. Silori and Khanam (2018) have studied the results of employing various modeling frameworks to GAMS for optimization modeling. The chosen strategy, according to the authors, has a significant impact on how the water network is designed. These techniques allow for the simultaneous or sequential selection of a solution.

1.2.3.1. Sequential approach

In both pinch analysis and mathematical programming methods, the sequential approach is frequently used to break down complicated nonisothermal WN problems into simpler issues, such as into water and heat exchange networks. The disadvantage of this technique is that it does not investigate the relationships between WN and HEN and does not allow for the creation of an ideal operating-to-investment cost ratio. To reduce total annual cost of HIWNs synthesis, a sequential strategy was put up by Jagannath and Almansoori (2016) in their study. Two models were used to solve the WN problem. In the first, the costs with water and energy were reduced, and ideal water flow rates were established. Utilizing the ideal flow rates from the first model, the stage-wise heat exchanger network in the second model was resolved. For problems of a small to medium magnitude, this model was used. To address significant industrial difficulties, this solution technique will need to be developed further.

1.2.3.2. Simultaneous approach

The sequential approach's aforementioned problems can be resolved by the simultaneous approach, which is primarily employed in mathematical programming techniques. Sequential techniques by themselves cannot concurrently account for the interactions between water and energy in terms of the investment cost of machinery like heat exchangers and wastewater treatment systems. Solving issues with water networks has typically been done using a simultaneous approach in published studies.

In the study by Ahmetovic and Kravanja (2014), process-to-process streams were included for heating integration in WN, and a network consisting of nonisothermal water-using and wastewater treatment were taken into consideration. For the integration of heat between process-to-process streams, two solutions have been suggested. One tactic was to put heat exchangers on each stream that went from one process to another. The second method allowed for the heating and splitting of cold streams as well as the cooling and splitting of hot streams. A superstructure approach has been created that provides many splitting and mixing choices with direct and indirect heat exchange to handle heat integrated WN challenges (Ibric et al., 2014b).

Ibric et al. (2014a) provided a two-step method to synthesis of HIWN including wastewater streams and their environmental restrictions, while Ahmetovic et al. (2014) experimented with a single-step superstructure-based approach. A simultaneous optimization model for nonisothermal WN was created by Zhou and Li (2015), taking stream pollutant concentrations into account. For the synthesis of nonisothermal WNs, Ibric et al. (2016) used a compact superstructure model and solved the issue in two steps. The superstructure has been used in numerous examples, to solve problems with single or multiple contaminants in addition to those addressed by the aforementioned applications.

Sujak et al. (2015) created a model that gives a dynamic cost profile that accounts for the necessary land cost for water reuse to calculate the cost of water and wastewater treatment networks. The superstructure solution technique put forth by Ibric et al. (2016) consists of initialization part and design part, for the concurrent synthesis of nonisothermal water networks. A combined WN, and heat integration model are all

solved in the first stage. To minimize the overall annual cost of the entire network, a combined water network and heat exchanger network are constructed in the second step.

To reduce the water and energy consumption in cooling water systems using a cooling tower and a cooler network in a float glass process, Dakwala et al. (2014) designed a water energy network (WEN). In this study, the WEN problem was solved by combining graphical methods with mathematical programming.

3R (Regeneration, reuse and recycling) concept generally reduces freshwater use and wastewater production. Zhao et al. (2016) created a technique for designing regeneration recycling water networks that combines the use of a linear programming (LP) model and the concentration potentials method. In order to solve simultaneous HIWNs, Yan et al. (2016) created a new technique employing the NLP model, which eliminates the binary variables from the MINLP model. Without the use of discrete variables, the stream roles have been discovered and the process matches has been enhanced.

Due to their nonlinear and nonconvex nature, HIWN synthesis problems are difficult to solve in large-scale applications. Hong et al. (2018) proposed a unique mathematical programming methodology with three steps that optimizes the freshwater usage and overall annual cost to get around this difficulty. A design methodology was created by Zhao et al. (2019) to address the issues with the complicated structure and high costs of heat-integrated water networks. The authors were able to estimate the concentration order of the water streams in water-using processes by calculating the value of the concentration potential of the demands and allocating the sources to the demands through the concept of maximum quasi-allocation amount in the first phase. The design of the heat exchanger network was then carried out using a self-heating technique. Nonlinear or linear models are used for HIWN synthesis. A nonlinear mathematical model is typically used to carry out the formulation for the heat-integrated water regeneration network (HIWRN) synthesis. Nevertheless, a linear mathematical model for HIWRNs was put forth in the paper of Kamat et al. (2019). The simultaneous and three stage sequential techniques used in this strategy, which depends on the transshipment model.

Torkfar and Avami (2016) suggested a different approach to address the issues associated with the simultaneous integration of water and electricity networks. The

proposed methodology took into account the pressure drop in the heat exchanger and its cost while calculating the ideal heat transfer coefficients and flow velocity. Using non-convex MINLP has reduced the overall annual expenditures. Additionally, other issues with water-energy integration, this study also looked at wastewater energy recovery.

When wastewater treatment techniques are incorporated into the water allocation network in water-energy integrated systems, the optimization is more precise. A strategy to reduce the cost of the wastewater system for oil refineries was put up by Tovar-Facio et al. (2016). The strategy took into account the effectiveness of reuse, recycling, and other waste-treatment technologies, as well as the peculiarities of water streams in processing units. The technological viability of the electrocoagulation approach has been explored in this study, and in two case studies, the best outcomes were attained. An Adaptive Discretization Algorithm was created to jointly optimize the cost of water usage and wastewater treatment system designs in a different study written by Koster and Kuhnke (2018). The proposed algorithm may take a long time to compute. In order to arrive at a quicker solution, the proposed algorithm must be constructed.

This section discussed the sequential and simultaneous procedures that are typically employed in order to solve WN challenges. Nonisothermal WN problems are separated into water and heat exchange networks in the sequential approach, and these networks are solved at various stages. The complex nonisothermal WN problems are not best served by this method since optimal balance cannot be reached at various stages. As a result, there aren't many research using this methodology that have been found in the literature. Due to the interplay between energy and water in industrial processes, nonisothermal WN problems have been used to more extensively study the simultaneous method that takes this interaction into account. This section also gives comprehensive information on the types of mathematical techniques that have been applied to solve WN issues with various constraints and objective functions.

2. METHODOLOGY

The water-intensive sectors in the Turkish manufacturing industry are the manufacture of basic and fabricated metal, the manufacture of chemicals, the manufacture of textiles, and the manufacture of food and beverage. A voluntary company from the textile and metal sectors could not be found to participate in this study. For this reason, it has been deemed appropriate to develop a mathematical model of the olive oil production process, which has critical importance in terms of wastewater.

In the first stage of the study, a field visit was organized to the olive oil production plant, and a cleaner production audit was carried out. Detailed information about the olive oil processes as well as production and consumption values were provided. In the scope of the audit, the electricity consumption of the equipment was measured, flue gas measurements were made and thermal leaks were detected. In addition, wastewater samples were collected from the processes.

In the second stage, the specific production and consumption values of the olive oil production were calculated. These data were compared with the data of similar production facilities in the literature. Chemical Oxygen Demand (COD) and Total Organic Carbon (TOC) parameters were analyzed in wastewater samples. According to the wastewater characterization, different treatment systems were examined with the treatment company.

In the third stage, the equations and constraints required for the mathematical model were determined based on the calculations and analyzes made after the audit. In the last stage, an appropriate optimization algorithm was selected to solve the mathematical model and determine the optimal solution in MATLAB.

2.1. Olive Oil Production

Olive fruit, which is the main raw material of the olive oil process, is brought to the plant and poured into the bunker after weighing. From the bunker, the olive fruit is fed to the leaf aspirator by means of the feeding screw. The leaves and branches on the olive fruit are removed from the olive by vacuum in the aspirator. The olive fruit coming out of the aspirator enters the washing tank and is washed there. After washing, olives are fed to the crusher. Crushed olives in the crusher are kneaded in the malaxer depending

on the maturity level of the olive fruits. After the kneading process is completed, the dough is fed to the decanter by means of a pump. The decanter is a 2-phase system, on the one hand, olive oil comes out and on the other hand, pomace comes out. The pomace coming out of the decanter is fed to the seed separation system, where the seed of the pomace is separated. The olive oil coming out of the decanter is fed to the separator in order to remove the impurities in it. In the separator, olive oil is cleaned by treating it with hot water. Apart from olive oil, wastewater is also released from the separator (Figure 2.1) (Dahdouh et al., 2023).

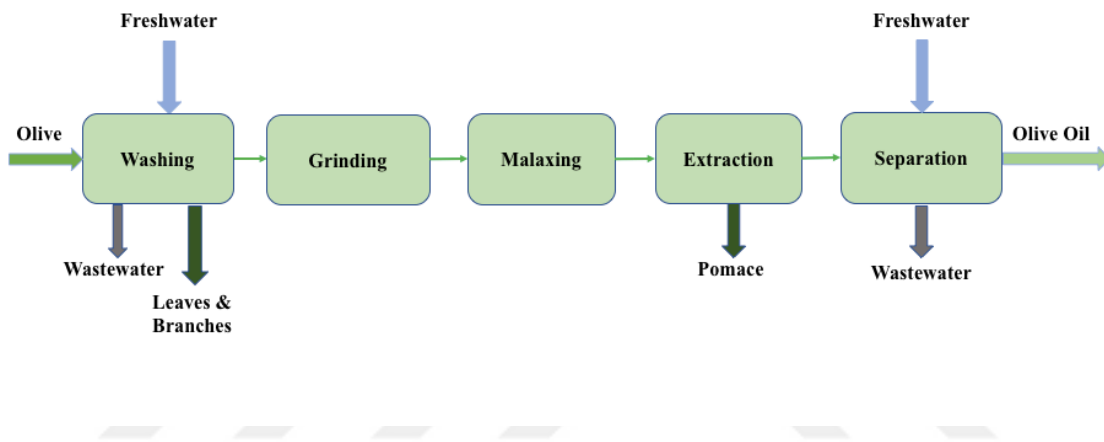


Figure 2.1. 2-phase olive oil production process (adapted from Dahdouh et al., 2023).

2.1.1. Water usage in olive oil production

During the olive oil production, water is used in different stages such as olive washing, malaxator drum heating and separation as well as for cleaning the machines. In olive oil plants, the olives that come to the plant are subjected to a washing process before the crushing process. The washing process is performed by giving water to the olive from the top and discharging the water at certain intervals from the bottom or by spraying it with high-pressurized water. With circulation, the water can be reused for washing, but this water needs to be renewed after a few uses. In general, the wastewater contains solid matter from the soil and crushed olives, a small amount of inorganic fertilizers, pesticides, and oil (ÇŞB, 2015).

The separation process, which is the last stage in olive oil production, aims to remove the impurities in the oil. While the oil leaving the decanter is purified from the particles

with the water added while passing through the separator, the water that acts as the carrier is used as the separator wastewater (ÇŞB, 2015).

When 1 ton of olives are processed in a 2-phase production plant approximately 0.12-0.18 m³ of washing water is used and comes out as wastewater. An average of 0.01 m³ of water is used in the separator unit to remove impurities in the oil (ÇŞB, 2015). The water consumption data for each process could not be obtained from the plant. Therefore, to calculate water consumption for each process, some assumptions were made.

Assumptions on water usage

In the olive oil process, water is used in washing, malaxation (both in the process and for heating), and separation processes at most. Inspired by the Cleaner Production Study carried out in an olive oil plant in Izmir, the amount of water consumption and wastewater generation were accepted as 1080 m³ and 1000 m³, respectively. Since water consumption is not monitored for each process, for the washing process some assumptions were made. Since wastewater is released in the washing and separation processes in the plant, the difference between the water consumption and the wastewater generated represents the water used in the boiler, that is, the water that enters the malaxator heating and malaxation process.

Assumption 1: It is assumed that the amount of water entering the washing and separation process and the wastewater leaving these processes are equal and there is no loss.

f_{water} : Amount of water consumption (m³)

f_{wastewater}: Amount of wastewater generation (m³)

f_{washing} : Amount of water entering the washing process (m³)

f_{separation} : Amount of water entering the separation process (m³)

f_{malaxing} : Amount of water entering the malaxing process (m³)

f_{boiler} : Amount of water entering the boiler (m³)

$$f_{washing} + f_{separation} + f_{malaxing} + f_{boiler} = f_{water} \quad (2.1)$$



$$f_{wastewater}$$

$$f_{water} = f_{wastewater} + f_{malaxing} + f_{boiler} \quad (2.2)$$

$$1080 = 1000 + f_{malaxing} + f_{boiler}$$

$$f_{malaxing} + f_{boiler} = 80 \text{ m}^3$$

Assumption 2: Minimization of the freshwater used in olive oil production was taken as the objective function. However, the amount of water used in these processes was not included in the model, since no reduction in the amount of water entering the boiler and the water entering the malaxation was aimed in the study. Since it has a share of approximately 6% of the total water consumption and the possibility of saving is not defined, it has been excluded from the system.

Assumption 3: Generally, in the washing process, the washing tank was cleaned 4 times on rainy days and approximately 2 times on other days. The number of days with precipitation (60%) and without precipitation (40%) in 2020 was taken into account, and with the knowledge that the plant operated for 120 days in 2020, approximately water consumption in the washing process was calculated.

The washing tank has a volume of approximately 1.5 m³ and the relevant calculations are given below.

$$120 \text{ day} * 0.6 * 4 \text{ times} * 1.5 \text{ m}^3 / \text{times} = 432 \text{ m}^3 \quad (2.3)$$

$$120 \text{ day} * 0.4 * 2 \text{ times} * 1.5 \text{ m}^3 / \text{times} = 144 \text{ m}^3 \quad (2.4)$$

$$f_{washing} = 576 \text{ m}^3$$

When the amount of water used in the washing process is subtracted from the total amount of wastewater, the amount of water used for separation is calculated by using Equation (2.5).

$$f_{washing} + f_{separation} = f_{wastewater} \quad (2.5)$$

$$576 + f_{separation} = 1000$$

$$f_{separation} = 424 \text{ m}^3$$

Specific water consumption was calculated by dividing the amount of water consumed in the washing and separation processes at the plant by the total production amount. The comparison of specific water consumption with the values in the literature is given in Table 2.1. It has been found that the plant uses a lot of water in both processes, based on the specific consumption described in the literature.

Table 2.1. Comparison of specific values with the literature

	Literature 1*	Literature 2**	X plant
Specific water consumption (Washing process) m ³ /ton	0.5-0.6	0.79	0.84
Specific water consumption (Separation process) m ³ /ton	-	0.31-0.44	0.62

*(Al-Othman, 2019)

**(ÇŞB, 2015)

2.1.2. Wastewater characterization

In the wastewater released during the olive oil production process, there are small amounts of inorganic fertilizers, pesticides, solids and oils from the soil and from the crushed olives. The fact that the production is 2 or 3 phases does not change the characterization of the wastewater released in the washing process. However, whether it is rainy or not on the day of olive harvest changes the amount of solid matter on the olive. In the separation process, which is the last step of olive oil production, olive oil is treated with water to remove impurities in olive oil. Here, the impurities in the olive oil pass into the water. The fact that the system is 2 or 3 phases affects the characterization of the wastewater coming out of the separation. The results were compared according to the 2-phase system since the production was carried out in 2 phases in the plant. The characterization of the wastewater supplied from the plant was carried out in the laboratories of the TÜBİTAK Marmara Research Center. It has been observed that the separation water contains more pollutants in terms of COD and TOC compared to the washing water (Table 2.2).

Table 2.2. Characterization of wastewater from washing and separation processes

Parameter	Unit	X plant	Literature*	X plant	Literature*
		Washing process (2 phase system)		Separation process (2 phase system)	
COD	mg/L	1,150	1,961-5,000	9,580	952-11,529
TOC	mg/L	376	559-1,337	3,197	508.5-2,316
pH	-	5.03	7.3-7.75	4.86	6.83-7.6
Conductivity	µS/cm	1,240	704-2,360	3,168	1,063-3,600
Oil-Grease	mg/L	28	55-894	380	69-280
Colour	Pt-Co	10,620	1,435-3,875	6,800	805-1,910

*(ÇŞB, 2015)

2.1.3. Wastewater treatment systems

Studies have been conducted with wastewater treatment companies. The wastewater treatment systems have been discussed regarding the collection and treatment of wastewater generated in the separation and olive washing processes in olive oil production and the use of the treated water in the washing process. 2 (two) Methods have been suggested in order to treat wastewater and use treated water. The first is the GENMBR system¹, and the second is the chemical treatment and membrane combined system².

2.1.3.1. Water recovery with the GENMBR system

First of all, it was planned to collect the wastewater from the washing and separation process in a warehouse or pool. As a result of the wastewater analysis, it was determined that the wastewater contained moderate levels of COD and TOC. Since the COD removal efficiency will be quite low with physical treatment methods, chemical or

¹ The offer has been received from MEMSİS Çevre Teknolojileri AR&GE A.Ş.

² The offer has been received from ARTEMİS Aritim A.Ş.

biological treatment systems for COD removal have been examined within the scope of the thesis. As the first system, GENMBR treatment technology, which combines biological and membrane systems, is examined (Figure 2.2).

Since the water treated in the GENMBR system will be of medium quality, treated water could be used for the washing process. Estimated effluent parameters as a result of the treatment of wastewater from the washing and separation process with GENMBR system are given in Table 2.3.

Table 2.3. Projected effluent (purified water) parameters

Parameter	BOD (mg/L)	COD (mg/L)	TSS(mg/L)	Ammonium Nitrogen (mg/L)	Total Phosphorus (mg/L)
Value	<5	<150	≈0	<1	<2

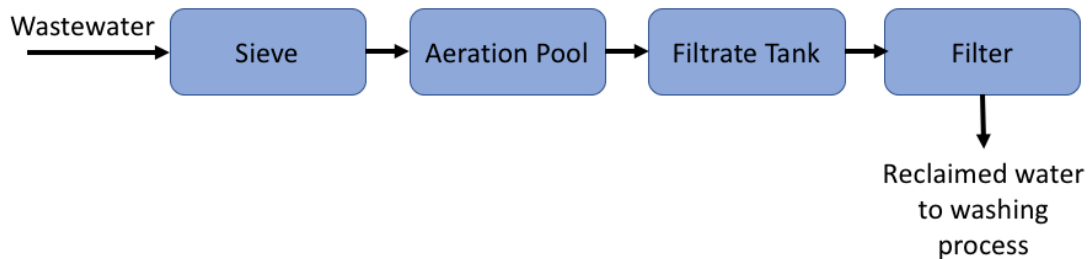


Figure 2.2. GENMBR system (Scenario 1).

With GENMBR Module system, which will be installed by accumulating both the separator and, if desired, washing wastewater in the same pool, these wastewaters could be treated at appropriate values, thus water recovery can be achieved and thus the freshwater usage of the plant could be significantly reduced.

In the calculation made by considering the wastewater data of the plant with the GENMBR system with a capacity of 5 m³/day, the annual amount of water to be recovered

is calculated as 700 m³/year. It is predicted that the system will operate with an average efficiency of 70%. In the calculations made regarding the freshwater cost and pumping cost, it was calculated that the total savings would be 980 Euro/year and the net savings would be 710 Euro/year, including the operating cost. The investment cost of the system is 21,460 Euro + VAT (Table 2.4).

Table 2.4. Operating and investment cost of GENMBR system (Scenario 1)

Parameters	Amount
System capacity	5 m ³ /day
The annual amount of water to be recovered	1000 m ³ /year*0.7=700 m ³ /year
³ Brackish water cost	1.35 Euro/m ³
Pumping cost	0.05 Euro/m ³
Electricity cost	0.2 Euro/kWh
Operating cost	0.27 – 0.31 Euro/m ³
The annual operating cost of the system ⁴	0.27 Euro/m ³ *1000 m ³ /year= 270 Euro /year
Annual savings	700m ³ /year*(1.35+0.05)Euro/m ³ 980 Euro/year
Net savings	980-270=710 Euro/year
Investment cost	21,460 Euro + VAT

2.1.3.2. Water recovery with chemical treatment and membrane combined system (Scenario 2)

Another water recovery system is a combined design consisting of a ceramic ultrafiltration membrane added to the chemical treatment. After the wastewater generated during the washing process is collected in a pool, it is passed through a static sieve with the help of a pump. After passing through the static sieve, the wastewater is collected in a 5 m³ capacity balancing tank. The wastewater collected here is taken to the Dissolved Air Floatation (DAF) tank by means of a pump. Wastewater is subjected to coagulation

³ Freshwater cost <https://www.izsu.gov.tr/tr/suveatiksutarifesi/41/103>.

⁴ Operating cost varies 0.27 – 0.31 Euro/m³ and it was taken 0.27 Euro/m³ in the calculation.

and flocculation processes before entering the DAF tank. These processes are performed automatically in the static mixer. After the completion of the chemical reactions, the wastewater is taken to the DAF tank, where the pollutants in the wastewater are floated. After the oils and flocs in the water are floated, the treated water is taken to the ARTCF feeding tank, and the collected oily sludge is first taken to the sludge tank and then to the dewatering system. After the oils are retained in the DAF tank, the wastewater is collected in the ARTCF feed tank. Polyaluminum Chloride (PAC) is added to the accumulated water and then passed through ceramic membranes. The filtered water becomes ready to feed into the Ultra Filtration (UF) system. All particles above 0.4 micrometers are retained during the Ceramic Membrane Filtration process. After this filtration process, regular backwashing will be done on the membranes, and the wastes generated during backwashing are collected in the sludge tank. The wastewater from the ARTCF system is passed through the UF and Ultraviolet (UV) systems, respectively (Figure 2.3).

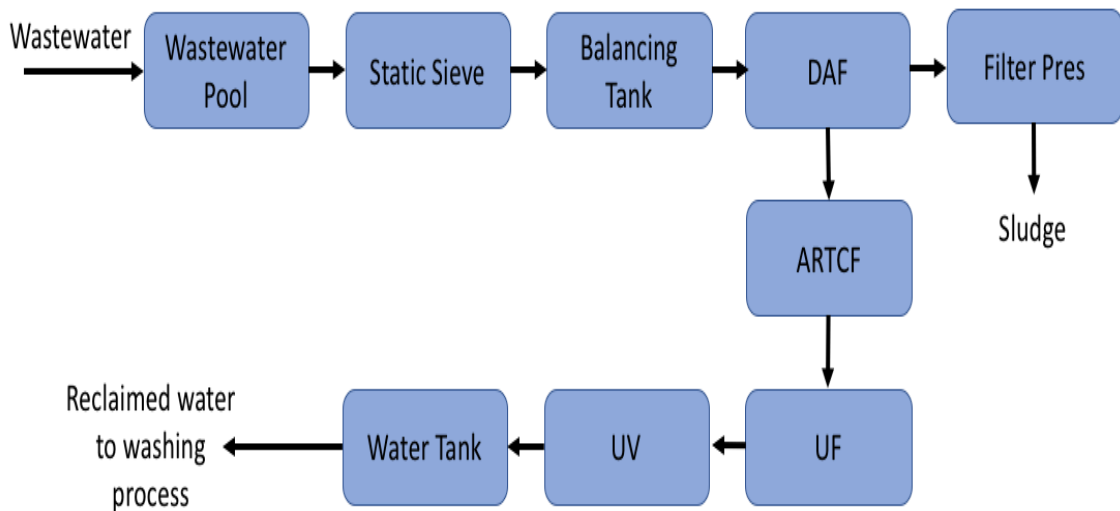


Figure 2.3. Chemical treatment and membrane combined system (1) (Scenario 2).

In Table 2.5, the feasibility study of the combined system (1) is given in detail. In the calculation made considering the wastewater data with the system with a capacity of 1 m³/hour, the annual amount of water to be recovered is calculated as 700 m³/year. It is predicted that the system will operate with an average efficiency of 70%. In the calculations made regarding the well water cost and pumping cost, it has been calculated that the total savings will be 980 Euro/year. The investment cost of the system is approximately 87,500 Euro + VAT (Table 2.5). Since the operating cost is 9,400 Euro

per year, the annual net savings are negative, and the system is not economical for such facilities with low water consumption.

Table 2.5. Operating and investment cost of combined system (1) (Scenario 2)

Parameters	Amount
System capacity	1 m ³ /day
The annual amount of water to be recovered	1000 m ³ /year*0.7=700 m ³ /year
⁵ Brackish water cost	1.35 Euro/m ³
Pumping cost	0.05 Euro/m ³
Electricity cost	0.2 Euro/kWh
Operating cost	9.4 Euro/m ³
The annual operating cost of the system ⁶	9.4 Euro/m ³ *1000 m ³ /year=9,400 Euro /year
Annual savings	700m ³ /year*(1.35+0.05)Euro/m ³ = 980 Euro/year
Net savings	980 -9,400=-8,420 Euro/year
Investment cost	87,500 Euro+VAT

2.1.3.3. Water recovery with chemical treatment and membrane combined system (Scenario 3)

Another water recovery system is a combined design consisting of a ceramic ultrafiltration membrane and a reverse osmosis (RO) membrane added to the chemical treatment (Figure 2.4.). After the wastewater generated during the washing process is collected in a pool, it is passed through a static sieve with the help of a pump. After passing through the static sieve, the wastewater is collected in a 5 m³ capacity balancing tank. The wastewater collected here is taken to the Dissolved Air Flootation (DAF) tank by means of a pump. Wastewater is subjected to coagulation and flocculation processes before entering the DAF tank. These processes are performed automatically in the static mixer. After the completion of the chemical reactions, the wastewater is taken to the DAF tank, where the pollutants in the wastewater are floated. After the oils and flocs in the

⁵ Freshwater cost <https://www.izsu.gov.tr/tr/suveatiksutarifesi/41/103>

⁶ Operating cost varies 9.4-10.5 Euro/m³ and it was taken 9.4 Euro/m³ in the calculation.

water are floated, the treated water is taken to the ARTCF feeding tank, and the collected oily sludge is first taken to the sludge tank and then to the dewatering system. After the oils are retained in the DAF tank, the wastewater is collected in the ARTCF feed tank. Polyaluminum Chloride (PAC) is added to the accumulated water and then passed through ceramic membranes. The filtered water becomes ready to feed into the Ultra Filtration (UF) system. All particles above 0.4 micrometers are retained during the Ceramic Membrane Filtration process. After this filtration process, regular backwashing will be done on the membranes, and the wastes generated during backwashing are collected in the sludge tank. The wastewater from the ARTCF system is passed through the UF, RO and Ultraviolet (UV) systems, respectively (Figure 2.4). The list of units and equipment selected in wastewater recovery facility is given in Table 2.6.

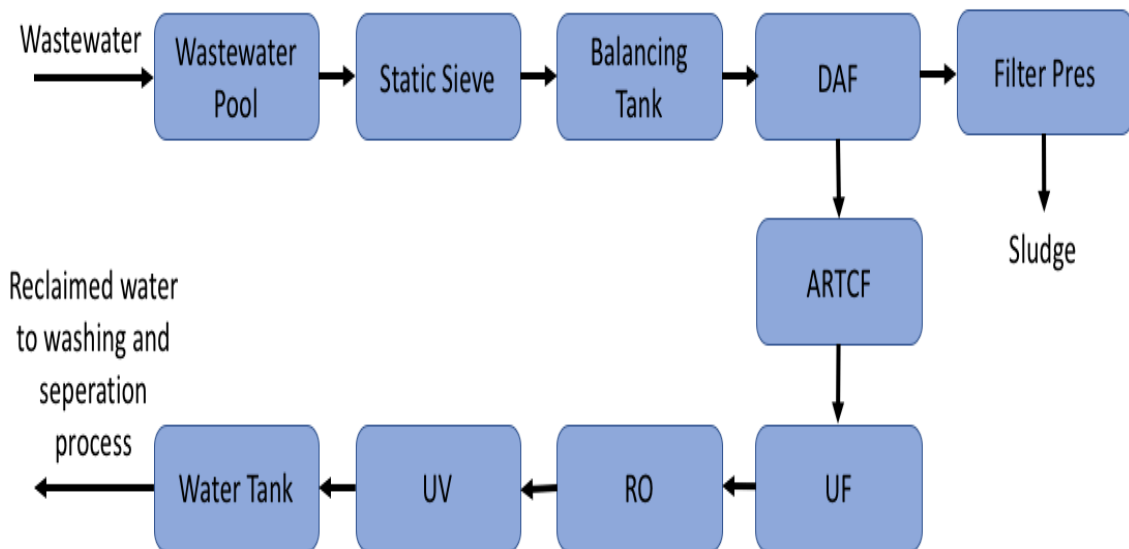


Figure 2.4. Chemical treatment and membrane combined system (2) (Scenario 3).

Table 2.6. List of units and equipment selected in wastewater recovery facility

1. Wastewater Collection Pool	
Amount	1 piece
Capacity	2 m ³
Material	Reinforced concrete
2. Booster Pump	
Amount	1 piece
Capacity	2 m ³ /h
Type	Plunger
Brand	Dreno, Sumak etc.
3. Static Sieve	
Amount	1 piece
Capacity	2 m ³ /h
Material	AISI 340
Pore space	1 cm
Accessory	Complete with entrance and exit structures and support legs
4. Balancing Tank	
Amount	1 piece
Capacity	5 m ³
Material	PE
Property	Open mouth vertical tank
5. Wastewater Booster Pump	
Amount	1 piece
Capacity	1 m ³ /h
Type	Plunger
Brand	Dreno, Sumak etc.
6. Caustic Dosing Pump	
Amount	1 piece
Capacity	10 lt/h – 3 bar
Type	Solenoid Dosing Pump
Brand	Emec etc.

Table 2.6. List of units and equipment selected in wastewater recovery facility (continued)

7. PAC Dosing Pump	
Amount	1 piece
Capacity	10 lt/h – 3 bar
Type	Solenoid Dosing Pump
Brand	Emec etc.
8. Poli Dosing Pump	
Amount	1 piece
Capacity	20 lt/h – 3 bar
Type	Solenoid Dosing Pump
Brand	Emec etc.
9. pH Meter	
Amount	1 piece
Material	Field type
Measurement Range	0-14
Accessory	With probe and prb holder
10. Dissolved Air Flootation (DAF) Tank	
Amount	1 piece
Capacity	1 m ³ /h
Property	Complete with oil tank, mud tank and ARTCF Feed tank
Material	st37 epoxy painted
Accessory	Oil scraper system and inlet and outlet structures
11. DAF Circulation Pump	
Amount	1 piece
Capacity	1 m ³ /h
Type	Microbubble Generator
Brand	Nikuni etc.
Accessory	Pressurization tank, flowmeters and manometers

Table 2.6. List of units and equipment selected in wastewater recovery facility (continued)

12. PAC Dosing Pump	
Amount	1 piece
Capacity	10 lt/h – 3 bar
Type	Solenoid Dosing Pump
Brand	Emec etc.
Explanation	It will be used in the coagulation process.
13. pH Meter	
Amount	1 piece
Material	Field type
Measurement Range	0-14
Accessory	With probe and prb holder
14. Sludge Tank Feed Pump	
Amount	1 piece
Type	Air diaphragm, plastic body
Capacity	400 lt/min.
Brand	Hugepump
15. Filter Press Feed Tank	
Amount	1 piece
Capacity	20 m ³
Material	PE or Reinforced concrete
Type	Open mouth silo
16. Filter Press Feed Pump	
Amount	1 piece
Capacity	560 lt/min.
Type	Air Diaphragm, metal body
Brand	Hugepump etc.

Table 2.6. List of units and equipment selected in wastewater recovery facility (continued)

17. Filter Press Unit	
Amount	1 piece
Plate size	630 mm* 630 mm
Number of plates	15 pieces
Type	Open discharge, manual shaking, joystick compression
Press Body Material	st 37 epoxy painted
18. ARTCF Feed Pump	
Amount	1 piece
Capacity	1 m ³ /h -4,5 bar
Type	Centrifugal
Brand	Ebara, Lowara etc.
19. ARTCF Unit	
Amount	1 set
Capacity	1000 lt/h
Property	Special ceramic membrane selected suitable for waste water
Accessory	Complete with inlet-outlet collector structure, pneumatic actuated valves and pressure transmitter.
20. ARTCF System Chemical Protective Dosing Pump	
Amount	1 piece
Type	Horizontal Stainless Pump
Brand	Sumak, Goulds etc.
Explanation	A low amount will be dosed onto the surface of the membranes
21. Chemical Preservative Preparation Tank	
Amount	1 set
Capacity	500 lt, Open Mouth Tank
Property	Including motor reducer, shaft, chassis and propeller
Material	PE

Table 2.6. List of units and equipment selected in wastewater recovery facility (continued)

22. Chemical Preservative Preparation Tank Mixer	
Amount	1 piece
Period	181 cycle/min.
Accessory	AISI 304 quality stainless steel shaft and impeller
23. ARTCF System CIP Pump	
Amount	1 piece
Brand	Sumak, Goulds etc.
24. ARTCF CIP Washing Tank	
Amount	1 set
Capacity	250 lt
Material	PE
25. UF System Feed Tank	
Amount	1 piece
Capacity	1000 lt
Type	Vertical Open mouth tank
Material	PE
26. UF System Feed Pump	
Amount	1 piece
Total Capacity	1 m ³ /h-3,5 bar
Accessory	Complete with connection equipment
Brand	Sumak, Goulds etc.
27. UF System	
Amount	1 set
Flow	1000 lt/h
Tank Size	8"x17"
Tank Material	FRP
Accessory	Complete with CIP system

Table 2.6. List of units and equipment selected in wastewater recovery facility (continued)

28. RO System Feed Tank	
Amount	1 piece
Capacity	1000 lt
Type	Vertical Open mouth tank
Material	PE
29. RO System Feed Pump	
Amount	1 piece
Total Capacity	1 m ³ /h
Accessory	Complete with connection equipment
Brand	Lowara, Goulds etc.
30. RO System	
Amount	1 set
Feed Flow	1000 lt/h
Membrane Size	4"x40"
Number of Membranes	3
Recovery	60%
Motor Power	1,5 kW
Accessory	Complete with automatic CIP and Rinse system
31. UV Disinfection System	
Amount	1 piece
Total Capacity	1000 lt/h
Accessory	Control Panel, UV glass, UV Capsule
Brand	Aqualine, etc.
32. Reclaimed Water Tank	
Amount	1 piece
Capacity	2 m ³
Material	Reinforced concrete

In Table 2.7, the feasibility study of the combined system (2) is given in detail. In the calculation made considering the wastewater data with the system with a capacity of 1 m³/hour, the annual amount of water to be recovered is calculated as 700 m³/year. It is predicted that the system will operate with an average efficiency of 70%. In the calculations made regarding the well water cost and pumping cost, it has been calculated that the total savings will be 980 Euro/year. The investment cost of the system is approximately 95,500 Euro + VAT (Table 2.7). Since the operating cost is 10,500 Euro per year, the annual net savings are negative, and the system is not economical for such facilities with low water consumption.

Table 2.7. Operating and investment cost of combined system (2) (Scenario 3)

Parameters	Amount
System capacity	1 m ³ /day
The annual amount of water to be recovered	1000 m ³ /year*0.7=700 m ³ /year
⁷ Brackish water cost	1.35 Euro/m ³
Pumping cost	0.05 Euro/m ³
Electricity cost	0.2 Euro/kWh
Operating cost	10.5 Euro/m ³
The annual operating cost of the system ⁸	10.5 Euro/m ³ *1000 m ³ /year=10,500 Euro /year
Annual savings	700m ³ /year*(1.35+0.05)Euro/m ³ = 980 Euro/year
Net savings	980 -10,500=-9,520 Euro/year
Investment cost	95.500 Euro+VAT

2.2. Mathematical Modeling

A model that incorporates the water and wastewater streams, water-using process and wastewater treatment units is shown in Figure 2.5. This section covers the problem statement and mathematical framework of the WN problem in detail.

⁷ Freshwater cost <https://www.izsu.gov.tr/tr/suveatiksutarifesi/41/103>

⁸ Operating cost varies 9.4-10.5 Euro/m³ and it was taken 10.5 Euro/m³ in the calculation.

2.2.1. Problem statement

This study aims to deal with the issue of minimizing freshwater usage in the water-using processes. The problem addressed in this work is illustrated in Figure 2.5.

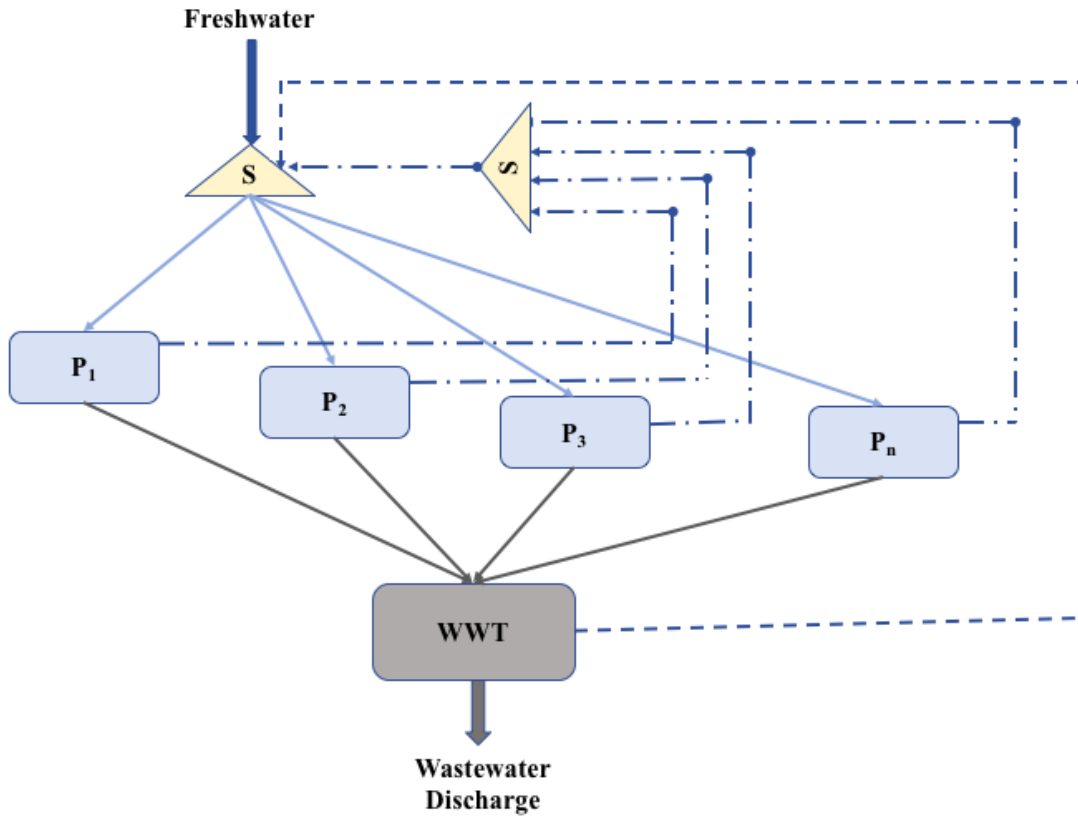


Figure 2.5. Schematic for water network synthesis problem (adapted from Ibric et al. 2021).

The WN synthesis problem includes water-using process units “p”, wastewater treatment unit “wwt” and the splitters, “s”. The input and output contaminant concentrations are given for the process units and treatment unit. The relevant information and assumptions for the problem is given as follows:

- Constant flowrates of water through the process and wastewater treatment unit
- Fixed mass load of contaminants within the processes
- Fixed removal ratio of contaminants in the wastewater treatment unit
- Fixed contaminant concentrations in the freshwater sources
- Water loss is negligible during processes

2.2.2. Mathematical framework

The water network model consists of three parts such as splitters, process units and wastewater treatment unit.

2.2.2.1. Mass balance of process units

According to the proposed WN synthesis problem, the freshwater stream from source, water streams for water reuse from process units and regenerated water streams from wastewater treatment unit are directed toward the process unit 'p'. Equations (2.6) and (2.7) describe the mass balance of process unit 'p' and the mass balance of contaminant 'c'.

f_p^{in} : Total amount of water entering the process (m^3)

$f_{s,p}$: Amount of water from source to process (m^3)

$f_{ww,p}$: Amount of regenerated water from wastewater treatment unit to process (m^3)

$f_{p',p}$: Amount of water from process to process (m^3)

$x_{p,c}^{in}$: Concentration of contaminant of water entering the process (kg/m^3)

$x_{s,c}$: Concentration of contaminant of water from source to process (kg/m^3)

$x_{ww,c}$: Concentration of contaminant of water from wastewater treatment unit to process (kg/m^3)

$x_{p',c}$: Concentration of contaminant of water from process to process (kg/m^3)

$$f_p^{in} = \sum_{s \in FW} f_{s,p} + \sum_{ww \in WWT} f_{ww,p} + \sum_{p' \in PU, p \neq p'} f_{p',p} \quad (2.6)$$

$$f_p^{in} * x_{p,c}^{in} = \sum_{s \in FW} f_{s,p} * x_{s,c} + \sum_{ww \in WWT} f_{ww,p} * x_{ww,c} + \sum_{p' \in PU, p \neq p'} f_{p',p} * x_{p',c} \quad (2.7)$$

2.2.2.2. Mass balance of wastewater treatment unit

The wastewater streams from water-using processes “p” are directed toward wastewater treatment unit “wwt”. The treatment unit mass balance and contaminant balance are given by Equation (2.8) and (2.9).

- f_{ww} : Total amount of wastewater generated in the production system (m^3)
- f_d : Amount of wastewater to be discharged (m^3)
- $f_{ww,p}$: Amount of regenerated water from wastewater treatment unit to process (m^3)
- $f_{p,ww}$: Amount of water from process to wastewater treatment unit (m^3)
- $x_{ww,c}$: Concentration of contaminant of water from wastewater treatment unit to process (kg/m^3)
- $x_{d,c}$: Concentration of contaminant of wastewater to be discharged (kg/m^3)
- $x_{p,c}$: Concentration of contaminant of water from the process to the wastewater treatment unit (kg/m^3)

$$f_{ww} = \sum_{p \in P_U} f_{p,ww} - f_d - \sum_{ww \in WW_T} f_{ww,p} \quad (2.8)$$

$$f_{ww} * x_{ww,c} = \sum_{p \in P_U} f_{p,ww} * x_{p,c} - f_d * x_{d,c} - \sum_{ww \in WW_T} f_{ww,p} * x_{ww,c} \quad (2.9)$$

2.2.2.3. Objective function

The objective of WN problem is to minimise the TAC which is defined as the sum of freshwater costs, wastewater treatment operating costs and discharge costs using by Equation (2.10).

- C_{FW} : Freshwater cost (Euro/ m^3)
- C_{WW} : Wastewater treatment operating cost (Euro/ m^3)
- C_D : Discharge cost (Euro/ m^3)
- H : Plant operating hours per annum (h)
- $f_{s,p}$: Amount of water from source to process (m^3)

f_{ww} : Total amount of wastewater generated in the production system (m^3)

f_d : Amount of wastewater to be discharged (m^3)

$$\min Z = H * \left[\sum_{s \in FW} f_{s,p} * C_{FW} + \sum_{ww \in WWT} f_{ww} * C_{WW} + f_d * C_D \right] \quad (2.10)$$

2.3. Industrial Application of WN Synthesis Model

The main water-using processes in olive oil production are washing and separation processes. In Figure 2.6, the input and output streams for washing, separation processes and wastewater treatment unit are defined. The value of a single pollutant is taken into consideration for the treatment of wastewater from washing and separation processes. Therefore, the model was created for a single contaminant.

Since there is no disinfection process in the GENMBR system recommended for the plant, the case of using treated water only in the washing process within the scope of the “Scenario 1” is discussed.

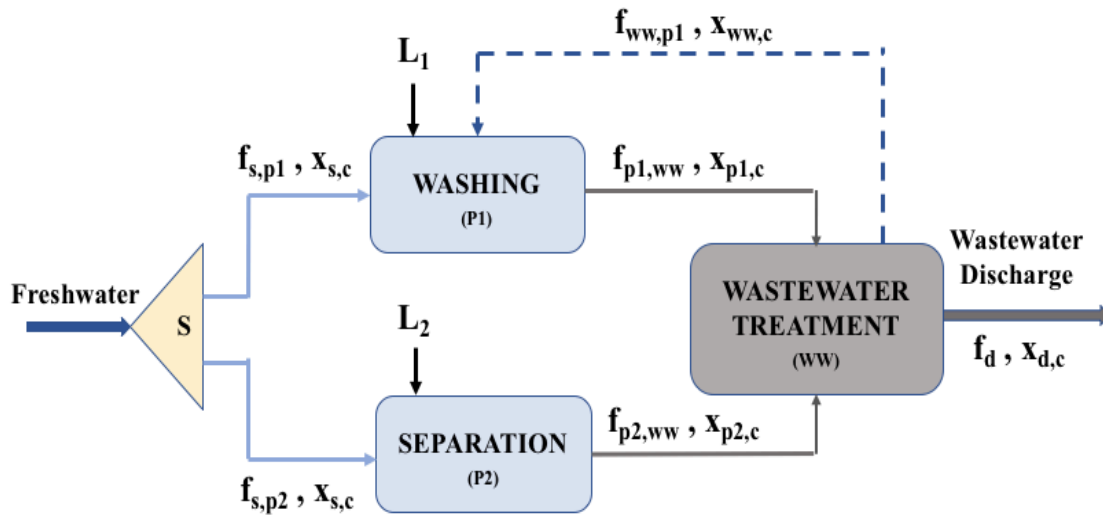


Figure 2.6. Schematic for olive oil production model (Scenario 1).

Constants:

$x_{s,c}$, $x_{p,c}$, L_1 , L_2 , r , C_{FW} , C_{WW} , C_D , H

$x_{s,c}$: Concentration of contaminant of water from source to process (kg/m^3)

$x_{p,c}$: Concentration of contaminant of water from the process to the wastewater treatment unit (kg/m^3)

L_i : Amount of pollution from olive/olive oil (kg)

r : Removal ratio of contaminant (%)

C_{FW} : Freshwater cost (Brackish water cost + Pumping cost) (EURO/ m^3)

C_{WW} : Wastewater treatment operating cost (EURO/ m^3)

C_D : Discharge cost (EURO/ m^3)

H : Plant operating hours per annum (h)

Variables:

$f_{s,p}$, $f_{ww,p}$, $f_{p,ww}$, f_d , $x_{ww,c}$, $x_{d,c}$

$f_{s,p}$: Amount of water from source to process (m^3)

$f_{ww,p}$: Amount of regenerated water from wastewater treatment unit to process (m^3)

$f_{p,ww}$: Amount of water from process to wastewater treatment unit (m^3)

f_d : Amount of wastewater to be discharged (m^3)

$x_{ww,c}$: Concentration of contaminant of water from wastewater treatment unit to process (kg/m^3)

$x_{d,c}$: Concentration of contaminant of wastewater to be discharged (kg/m^3)

Constraints:

Constraints were created by considering the following equations:

1. Contaminant mass balance of the washing process (Eq. (2.11))
2. Contaminant mass balance of the separation process (Eq. (2.12))
3. Contaminant mass balance of the treatment process (Eq. (2.13))
4. Mass balance of treatment process (Eq. (2.14) and (Eq. (2.15))
5. Overall contaminant mass balance of the olive oil process (Eq. (2.16))
6. Equivalence showing the relationship between wastewaters from washing and separation process (Eq. (2.17), and (Eq. (2.18)).

Constraints

$$f_{s,p1} * x_{s,c} + L_1 + f_{ww,p1} * x_{ww,c} = f_{p1,ww} * x_{p1,c} \quad (2.11)$$

$$f_{s,p2} * x_{s,c} + L_2 = f_{p2,ww} * x_{p2,c} \quad (2.12)$$

$$f_{p2,ww} * x_{p2,c} + f_{p1,ww} * x_{p1,c} = f_{ww,p1} * x_{ww,c} + f_d * x_{d,c} \quad (2.13)$$

$$r * (f_{p1,ww} + f_{p2,ww}) = f_{ww,p1} \quad (2.14)$$

$$(1 - r) * (f_{p1,ww} + f_{p2,ww}) = f_d \quad (2.15)$$

$$f_{s,p1} * x_{s,c} + L_1 + f_{s,p2} * x_{s,c} + L_2 = f_d * x_{d,c} \quad (2.16)$$

$$0.31 * (f_{s,p1} + f_{ww,p1}) = 0.5 * f_{s,p2} \quad (2.17)$$

$$f_{s,p1} + f_{ww,p1} = f_{p1,ww} \quad (2.18)$$

Min Operating Hours * \sum (Freshwater costs (Brackish water cost +Pumping cost)+
Wastewater treatment operating cost (operational cost) + Wastewater discharge cost)

$$\text{Min } f(x) \quad H^*[(f_{s,p1} + f_{s,p2}) * C_{FW} + (f_{p1,ww} + f_{p2,ww}) * C_{WW} + f_d * C_D] \quad (2.19)$$

According to Table 2.1, the specific water consumption of the plant is high when compared to the literature. In this situation, the amount of water used in both the washing and separation processes in the plant can be reduced. While creating the model, an equation was written between the amount of water consumed in the washing and separation processes. The lowest specific values in the literature were taken as a basis while the equation was written (Eq. (2.20)).

$$\frac{(f_{s,p1} + f_{ww,p1})}{(f_{s,p2} + f_{ww,p2})} = \frac{0.5}{0.31} \quad (2.20)$$

By multiplying the minimum specific water consumption amounts given in the literature with the total production amount of the plant, the minimum amount of water that the plant can use is calculated for both processes.

$$(f_{s,p1} + f_{ww,p1}) = 0.5 \frac{m^3}{ton} * 687 ton = 343.5 m^3 \quad (2.21)$$

$$(f_{s,p2} + f_{ww,p2}) = 0.31 \frac{m^3}{ton} * 687 ton = 212.97 m^3 \quad (2.22)$$

The data obtained by using Eq. (2.21) and Eq. (2.22) contributes to the model as a lower bounds (lb) value. The following calculations were made in order to determine the constants (L1 and L2), which express the pollution load from olives and olive oil in the mathematical model.

Calculation of L₁ pollution load

There is no treatment system in the plant. For this reason, the expression for the use of treated/regenerated water, expressed in the model, ($f_{ww,p1}, X_{ww,c}$) is equal to “0”. In addition, the L1 value was calculated by solving the following equation (Eq. (2.23)), assuming that the amount of water entering the process and the wastewater leaving the process are equal, that is, there is no water loss.

$$f_{s,p1} * x_{s,c} + L_1 + f_{ww,p1} * x_{ww,c} = f_{p1,ww} * x_{p1,c} \quad (2.23)$$

$$576 \text{ m}^3 * 0.03 \frac{\text{kg}}{\text{m}^3} + L_1 + 0 = 576 \text{ m}^3 * 1.15 \frac{\text{kg}}{\text{m}^3}$$

$$L_1 = 645.12 \text{ kg}$$

Calculation of L₂ pollution load

The L₂ value was calculated by solving the equation below (Eq. (2.24)), assuming that the amount of water entering the separation process and the wastewater leaving the process are equal to each other, that is, there is no water loss.

$$f_{s,p2} * x_{s,c} + L_2 + f_{ww,p2} * x_{ww,c} = f_{p2,ww} * x_{p2,c} \quad (2.24)$$

$$424 \text{ m}^3 * 0.03 \frac{\text{kg}}{\text{m}^3} + L_2 + 0 = 424 \text{ m}^3 * 9.58 \frac{\text{kg}}{\text{m}^3}$$

$$L_2 = 4,049 \text{ kg}$$

In Scenario 2, the chemical treatment and membrane combined system (1) which includes ceramic membrane, UF, and UV systems, is discussed. Since Scenario 1 and Scenario 2 are the same in terms of mathematical modelling, the formulas in Scenario 1 are also valid for Scenario 2.

In order to use the treated water in both washing and separation processes, the combined system was further developed and examined within the scope of Scenario 3. In Scenario 3, the chemical treatment and membrane combined system (2) which includes ceramic membrane, UF, RO, and UV systems, is discussed (Figure 2.7).

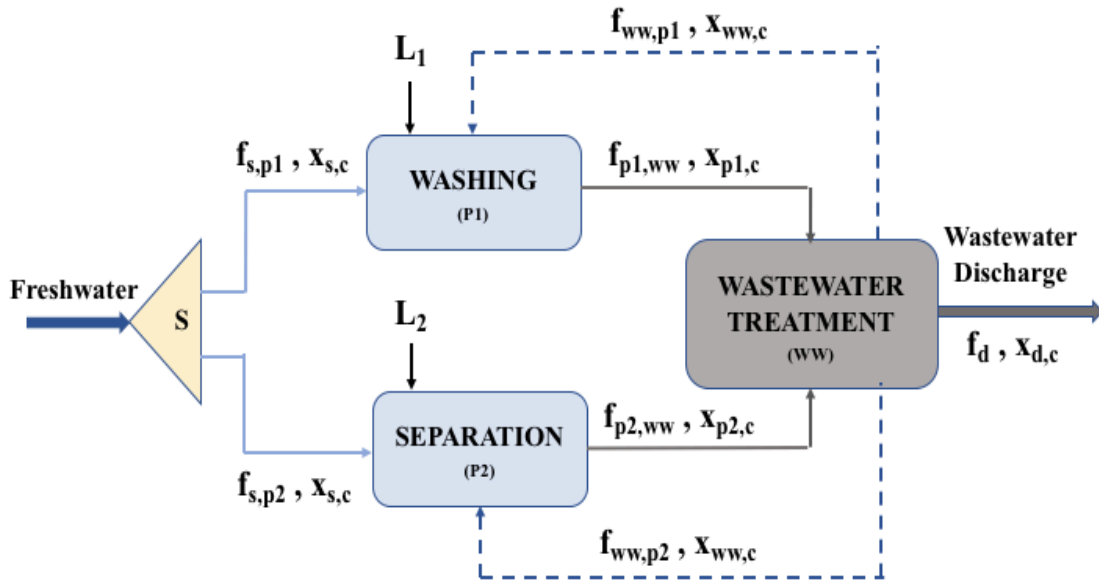


Figure 2.7. Schematic for olive oil production model (Scenario 3).

$$f_{s,p1} * x_{s,c} + L_1 + f_{ww,p1} * x_{ww,c} = f_{p1,ww} * x_{p1,c} \quad (2.25)$$

$$f_{s,p2} * x_{s,c} + L_2 + f_{ww,p2} * x_{ww,c} = f_{p2,ww} * x_{p2,c} \quad (2.26)$$

$$\begin{aligned} & f_{p2,ww} * x_{p2,c} + f_{p1,ww} * x_{p1,c} \\ & = f_{ww,p1} * x_{ww,c} + f_{ww,p2} * x_{ww,c} + f_d * x_{d,c} \end{aligned} \quad (2.27)$$

$$r * (f_{p1,ww} + f_{p2,ww}) = (f_{ww,p1} + f_{ww,p2}) \quad (2.28)$$

$$(1 - r) * (f_{p1,ww} + f_{p2,ww}) = f_d \quad (2.29)$$

$$f_{s,p1} * x_{s,c} + L_1 + f_{s,p2} * x_{s,c} + L_2 = f_d * x_{d,c} \quad (2.30)$$

$$0.31 * (f_{s,p1} + f_{ww,p1}) = 0.5 * (f_{s,p2} + f_{ww,p2}) \quad (2.31)$$

$$f_{s,p1} + f_{ww,p1} = f_{p1,ww} \quad (2.32)$$

$$f_{s,p2} + f_{ww,p2} = f_{p2,ww} \quad (2.33)$$

2.4. Solution Strategy

When considering the model of olive oil production, the objective function is linear but the model consists of 4 nonlinear constraints. Because of the nonlinear functions, the model has nonlinear programming properties. In order to realize the solution to the problem, it is necessary to choose algorithms suitable for nonlinear programming. Nonlinear programming models are examined in two stages.

1. Univariate Models: These models are divided into two groups constrained and unconstrained models.

2. Multivariate Models: These models are also divided into two groups constrained and unconstrained models.

In the model, it is defined that the variables x_1, x_2, \dots, x_n in the multivariate $f(x_1, x_2, \dots, x_n)$ function are associated with more than one equation. For this reason, the model falls within the definition of *constrained nonlinear programming*.

2.4.1. Selection of the Solver

To solve nonlinear optimization problem, there are two approaches such as problem-based and solver-based in MATLAB. Problem-based optimization approach is easier than the solver-based optimization approach to create the model. Problem-based approach needs to be transformed from problem form to matrix form, whereas solver-based approach does not require. Using a solver-based technique has the benefit of enabling the use of a Hessian or Jacobian multiply function to conserve memory in complex situations. In this study, the *solver-based optimization approach* has been applied to the mathematical model as shown in Figure 2.8.

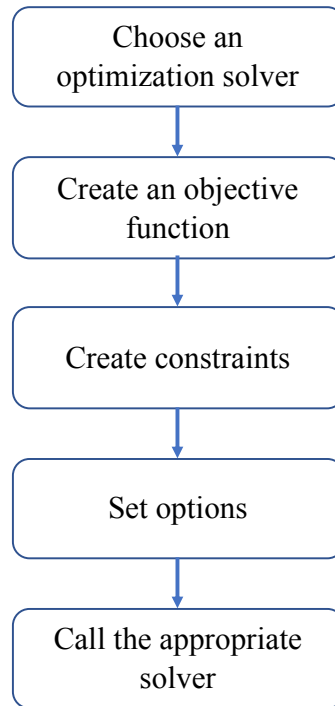


Figure 2.8. The steps in solver-based optimization problem setup.

Since the mathematical model has a constrained nonlinear problem with one objective, *fmincon* solver from a solver-based optimization setup has been selected. *fmincon* minimizes the problem specified as given below:

$$\min f(x) \begin{cases} Aeq \cdot x = beq \\ ceq(x) = 0 \\ A \cdot x \leq b \\ c(x) \leq 0 \\ lb \leq 0 \leq ub \end{cases} \quad (2.34)$$

Regarding the olive oil production model, the following equations Eq. (2.25), Eq. (2.26), Eq. (2.27), and Eq. (2.30) are nonlinear equalities such $ceq(x) = 0$. The other equations Eq. (2.28), Eq. (2.29), Eq. (2.31), Eq. (2.32), and Eq. (2.33) are linear equalities such $Aeq \cdot x = beq$. In the model, there is no linear and nonlinear inequalities such $c(x) \leq 0$ and $A \cdot x \leq b$. In MATLAB, syntax is used in Eq. (2.35).

$$x=fmincon (fun, x0, A, b, Aeq, beq, lb, ub, nonlcon, options) \quad (2.35)$$

The constraints, variables, constants, upper and lower bounds related to the Scenario 1, Scenario 2 and Scenario 3 have been revised according to `fmincon` function as in the Table 2.8, Table 2.9, and Table 2.10.

fmincon Solver

`fmincon` has five algorithms such as interior-point, trust-region-reflective, `sqp`, `sqp-legacy` and active-set.

Interior-point algorithm can recover from NaN or Inf results and fulfills bounds at all iterations. Large-scale problems can be solved by the algorithm using specialized methods.

Sqp is an iterative method for constrained nonlinear optimization to fulfill the bounds at each iteration. Results of NaN or Inf can be recovered by the algorithm.

Sqp-legacy is comparable to 'sqp' but typically slower and needs more memory.

The ability to take big steps via the "*active-set*" enhances speed. On a few non-smooth constraint issues, the technique works well.

You must supply a gradient for "*trust-region-reflective*" which only accepts bounds or linear equality restrictions and not both. Within these constraints, the algorithm effectively manages both big sparse issues and little dense problems (Mathworks, 2023).

Table 2.8. Constraints and objective function in the programming language of MATLAB (Scenario 1)

Objective function and constraints	Programming language
Min $f(x) [(f_{s,p1} + f_{s,p2}) * C_{FW} + (f_{p1,ww} + f_{p2,ww}) * C_{WW} + f_d * C_D]$	<code>fun = @(x) (1.4*(x(1)+x(2))+0.27*(x(3)+x(2))+ 0.67*x(6));</code>
$f_{s,p1} * x_{s,c} + L_1 + f_{ww,p1} * x_{ww,c} = f_{p1,ww} * x_{p1,c}$	<code>ceq1 = (x(1)*c1) + L1 + (x(4)*x(5)) - (x(3)*c2);</code>
$f_{s,p2} * x_{s,c} + L_2 = f_{p2,ww} * x_{p2,c}$	<code>ceq2 = (x(2)*c1) + L2 - (x(2)*c3);</code>
$f_{p2,ww} * x_{p2,c} + f_{p1,ww} * x_{p1,c} = f_{ww,p1} * x_{ww,c} + f_d * x_{d,c}$	<code>ceq3 = (x(2)*c3) + (x(3)*c2) - (x(4)*x(5)) -(x(6)*x(7));</code>
$f_{s,p1} * x_{s,c} + L_1 + f_{s,p2} * x_{s,c} + L_2 = f_d * x_{d,c}$	<code>ceq4 = (x(1)*c1) + (x(2)*c1) + L1 + L2 - (x(6)*x(7));</code>
$r * (f_{p1,ww} + f_{p2,ww}) = f_{ww,p1}$	<code>Aeq1=r*x(3)+r*x(2)-x(4);</code>
$(1 - r) * (f_{p1,ww} + f_{p2,ww}) = f_d$	<code>Aeq2= (1-r)*x(3)+ (1-r)*x(2)-x(6);</code>
$0.31 * (f_{s,p1} + f_{ww,p1}) = 0.5 * f_{s,p2}$	<code>Aeq3=0,31*(x(1)+x(4))-0,5*x(2);</code>
$f_{s,p1} + f_{ww,p1} = f_{p1,ww}$	<code>Aeq4=x(1)+x(4)-x(3);</code>
$x_1, x_2, x_3, x_4, x_5, x_6, x_7$	<code>x1 ≥ 0, x2 ≥ 212, x3 ≥ 0, x4 ≥ 0, x5 ≥ 0.2, x6 ≥ 0, x7 ≥ 0</code>
	<code>lb=[0 200 300 350 0 200 0];</code>
	<code>ub=[500 500 500 1000 5 500 20];</code>
	<code>x0=[100,200,300,350,0.5,300,10]</code>
	<code>options=optimoptions ('fmincon', 'Display', 'iter', 'Algorithm', 'sqp')</code>

Table 2.9. Constraints and objective function in the programming language of MATLAB (Scenario 2)

Objective function and constraints	Programming language
Min $f(x) [(f_{s,p1} + f_{s,p2}) * C_{FW} + (f_{p1,ww} + f_{p2,ww}) * C_{WW} + f_d * C_D]$	<code>fun = @(x) (1.4*(x(1)+x(2))+9.4*(x(3)+x(2))+ 0.67*x(6));</code>
$f_{s,p1} * x_{s,c} + L_1 + f_{ww,p1} * x_{ww,c} = f_{p1,ww} * x_{p1,c}$	<code>ceq1 = (x(1)*c1) + L1 + (x(4)*x(5)) - (x(3)*c2);</code>
$f_{s,p2} * x_{s,c} + L_2 = f_{p2,ww} * x_{p2,c}$	<code>ceq2 = (x(2)*c1) + L2 - (x(2)*c3);</code>
$f_{p2,ww} * x_{p2,c} + f_{p1,ww} * x_{p1,c} = f_{ww,p1} * x_{ww,c} + f_d * x_{d,c}$	<code>ceq3 = (x(2)*c3) + (x(3)*c2) - (x(4)*x(5)) -(x(6)*x(7));</code>
$f_{s,p1} * x_{s,c} + L_1 + f_{s,p2} * x_{s,c} + L_2 = f_d * x_{d,c}$	<code>ceq4 = (x(1)*c1) + (x(2)*c1) + L1 + L2 - (x(6)*x(7));</code>
$r * (f_{p1,ww} + f_{p2,ww}) = f_{ww,p1}$	<code>Aeq1=r*x(3)+r*x(2)-x(4);</code>
$(1 - r) * (f_{p1,ww} + f_{p2,ww}) = f_d$	<code>Aeq2= (1-r)*x(3)+ (1-r)*x(2)-x(6);</code>
$0.31 * (f_{s,p1} + f_{ww,p1}) = 0.5 * f_{s,p2}$	<code>Aeq3=0,31*(x(1)+x(4))-0,5*x(2);</code>
$f_{s,p1} + f_{ww,p1} = f_{p1,ww}$	<code>Aeq4=x(1)+x(4)-x(3);</code>
$x_1, x_2, x_3, x_4, x_5, x_6, x_7$	<code>x1 ≥ 0, x2 ≥ 212, x3 ≥ 0, x4 ≥ 0, x5 ≥ 0.2, x6 ≥ 0, x7 ≥ 0</code>
	<code>lb=[0 200 300 350 0 200 0];</code>
	<code>ub=[500 500 500 1000 5 500 20];</code>
	<code>x0=[100,200,300,350,0.5,300,10]</code>
	<code>options=optimoptions ('fmincon', 'Display', 'iter', 'Algorithm', 'sqp')</code>

Table 2.10 Constraints and objective function in the programming language of MATLAB (Scenario 3)

Objective function and constraints	Programming language
Min $f(x) [(f_{s,p1} + f_{s,p2}) * C_{FW} + (f_{p1,ww} + f_{p2,ww}) * C_{WW} + f_d * C_D]$	<code>fun = @(x) (1.4*(x(1)+x(2))+10.5*(x(3)+x(4))+ 0.67*x(8));</code>
$f_{s,p1} * x_{s,c} + L_1 + f_{ww,p1} * x_{ww,c} = f_{p1,ww} * x_{p1,c}$	<code>ceq1 = (x(1)*c1) + L1 + (x(5)*x(6)) - (x(4)*c3);</code>
$f_{s,p2} * x_{s,c} + L_2 + f_{ww,p2} * x_{ww,c} = f_{p2,ww} * x_{p2,c}$	<code>ceq2 = (x(2)*c1) + L2 +(x(7)*x(6))- (x(3)*c2);</code>
$f_{p2,ww} * x_{p2,c} + f_{p1,ww} * x_{p1,c}$ $= f_{ww,p1} * x_{ww,c} + f_{ww,p2} * x_{ww,c} + f_d * x_{d,c}$	<code>ceq3 = (x(3)*c2) + (x(4)*c3) - (x(5)*x(6)) - (x(7)*x(6))- (x(8)*x(9));</code>
$f_{s,p1} * x_{s,c} + L_1 + f_{s,p2} * x_{s,c} + L_2 = f_d * x_{d,c}$	<code>ceq4 = (x(1)*c1) + (x(2)*c1) + L1 + L2 - (x(8)*x(9));</code>
$r * (f_{p1,ww} + f_{p2,ww}) = (f_{ww,p1} + f_{ww,p2})$	<code>Aeq1=r*x(4)+r*x(3)-x(5)-x(7);</code>
$(1 - r) * (f_{p1,ww} + f_{p2,ww}) = f_d$	<code>Aeq2= (1-r)*x(4)+ (1-r)*x(3)-x(8);</code>
$0.31 * (f_{s,p1} + f_{ww,p1}) = 0.5 * (f_{s,p2} + f_{ww,p2})$	<code>Aeq3=0,31*(x(1)+x(5))-0,5*(x(7)+x(2));</code>
$f_{s,p1} + f_{ww,p1} = f_{p1,ww}$	<code>Aeq4=x(1)+x(5)-x(4);</code>
$f_{s,p2} + f_{ww,p2} = f_{p2,ww}$	<code>Aeq5=x(2)+x(7)-x(3);</code>
$x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9$	<code>x1 ≥ 0, x2 ≥ 0, x3 ≥ 0, x4 ≥ 0, x5 ≥ 0, x6 ≥ 1, x7 ≥ 0, x8 ≥ 0, x9 ≥ 0</code>
	<code>lb=[0 0 0 0 0 0 0 0 0];</code>
	<code>ub=[600 600 900 900 600 0.15 600 900 40];</code>
	<code>x0=[80,80,100,200,50,0.02,100,200,20];</code>
	<code>options=optimoptions ('fmincon', 'Display', 'iter', 'Algorithm', 'sqp')</code>

2.4.1.1 Interior-point algorithm

The aim of the interior-point algorithm is to find the optimal solution from the interior of the feasible set. The algorithm is solved iteratively using the Newton Method. By going from one point on the objective function to another position in the middle of the feasible region, interior-point is used to locate the best solution to a mathematical optimization issue. Nonlinear programming issues can also be resolved using interior point methods, which are frequently employed to address linear programming issues. The method frequently uses a two-phase method, with the first phase being used to get a feasible solution and the second phase being used to optimize the solution (Mathworks, 2023).

2.4.1.2 Active-set algorithm

All active set approaches operate on the general principle that the active inequality constraints are treated as equality constraints at each iteration and the remaining constraints are ignored. In bound-constrained problems, an active constraint is a variable with a constant value, which simplifies the solution by removing the variables that correspond to the active constraints from the resulting optimization problem. The Karush-Kuhn-Tucker (KKT) optimality requirements are examined after a minimum to this problem is discovered. The algorithm terminates if they are satisfied; else, one of the current constraints that would have violated the KKT requirements is eliminated (Schofield, 2008; Wong, 2011).

2.4.1.3 Sequential quadratic programming (SQP) algorithm

Sequential Quadratic Programming is one of the most effective algorithms applied to solve constrained nonlinear optimization problems (NLP). It makes use of a strong theoretical underpinning and offers potent algorithmic tools for the resolution of significant technologically important problems on a large scale. The algorithm uses an iterative approach in which the NLP for a given iterate, x^n , is represented by a Quadratic Programming (QP) subproblem, which is then solved, and the result is used to generate a new iterate, x^{n+1} . By using this technique, the sequence is made to converge to a local minimum x of the NLP (University of Houston, 2023).

Although it has a new implementation, the sqp algorithm is substantially the same as the sqp-legacy algorithm. Sqp typically uses less memory and executes programs more quickly than sqp-legacy.

The following are the main differences between the sqp and active-set algorithms (Mathworks, 2023):

1. In the bounds-constrained region, the sqp algorithm performs each iterative step. Also respecting bounds are finite difference steps. Boundaries are flexible, allowing a step to precisely touch one.
2. The sqp algorithm may try to take a step that fails during one of its iterations. This indicates that a value of Inf, NaN, or a complex value is returned by an objective function or nonlinear constraint function you supply. The algorithm tries to take a smaller step in this situation.
3. The QP subproblem is solved using a separate set of linear algebra algorithms using the sqp algorithm. These procedures are quicker and more memory-efficient than active-set procedures.

2.4.1.4 Trust region reflective algorithm

With the help of the objective function and its derivatives, trust-region techniques, a class of iterative algorithms, create a quadratic model that, to a reasonable degree of precision around a particular point x_k , accurately approximates the objective function. The iteration starts with the point “x” in n-space and it is relocated to a place with a lower function value in order to improve. The main idea is to approximate f with a simpler function q that accurately captures how function f behaves in an area N surrounding the point x . The trust area is this neighborhood (Mathworks, 2023).

First, it is recommended to use the interior point algorithm to minimize the objective function for NLP problems. If the minimization is not successful, then the sqp and active-set algorithms are tried to run an optimization. If the problem meet the following conditions (but not both): objective function includes gradient, only boundaries, or only linear equality constraints, trust-region-reflective algorithm can be used (Mathworks, 2023).



3. RESULTS AND DISCUSSION

In olive oil production, the characterization of the wastewater taken from the two water intensive processes has been analyzed. Based on the COD parameter, two different wastewater treatment systems such as GENMBR and Combined System as well as three scenarios associated with these systems were studied. In order to reduce water and wastewater in the olive oil process, a mathematical model has been created that includes the water using process and wastewater treatment process. The model has been derived and run for three different scenarios. The results for each scenario are given in detail in the Table 3.1, Figure 3.1, Figure 3.2, and Figure 3.3.

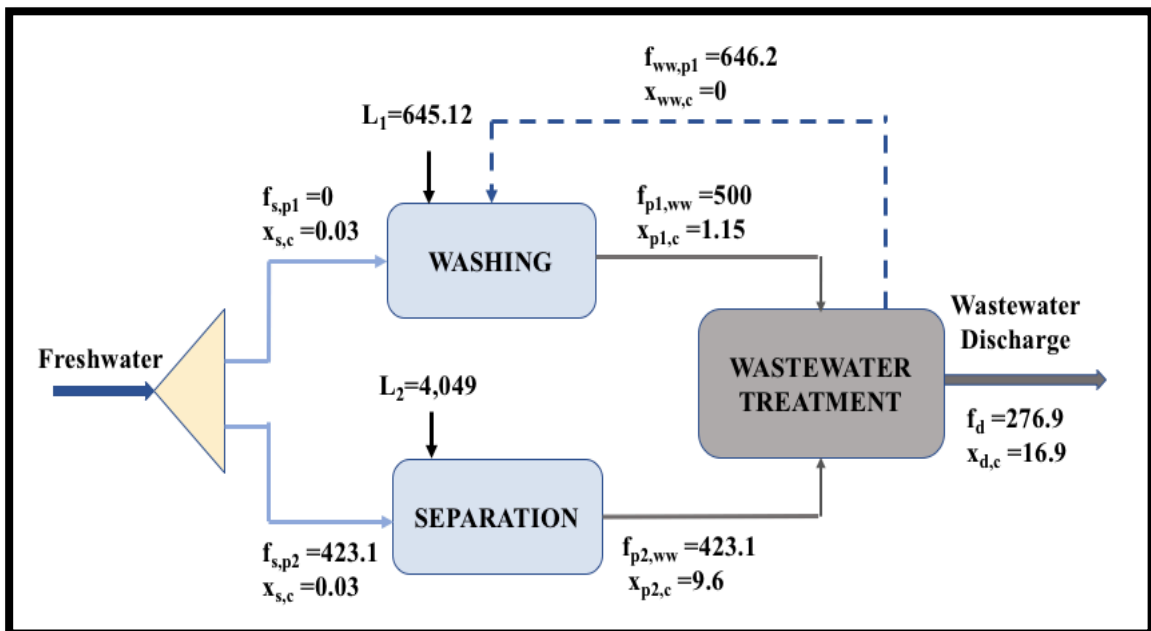


Figure 3.1. The results related to the Scenario 1.

In Scenario 1, the use of treated water from the treatment plant (GENMBR system) only in the washing process was examined. As initial point, 100 m³ and 200 m³ of water entered the washing and separation processes in the system, respectively. As a result of the model iteration, it reached the optimum values detailed in Figure 3.1. In the scenario where 70% treatment is foreseen, the MATLAB simulation (Figure 3.4) of the model calculated the optimum total freshwater consumption as 423.1 m³. In the existing situation of the plant, the total freshwater consumption is approximately 1000 m³/year for washing and separation processes. By reusing treated water, 58% water savings will be achieved and the total annual cost will be 1,027 Euros. The mathematical model was evaluated using

different algorithms such as Sequential Quadratic Programming (sqp), sqp-legacy, active-set, and interior-point. The optimal solution for the problem was obtained with sqp algorithm. It was also observed that the same results were achieved with both sqp and sqp-legacy algorithms.

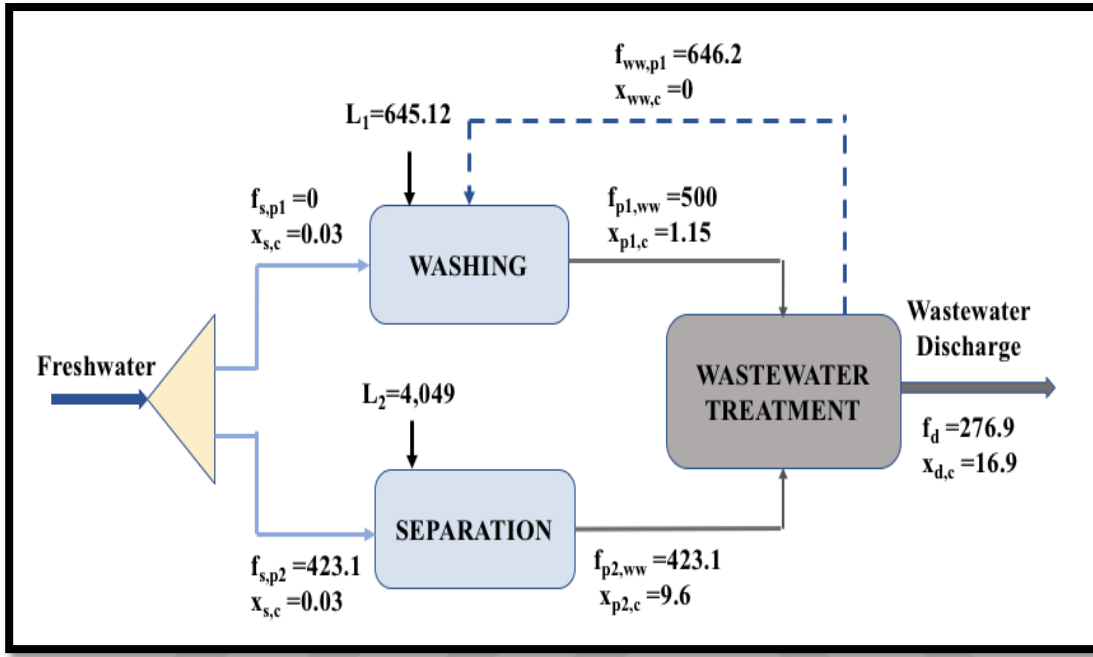


Figure 3.2. The results related to the Scenario 2.

Within the scope of Scenario 2, UF and UV systems were integrated into the chemical treatment and membrane combined system. In the scenario, the use of treated water from the treatment plant only in the washing process was examined. As an initial point, 100 m³ and 200 m³ of water entered the washing and separation processes in the system, respectively. As a result of the model iteration, it reached the optimum values detailed in Figure 3.2. The optimum results of the first scenario are the same as the optimum results of the second scenario. The total cost varies because the operation costs of the systems are different, and in the second scenario, the total annual cost is high because its operation cost is higher than in the first scenario. The model calculated the optimum total freshwater consumption as 423.1 m³. In the existing situation of the plant, the total freshwater consumption is approximately 1000 m³/year for washing and separation processes. By reusing treated water, 58% water savings will be achieved and the total annual cost will be 9,454.9 Euros. The mathematical model was evaluated using different algorithms such as Sequential Quadratic Programming (sqp), sqp-legacy, active-set, and interior-point.

The optimal solution for the problem was obtained with sqp algorithm. It was also observed that the same results were achieved with both sqp and sqp-legacy algorithms.

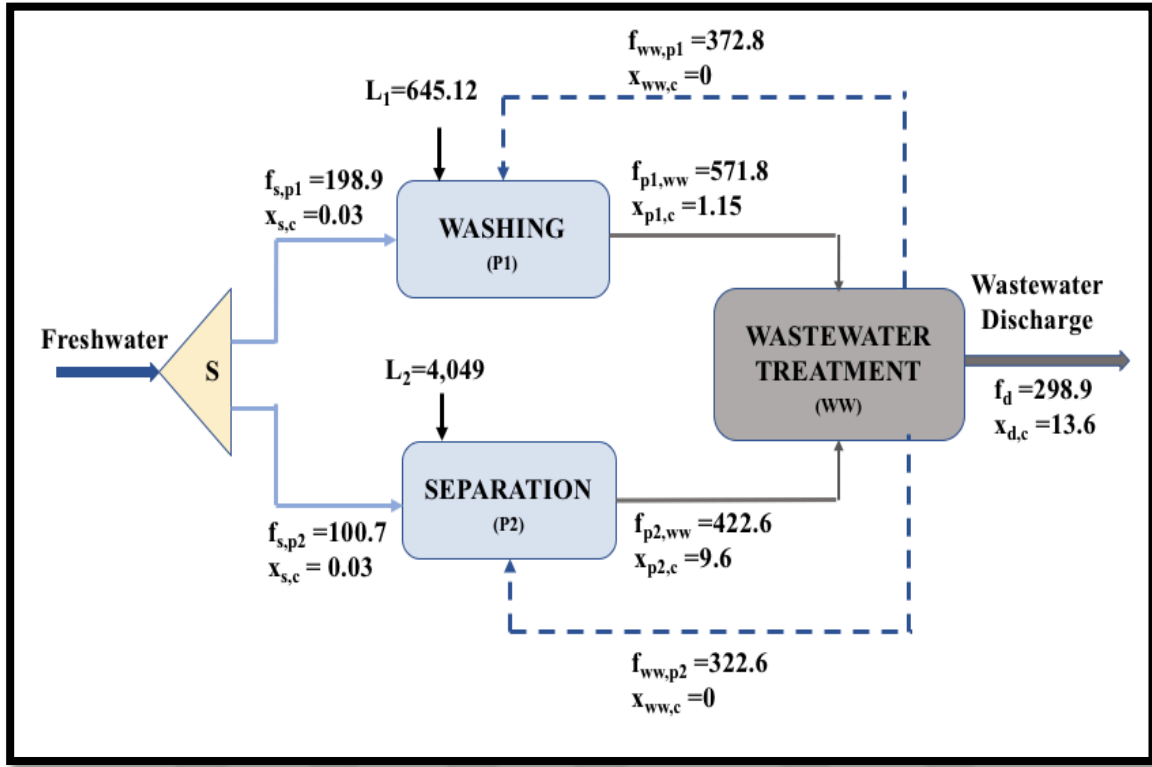


Figure 3.3. The results related to the Scenario 3.

In Scenario 3, UF, RO, and UV systems were integrated into the chemical treatment and membrane combined system. In this scenario, it has been aimed to use the treated water in the separation and also washing processes. With the addition of the RO system, the total annual cost (11,061 Euros) has increased even more. On the other hand, a 70% decrease in freshwater usage has been observed compared to the current situation because the purified water is of better quality and is used in both processes.

According to Scenario 1, Scenario 2 and Scenario 3, the current freshwater consumption of the plant decreases by 58%, 58% and 70%, respectively. According to Scenario 1, the total annual cost of the plant decreases by almost 50%. In other scenarios, due to the increase in treatment quality as well as operation costs, the total cost increased by 4.5 and 5 times, respectively, compared to the current situation.

One of the best techniques for numerically solving restricted nonlinear optimization problems is SQP. It makes use of a strong theoretical foundation and offers algorithmic

tools for the resolution of significant problems. SQP meets all boundaries at each iteration. Piotrowski et al. (2018) used the SQP algorithm and the others (branch and bound algorithm, direct search method etc.) to solve the hybrid nonlinear optimization problem related to the wastewater treatment plant. They have obtained the best solution by using the SQP algorithm. In another study carried out by Khor et al. (2020), an optimization model has been created to manage the integrated urban water. This model has been solved by using SQP algorithm because the problem had linear and nonlinear constraints.

Sqp-legacy is similar to sqp algorithm in terms of problem structure and solution steps. For this reason, the same results were obtained as Sqp algorithm. Active set algorithm is effective in the problem that has nonsmooth constraints. Interior point algorithm achieves the best solution for large-scale problems. To use trust-region-reflective algorithm, there are only bounds or linear equality constraints. When these algorithms are used to solve the problem, it has been faced the model converged to an infeasible solution. Therefore, sqp algorithm was preferred for restricted nonlinear optimization problems.

Table 3.1. Table of results by optimization methods

Scenario	Algorithm	X ₁	X ₂	X ₃	X ₄	X ₅	X ₆	X ₇	X ₈	X ₉	X ₁ +X ₂	Min f(x)
S1	Sqp	0	423.1	500	646.2	0	276.9	16.9	-	-	423.1	1,027.1
	Sqp-legacy	0	423.1	500	646.2	0	276.9	16.9	-	-	423.1	1,027.1
S2	Sqp	0	423.1	500	646.2	0	276.9	16.9	-	-	423.1	9,454.9
	Sqp-legacy	0	423.1	500	646.2	0	276.9	16.9	-	-	423.1	9,454.9
S3	Sqp	198.9	100.7	422.6	571.8	372.8	0	322.6	298.9	13.6	299.6	11,061
	Sqp-legacy	198.9	100.7	422.6	571.8	372.8	0	322.6	298.9	13.6	299.6	11,061

```

function f=objective_function(x)
f=1.4*(x(1)+x(2))+10.5*(x(3)+x(4))+0.67*x(8); % Enter the objective function
end
function [c,ceq] = constraint_function

%Enter the constants in the problem
L1=645.12; %Enter the pollution load from the olive in "kg"
L2=4,049; %Enter the pollution load from the olive oil in "kg"
a1=1.4; %Enter the cost (in Euro) of 1 m3 of freshwater
a2=10.5; %Enter the treatment cost (in Euro) of 1 m3 wastewater
a3=0.67; %Enter the discharge cost (in Euro) of 1 m3 wastewater
c1=0.03; %Enter the COD value of the freshwater in kg/m3
c2=1.15; %Enter the COD value of the wastewater from washing process in kg/m3
c3=9.6; %Enter the COD value of the wastewater from separation process in
kg/m3
r=0.7; %Enter the wastewater return rate according to the wastewater treatment
option

%Define the constraint functions
c=[];
ceq(1) = x(1)*0.03 + L1 + x(5)*x(6) - x(4)*9.6;
ceq(2) = x(2)*0.03 + L2 + x(7)*x(6) - x(3)*1.15;
ceq(3) = x(3)*1.15 + x(4)*9.6 - x(5)*x(6) - x(6)*x(7) - x(8)*x(9);
ceq(4) = x(1)*0.03 + x(2)*0.03 + L1 + L2 - x(8)*x(9);
end
function main_script

%Enter the specified starting point values
A=[-1 0 0 0 0 0 0 0;0 -1 0 0 0 0 0 0;0 0 -1 0 0 0 0 0;0 0 0 -1 0 0 0 0;0 0 0 0 -1
0 0 0 0;0 0 0 0 0 -1 0 0 0;0 0 0 0 0 0 -1 0 0;0 0 0 0 0 0 0 -1 0;0 0 0 0 0 0 0 0 -1];
b=[0;0;-212;-343;0;0;0;0;0];
Aeq =[0 0 0.7 0.7 -1 0 -1 0 0;0 0 0.3 0.3 0 0 0 -1 0;0.31 -0.5 0 0 0.31 0 -0.5 0 0;1 0 0 -
1 1 0 0 0 0;0 1 -1 0 0 0 1 0 0];
beq=[0;0;0;0;0];
lb=[0 0 0 0 0 0 0 0 0];
ub=[600 600 900 900 600 0.15 600 900 40];
x0=[80,80,100,200,50,0.02,100,200,20];
%Determine the optimization function
options =
optimoptions('fmincon','Display','iter','Algorithm','sqp','ConstraintTolerance',1e+0,'Ste
pTolerance',1e+0);
[x,fval,exitflag,output,lambda,grad,hessian]=fmincon(fun,x0,A,b,Aeq,beq,lb,ub,nonlc
on,options);
fprintf('Optimum x(1):%.6f\n',x_opt(1));
fprintf('Optimum x(2):%.6f\n',x_opt(2));
end

```

Figure 3.4. Schematic for olive oil production model.

4. CONCLUSIONS

The food industry is among the water-intensive industries. Water is used extensively in many processes, from washing fruits and vegetables to cooling and heating processes, from separation processes to cleaning of equipment and floor. In particular, it is desirable that the water in contact with the final product should not contain any microbial content. In order to minimize water consumption, first of all, the minimum amount of water and water quality for each process should be determined. After the requirements are determined, minimum treatment conditions should be identified in order to reuse the water from process in different processes or to purify the water.

Since hygiene is kept in the forefront in the food sector, it is not possible to reuse the water from processes without purification. For this reason, besides determining the minimum requirement for water consumption, it is important to evaluate the option of treating the wastewater according to the required parameters in terms of COD, BOD, and microbial.

This study explored a structure for the water network synthesis in the manufacturing industry. The structure includes a reduction in freshwater consumption and wastewater generation. The NLP model proposed is solved using different algorithms. The usefulness and efficiency of the proposed NLP model have been demonstrated on a problem from a real case study in the olive oil industry.

When similar studies in the literature are examined, it has been observed that pinch analysis is generally used for water optimization, and water-energy integration is generally considered in the structure of problems solved by mathematical modeling. Since there is no need for water input at high temperatures in the olive oil sector discussed in this study, the problem has been evaluated only through optimizing the water network. In the literature, it has been noted that the treatment plants are not studied in detail in a way specific to the problem. A general wastewater treatment plant is included in the majority of problems. However, it is important to study the wastewater treatment methods separately, especially in the food sector. For this reason, the case study of the wastewater treatment was specially handled and examined in the study. Due to this scope, this study is very significant and original.

In the literature on olive oil production, the minimum amount of water consumption for each process was determined and defined as a constraint in the model. In addition, the mass balances of the processes were created, and the constants of the problem were calculated by analyzing the wastewater streams. Since no information could be obtained from the literature on the pollution load from olive and olive oil defined in the problem, the pollution load was calculated with assumptions.

As a result of the three scenarios defined for the olive oil production process, the third Scenario achieved better results than the other scenarios in terms of total annual freshwater consumption. In the third Scenario, it is envisaged that purified water will be used in both processes, as higher quality water is obtained. For this reason, compared to other scenarios, while Scenario 3 gave the best results in terms of water reduction, however, it causes the highest annual cost. Compared to the current situation of the plant, water consumption can be decreased by 70%, while total annual cost is increased by 5 times. The first Scenario gives better results if the plants make cost-oriented decisions. While water consumption is reduced by 58%, the total annual cost is reduced by approximately 50%.

This study was carried out with instant wastewater analysis and consumption amounts from the plant. Olives processed in olive oil production plants vary during the day and season. For the model to give more accurate results, it is important to examine the production throughout the season and to determine the variability of wastewater analysis. In addition, the determination of the pollution load from olive and olive oil by analysis is critical in terms of determining the constants in the model. Future work should focus on the aforementioned issues. Secondly, it is suggested that this model should be tested in other sub-sectors such as the seafood processing in the food sector.

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BIOGRAPHY

TUBA BUDAK

Educational Background	Doctor of Phil. (Ph.D) (candidate) – Marmara University – Engineering Management 2015-Present Master of Science – Istanbul Technical University – Chemical Engineering 2011-2014 Bachelor Degree – Yildiz Technical University – Chemical Engineering 2006-2010
Professional Experience	TUBITAK Marmara Research Center (MRC) – Circular Economy and Resource Efficiency Research Group; Group Leader; 2022-Present TUBITAK MRC – Environment and Cleaner Production Institute; Senior Researcher; 2014-2022 Standard Profil A.Ş. ; Laboratory Project Responsible; 2012-2013 Planning all tests for semi- and final products until SOP Determine of the specs for each test & test apparatus Solve the quality problems Make product improvements and optimize the process to improve process efficiency Farplas A.Ş. ; Project Engineer; 2013-2014 Planning all tests for semi- and final products until SOP Solve the quality problems Make product improvements and optimize the process to improve
Language	English, German

Computer Literacy	OpenLCA, GaBi Microsoft Office (Word, Excel, Powerpoint, Visio, Project, vd.) Matlab Chemcad, Aspen Minitab
Certificates	Asian Productivity Organization (APO)- Certified Green Productivity Specialist Professional Management Project APQP, FMEA
Publications	Budak Duhbaci, T., Özel, S. & Bulkan, S. Water and energy minimization in industrial processes through mathematical programming: A literature review. Journal of Cleaner Production (2021). https://doi.org/10.1016/j.jclepro.2020.124752 Atilgan Türkmen, B., Budak Duhbaci, T. & Karahan Özbilen, Ş. Environmental impact assessment of ceramic tile manufacturing: a case study in Turkey. Clean Techn Environ Policy (2021). https://doi.org/10.1007/s10098-021-02035-w Atilgan Türkmen, B., Karahan Özbilen, Ş. & Budak Duhbaci, T. Improving the sustainability of ceramic tile production in Turkey. Sustainable Production and Consumption (2021). https://doi.org/10.1016/j.spc.2021.05.007

PUBLICATIONS

Journal Papers

-Accepted

1. Budak Duhbacı, T., Özel, S. & Bulkan, S. Water and energy minimization in industrial processes through mathematical programming: A literature review. *Journal of Cleaner Production* (2021). <https://doi.org/10.1016/j.jclepro.2020.124752>

