DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

OPTIMIZATION OF HARVEST AND PRODUCTION PLANNING FOR OLIVE OIL INDUSTRY

by
Tuğçe TAŞKINER

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İZMİR

OPTIMIZATION OF HARVEST AND PRODUCTION PLANNING FOR OLIVE OIL INDUSTRY

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"OPTIMIZATION OF HARVEST AND PRODUCTION PLANNING FOR OLIVE OIL INDUSTRY"** completed by **TUĞÇE TAŞKINER** under supervision of **PROF. DR. BİLGE BİLGEN** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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OPTIMIZATION OF HARVEST AND PRODUCTION PLANNING FOR OLIVE OIL INDUSTRY

ABSTRACT

Agri-food supply chains are accountable for providing agricultural products to consumer societies through several activities. As a result, agri-food supply chain management has gained an important role in solving complex problems. This thesis aims to solve an agri-food supply chain problem.

Firstly, a systematic literature review on harvest and production planning problems is presented. Initially, previous agri-food supply chain literature reviews are analyzed in order to reveal the research opportunities. After the consideration of the previous literature reviews, a classification scheme is developed to analyze the existed research articles on harvest and production planning problems in the agri-food supply chains. Within the determined review criteria, research articles are examined according to problem scope, model characteristics, and modeling approaches.

Harvest and production planning problem of a small producer in the olive oil industry is studied in this thesis. A novel mixed-integer linear programming model is developed to solve an olive oil supply chain network problem. This model determines the harvest and production planning simultaneously in order to maximize producer's profit. A hypothetical case study is applied to demonstrate the applicability of the model. After, an extended version of the model is proposed to examine olive loss in the olive groves which can occur because of the severe climatic conditions. Lastly, sensitivity analysis is presented to indicate critical parameters which can affect the supply network significantly.

Keywords: Agri-food supply chain, harvest planning, production planning, olive oil industry, mixed-integer linear programming

ZEYTİNYAĞI ENDÜSTRİSİ İÇİN HASAT VE ÜRETİM PLANLAMA OPTİMİZASYONU

ÖZ

Tarım-gıda tedarik zincirleri, çeşitli aktiviteler ile tarım ürünlerini tüketici topluluklarına ulaştırmakla sorumludur. Sonuç olarak, tarım-gıda tedarik zinciri yönetimi karışık problemlerin çözümünde önemli bir rol kazanmıştır. Bu tez bir tarım-gıda tedarik zinciri problemini çözmeyi amaçlamaktadır.

İlk olarak, hasat ve üretim planlama problemleri üzerine bir literatür araştırması sunulmuştur. Başlangıçta, araştırma olanaklarını ortaya çıkarmak için önceki tarım-gıda tedarik zinciri literatür araştırmaları analiz edilmiştir. Önceki literatür araştırmalarının değerlendirilmesinden sonra, tarım-gıda tedarik zincirlerindeki hasat ve üretim planlama problemleri ile ilgili var olan araştırma makalelerini analiz etmek için bir sınıflandırma şeması oluşturulmuştur. Belirlenen inceleme kriterleri içerisinde, araştırma makaleleri; problem kapsamı, model özellikleri ve modelleme yaklaşımlarına göre incelenmiştir.

Bu tezde, zeytinyağı endüstrisindeki küçük bir üreticinin hasat ve üretim planlama problemi çalışılmıştır. Bir zeytinyağı tedarik zinciri ağı problemini çözmek için yeni bir karışık tamsayılı programlama modeli geliştirilmiştir. Bu model, üreticinin karını maksimize etmek için hasat ve üretim planlamalarını eş zamanlı olarak belirler. Modelin uygulanabilirliğini göstermek için varsayımsal bir vaka çalışması uygulanmıştır. Daha sonra, sert iklim koşulları sebebiyle zeytinliklerde oluşabilecek zeytin kaybını incelemek için modelin genişletilmiş bir versiyonu önerilmiştir. Son olarak, tedarik ağını önemli ölçüde etkileyebilecek kritik parametreleri göstermek için duyarlılık analizi sunulmuştur.

Anahtar kelimeler: Tarım-gıda tedarik zinciri, hasat planlama, üretim planlama, zeytinyağı endüstrisi, karışık tamsayılı doğrusal programlama

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CHAPTER ONE
INTRODUCTION

1.1 Motivations

In recent years, agricultural food production has grown considerably and nowadays has become more complex because of the number of issues such as food security, demanded food traceability, required regulations, and climate change. Therefore, agri-food supply chains (AFSCs) consider various activities and several stakeholders in order to overcome challenging issues.

Research on AFSC problems include numerous topics such as producing food to our growing world, dealing with seasonality of crops, preventing food waste. For the purpose of providing a decision-making tool for one of the many problems which AFSCs encounter, this research study is conducted. The research objective of this thesis is to develop a mathematical model to solve an AFSC problem more effectively and efficiently. Regarding the research objective, several research questions are asked in the process of the development of this thesis. The first research question is:

- What are the neglected problem topics in AFSCs which have prominent research gaps and promising research opportunities?

For this research question, previous literature review studies are examined to reveal the problem topics which require more attention. According to previous review studies, in order to find solutions to the abovementioned complexities, several planning problems have been addressed such as cultivation planning, harvest planning, production planning, and distribution planning. It is concluded that the research field of integrated harvest and production planning problems needs further investigation by academia. Given this research gap, second research question is asked:

- What is the present status of harvest and production planning problems in the literature?

In order to find answers to the above research question, a comprehensive and systematic literature review focused on harvest and production planning problems in the context of AFSC is conducted.

Harvest planning is a crucial activity to meet the preferred quantity and quality of crops. Production planning of harvested crops is also a vital activity to obtain desirable quantity and quality of products and therefore to supply market demands. Ultimately, coordination of the harvest and production activities are critical to decision-makers.

Most of the crops have different specifications and quality requirements and one of these crops which have distinct characteristics is olive fruit. Olive and olive oil production are taken place mostly in the Mediterranean basin countries and Turkey is one of the leading producer countries in the world. Olive and olive oil production is an integral part of the culture and heritage of small olive farmers and olive oil producers who transmit traditions to the next generations. Furthermore, olive oil production has a significant place in the economy. Nevertheless, olive oil related quantitative studies are scarce in the literature despite the wide production in the world.

In conclusion, harvest planning for olive fruits and production planning for olive oil are considered for this thesis. Thus, a last research question is asked:

- What is the status of olive harvest and olive oil production planning problems in the literature and what can we propose to make contributions to the literature?

In order to find answers to the last research question, olive harvest and olive oil production planning studies are thoroughly analyzed. As a result of the analysis, a novel mathematical model is developed to solve an integrated harvest and production planning problem with the perspective of an olive oil producer in the olive oil industry. This problem considers owned olive groves for harvesting, candidate olive farmers who may supply organically or conventionally grown olives, and production of several olive oil products. This optimization model may assist small-size olive oil producers in the decision-making process by proposing an effective and useful tool.

1.2 Contributions of the Thesis

The main contributions of this thesis to the literature are threefold and explained as follows.

Firstly, a comprehensive literature review is presented on harvest and production planning models in the AFSC context. A new classification scheme is developed to analyze research gaps and trends in the literature. Problem scope, model characteristics, and modeling approaches are discussed.

Secondly, a novel mixed-integer linear programming (MILP) model is developed to solve a harvest and production planning problem. The proposed model distinguishes from the literature by considering four elements: (1) integrated harvest and production planning for the entire production season; (2) organic and conventional farming systems to produce differently labeled olive oil products; (3) olive supplier selection to be able to produce more olive oil products and (4) by-product management to handle generated by-products of olive oil. Multi-period, multi-product harvest and production planning problem aims to maximize producer's total profit.

Thirdly, several analyses are made to demonstrate the effectiveness of the developed model. At first, a hypothetical case study is used to validate the applicability of the mathematical model. After, through scenario analysis, a possible olive loss which can take place during the harvest and production season is examined. Lastly, sensitivity analysis is conducted to understand the system in-depth and to point out the critical parameters that affect the optimal plan.

1.3 Structure of the Thesis

This thesis consists of six chapters and the rest of the thesis is as follows.

Chapter 2 presents a brief introduction to AFSCs, proposes a classification scheme for a systematic literature review, and presents an extensive literature review on harvest and production planning models.

Chapter 3 expresses information about olive and olive oil production in the world and in Turkey and provides an overview about olive tree cultivation, olive harvesting, and olive oil production.

Chapter 4 presents this thesis' position in the literature, describes the considered harvest and production planning problem, and presents the developed mathematical model.

Chapter 5 includes a case study to validate the model, analyzes computational results, examines an extended version of the proposed model for severe climatic conditions, and presents sensitivity analysis.

Chapter 6 summarizes this thesis and suggests possible future research directions.

CHAPTER TWO

LITERATURE REVIEW ON HARVEST AND PRODUCTION PLANNING IN AGRI-FOOD SUPPLY CHAINS

In this chapter, an extensive literature review on harvest and production planning in AFSCs is presented. Section 2.1 presents a brief introduction to AFSCs. Section 2.2 outlines an overview of previous AFSC related review studies. Section 2.3 proposes a framework for the evaluation and states the review methodology. Section 2.4 presents the literature review of the selected articles. Section 2.5 points out findings from the evaluation and discusses future research directions.

2.1 Agri-Food Supply Chains

AFSCs consist of several activities to provide agricultural products from farm to table with the intention of satisfying customers' demands (Ahumada & Villalobos, 2009). The supply chain of agri-food products mainly includes cultivation, harvesting, processing, distribution, and storage activities Kusumastuti, van Donk, & Teunter, 2016). These activities can be made with the participation of farmers, processors, cooperatives, regulators, transporters, research institutes, traders, retailers, and customers (Tsolakis, Keramydas, Toka, Aidonis, & Iakovou, 2014). Figure 2.1 presents an outline for the main AFSC actors.

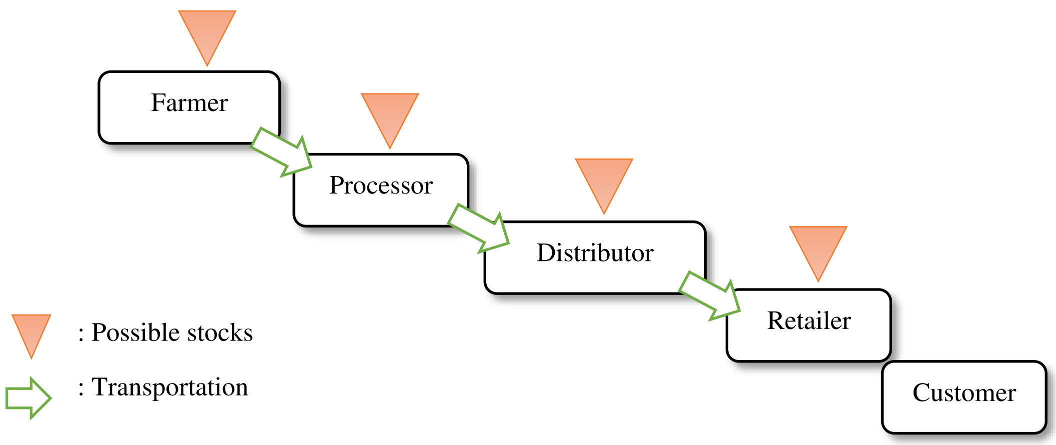

Figure 2.1 General agri-food supply chains (Kusumastuti et al., 2016; Tsolakis et al., 2014)

There are studies which categorize AFSCs in different perspectives. Behzadi, O'Sullivan, Olsen, & Zhang (2018) classify agricultural products into two main categories: crops and livestock. Crops are the products obtained directly from plants, while livestock includes animal-related products such as meat, cattle, seafood, dairy, and wool. Kusumastuti et al. (2016) differentiate agri-food products as fresh products (preserve original characteristics e.g. packaged food) and processed products (value-added products e.g. canned food, wine, juice). On the other hand, Ahumada & Villalobos (2009) state two main types of agri-foods: perishable (e.g. vegetables and fruits) and non-perishable (e.g. grain, nuts).

AFSCs are more complex and difficult to manage than other supply chains because of some specific and inherent characteristics. These characteristics can be:

- perishability in supply chain stages,
- seasonality of agri-food production,
- variability of weather conditions,
- fluctuations in yield and demand,
- required specifications regard to storage and transportation conditions,
- food quality and safety,
- regulations to follow in all stages,
- limited shelf life,
- price variability (Ahumada & Villalobos, 2009; Kusumastuti et al., 2016; Tsolakis et al. (2014).

2.2 Previous Reviews

In recent years, several review studies have been conducted focusing on agricultural supply chains. Related previous review studies are analyzed in this section, and Table 2.1 briefly displays their objectives and proposed research opportunities.

To best of our knowledge, Glen (1987) made the first review on agricultural planning to address mathematical models on crop and livestock sectors. Later, Lowe

& Preckel (2004) focused on modeling approaches in their review to highlight the agribusiness problems on crop planning, harvest planning, and risk management. Ahumada & Villalobos (2009) presented a review of production and distribution planning models for agricultural products. They classified the articles by two main categories, perishable and non-perishable agricultural products. Also, articles were evaluated according to their planning scope, decision variable, and modeling approach. On the other hand, Zhang & Wilhelm (2011) considered only specialty crops industry and performed a review on operational research models. This review included fruits, grapes and wine, floriculture, tree nuts, berries, and dried fruits.

In their extensive review, Shukla & Jharkharia (2013) presented the existing literature of fresh produce covering fruits, flowers, and vegetables. The articles were analyzed by focusing on operational problems that cause post-harvest wastes. They classified the articles in terms of demand forecasting, production planning, inventory management, and transportation. Additionally, Tsolakis et al. (2014) conducted a review on the design and management of AFSCs and classified papers in terms of strategic, tactical, and operational decision levels.

By focusing on harvesting and processing activities in the agricultural supply chain, Kusumastuti et al. (2016) reviewed the literature and indicated the need for integrated planning models. Moreover, operational research models in fresh fruit supply chain were evaluated by Soto-Silva, Nadal-Roig, González-Araya, & Pla-Aragones (2016). They analyzed the articles in terms of decision level, modeling approach, and purpose of the study, application type, novelty, and research segmentation by journal. Within the context of the AFSC, Siddh, Soni, Jain, Sharma, & Yadav (2017) conducted a comprehensive literature review focusing on chain quality. Three crucial quality elements for AFSCs were identified as information, sustainability, and logistics management.

Esteso, Alemany, & Ortiz (2018) offered a conceptual framework for the design of AFSCs addressing chain characteristics, uncertainty modeling, decision characteristics, and modeling approaches. Following that, a comprehensive review was conducted for mathematical programming models. Luo, Ji, Qiu, & Jia (2018) summarized the existing literature from 1985 to 2017 in AFSC management via bibliometric and content analysis. The bibliometric analysis contains author influence, journal quality, affiliation statistics, and citation analysis. As a result of the content analysis of 188 articles, six different research areas were generated.

Behzadi et al. (2018) classified the risk management papers according to product types, risk types, risk management strategies, and modeling approaches. Resilience related research fields were reviewed by Stone & Rahimifard (2018). Afterwards, according to the outcomes of the review, a framework which consists of specific resilience elements and strategies for the AFSCs were generated. Villalobos, Soto-Silva, González-Araya, & González–Ramirez (2019) pointed out the information technologies enabled in the echelons of fresh produce supply chains.

A recent review study was presented by Kamble, Gunasekaran, & Gawankar (2020) to understand the elements of a sustainable agricultural supply chain in a data-driven environment. They also provided a framework focused on supply chain visibility, integration of resources, sustainable performances, and data analytics capability to aid decision-makers. Nematollahi & Tajbakhsh (2020) conducted a comprehensive review which consists of 247 quantitative articles which are about sustainable agricultural supply chains. Articles were reviewed regarding four research fields: agricultural planning, supply chain management, sustainability development, and modeling methodology.

Table 2.1 Previous review studies

Author	Objective of the research	Future research opportunities
Glen (1987)	Point out operations research models on agricultural planning at farm level	Farm planning models that convenient to use by individual farmers, development of research tools
Lowe & Preckel (2004)	Highlight the operation management problems of crop production	Efficient management of transportation, distribution, and inventory management
Ahumada & Villalobos (2009)	Evaluation of production and distribution planning models of agricultural crops	Operational models which integrate production and distribution decisions, models that include uncertain information
Zhang & Wilhelm (2011)	Provide possible improvements for the decision-making process and future research areas for academics	Operational research for individual growers, food security, interdisciplinary research, risk management
Shukla & Jharkharia (2013)	Present literature review on operational issues that cause post-harvest losses of fresh produce	Demand forecasting, harvest scheduling, integration of production and inventory for fresh produce
Tsolakis et al. (2014)	Provide a framework for natural decision-making process on designing AFSCs	Integrated systematic approach on agri-food, real-time optimization tools for dynamic and stochastic nature
Kusumastuti et al. (2016)	Investigate the modeling approaches for operational models on harvesting and processing planning	Integration of harvesting and processing models, including sustainability, incorporating harvesting time window, yield perishability, inventory control
Soto-Silva et al. (2016)	Review of the operational research models on fresh fruit supply chain	Holistic designs and management, organic fruit production, climate adaptation, food security, integration of sustainability
Siddh et al. (2017)	Deliver a wider perspective of quality measures in fresh AFSCs	Research in developing countries, realistic research models, information management, and collaboration with suppliers for quality
Behzadi et al. (2018)	Review quantitative risk management models in agribusiness supply chains	Modeling perishability, considering supply and demand risks, multi-period modeling, resilient strategies
Esteso et al. (2018)	Propose a conceptual framework for AFSC designs and present a review of mathematical models	Integration of AFSC stages, including multiple products and product characteristics, inclusion of multiple objectives, incorporating uncertain elements
Luo et al. (2018)	Determine the literature of AFSC management and assess the structures of the models	Research in developing countries, integration of sustainability, resilience in AFSCs
Stone & Rahimifard (2018)	Find ways of applying the multidisciplinary concept to the AFSCs	Empirical validation of the developed framework, applying the framework to the developing world countries

Table 2.1 continues

Author	Objective of the research	Future research opportunities
Villalobos et al. (2019)	Address a research agenda for the application of information technology opportunities in fresh produce supply chain	Real-time data inclusion, including new sensor and information technologies
Kamble et al. (2020)	Find answers to how to achieve sustainability in a data driven AFSC	Improving supply chain visibility, using blockchain technology, internet of things applications, new data collection ways
Nematollahi & Tajbakhsh (2020)	Review of sustainability-driven agricultural supply chain management models	Reverse logistics and closed-loop supply chains for agricultural systems, decentralized systems, analyzing logistic systems

According to Kusumastuti et al. (2016) integrated AFSC studies are very limited in the literature, especially in the case of coordinating harvesting and processing activities. Hence, we seek to demonstrate the harvest and production planning problems in the AFSCs to analyze the trends and gaps in the literature through the following research question:

RQ1: How are the harvest and production planning problems in AFSCs evolving with inherent challenges and complexities over the years?

Previous review studies provide an understanding of AFSC systems and therefore more detailed questions are asked to address RQ1. This review is seeking answers to the following sub-research questions:

RQ1.1: What type of decision variables and objective functions have been used to design harvest and production planning in AFSCs?
RQ1.2: What type of crops and characteristics have been investigated in the harvest and production planning studies?
RQ1.3: Which solution methodologies have been used to address the problems?

For the purpose of finding answers to the above research questions, a systematic literature review is conducted. This review aims to establish a framework in order to gain a better understanding of the existing literature focused on harvest and production planning problems in AFSCs. Thus, a framework based on AFSC problems, characteristics, and mathematical modeling approaches is generated, and then AFSC concepts and differences are investigated. Research gaps and trends are discussed for future research opportunities.

2.3 Review Method

In the light of the information gained from the previous reviews, a classification scheme is developed for a systematic literature review. Then, research methodology is stated to understand the scope and limitations of this study.

2.3.1 Classification Scheme

The main purpose of this classification is to form a framework for our research. A new classification scheme (Figure 2.2) is developed based on the studies of Kusumastuti et al. (2016), Soto-Silva et al. (2016), and Esteso et al. (2018). First of all, the articles are classified based on supply chain problem scope. Secondly, model characteristics are indicated. Lastly, modeling approaches are discussed.

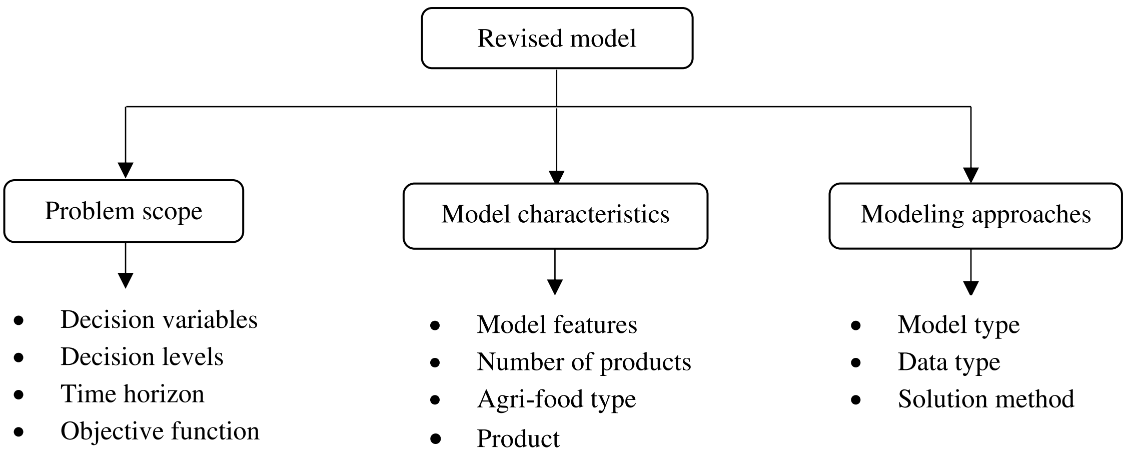

Figure 2.2 Classification scheme

2.3.2 Material selection

This review is focused on published scientific articles which study AFSC problems. Papers were found from widely accessible online databases (e.g. Scopus, Elsevier, Web of Science, Google Scholar) with keywords such as: “agri-food supply chain”, “agricultural supply chain”, “harvest planning”, “agri-food production”, “processed agri-food”, “agri-food production”, “vegetable supply chain”, and “fruit supply chain”. Firstly, the title and abstract review were made on papers.

Because of the scope of this review, articles are restricted according to the following criteria:

- Papers written in the English language between the years 2000 and 2020.
- Articles with mathematical programming models in the context of AFSCs. To exemplify, frameworks, exploratory researches, simulation studies, and guidelines are excluded.
- Models which have at least one of the decision variables related to harvest planning and production planning. This review is focused on harvest planning and production planning models; therefore, articles related to these topics are selected through decision variables.
- Articles included food crops which provide food for human consumption. For example, products not directly related to crops such as livestock and fish, biomass production from crop wastes, wood production from forest, and floriculture management are excluded.

According to the above criteria, articles were selected from online databases. In addition, some of the articles were obtained from the selected articles’ and previous reviews’ reference section. Ultimately, after a content analysis, 68 papers on AFSCs were selected for the evaluation.

2.4 Review of Harvest and Production Planning in Agri-Food Supply Chains

In this section, literature review on harvest and production planning models in AFSCs is presented according to the classification scheme.

Figure 2.3 indicates the number of papers published over the 20-year period regarding this review’s criteria. Also, the articles' journals and countries are listed in Appendix 1.

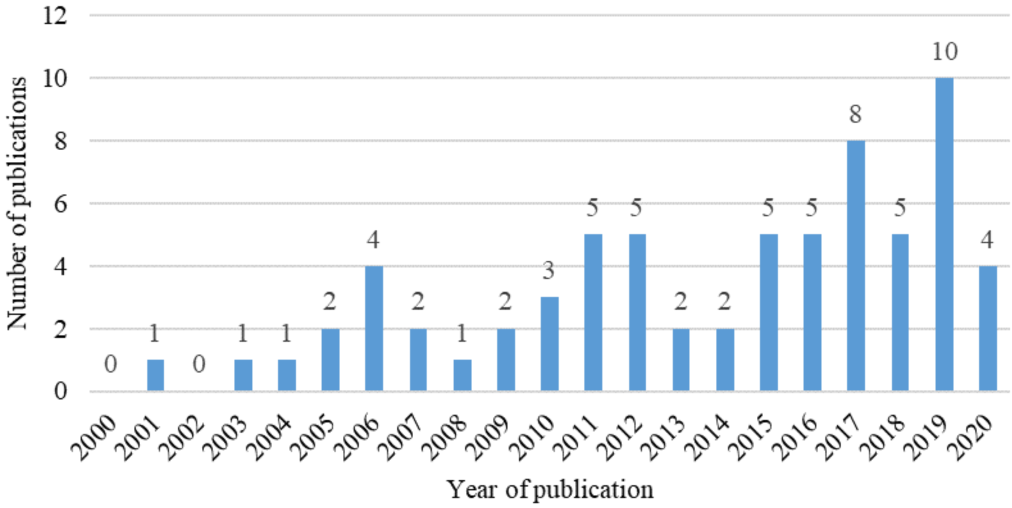

Figure 2.3 Number of revised articles between 2000-2020 (2020 includes four-month worth of data)

2.4.1 Problem Scope

2.4.1.1 Decision Variables

AFSCs may include different supply chain activities, thus related five types of decision variables are determined. Decision variables are related to cultivation planning (e.g. decisions on selecting crops and land), harvest planning (e.g. decisions on scheduling, routing), production planning (e.g. decisions on processing, packaging), distribution planning (e.g. decisions on transporting and shipping), and inventory planning (e.g. decisions on managing inventory).

As stated earlier, our focus is on harvest and production planning models. Therefore, studies which have at least one containing decision variables related to harvest planning and production planning are selected. Next, we try to summarize the nature of the problems. Table 2.2 summarizes the reviewed literature. The papers are ordered chronologically. For each selected article studied, the table illustrates (1) decision variables related to AFSC, (2) decision levels, (3) time horizon and (4) objective function considered.

There are twelve papers which only focused on harvest planning activities. Jiao, Higgins, & Prestwidge (2005) clustered farms according to their sugar content patterns and then planned the harvesting schedule in order to maximize total sugar content in the sugarcanes. Caixeta-Filho (2006) optimized an orange harvesting schedule in orchards for the juice extraction according to the maturation curve.

In their pioneering paper, Ferrer, Mac Cawley, Maturana, Toloza, & Vera (2008) presented an optimization model for wine grape harvest operations to minimize harvest operation costs and penalty costs for quality loss. The model comprises of harvest scheduling, resource assignments, and routing decisions. Bohle, Maturana, & Vera (2010) considered the model of Ferrer et al. (2008) and developed a robust optimization model to deal with uncertain elements. Arnaout & Maatouk (2010) altered the work of Ferrer et al. (2008) and added new constraints not to allow gaps between the harvest days, meaning if harvesting starts in a block, it must be finished at the following days. Furthermore, Varas, Basso, Maturana, Osorio, & Pezoa (2020) extended the work of Ferrer et al. (2008) and developed a multi-objective harvest scheduling problem through presenting the objective function by maximizing grape quality and minimizing cost of harvest operations.

González-Araya, Soto-Silva, & Espejo (2015) proposed a harvest scheduling model which seeks to minimize costs. Costs are twofold: costs from harvest resource utilization and penalty cost from the loss of apple quality. The decisions include the determination of harvest quantity, labor and harvest means allocation. Thuankaewsing, Khamjan, Piewthongngam, & Pathumnakul (2015) suggested a model that finds the optimal harvest schedule for a group of sugarcane farmers with the aim of maximizing harvested sugarcane.

Two articles focused on finding an optimal harvesting sequence. For this goal, Stray, Van Vuuren, & Bezuidenhout (2012) developed a decision support system for growers to sequence the harvesting operations throughout the entire harvesting season in sugarcane fields. However, Junqueira & Morabito (2019) proposed a harvest resource scheduling problem to find the balance between the different harvest resource capacities and transportation capacity.

The model presented by He & Li (2019) tackles the two-echelon multi-trip vehicle routing problem for the decision making in grain harvesting operations. The model minimizes the number of harvesters, total travel costs, and waiting time.

There are several articles that considered both cultivation and harvest planning simultaneously. Vitoriano, Ortuño, Recio, Rubio, & Alonso-Ayuso (2003) aimed at determining a schedule of tasks that are needed for cultivation and harvest planning in the farm. The main features of this study are (a) the use of a precedence graph among tasks and (b) the determination of allocating resources which are needed to grow plants. Piewthongngam, Pathumnakul, & Setthanan (2009) proposed a framework to maximize sugar production according to mill's capacity. Firstly, expected sugar yields are calculated by crop growth simulation then, the mathematical model determines optimum cultivar, planting and harvesting schedule. Tan & Çömden (2012) studied a firm that buys seeds and makes contracts with different farms to plant and grow the seeds. The model determines the farm areas to contract with farmers and planting times. Although specific harvesting decisions were not considered, harvest planning was made via planting decisions.

To address the need for recovering production wastes, Banasik, Kanellopoulos, Claassen, Bloemhof-Ruwaard, & van der Vorst (2017) developed a closed-loop mushroom supply chain. The planning model consists of raw material production, mushroom cultivation, and selling mushrooms to consumers. Banasik, Kanellopoulos, Bloemhof-Ruwaard, & Claassen (2019) explored a stochastic programming model, which is based on the study of Banasik et al. (2017), to consider uncertainties in industrial mushroom production supply chain.

Wishon, Villalobos, Mason, Flores, & Lujan (2015) determined vegetable planting and harvesting decisions with the focus on immigrant and domestic labor force recruitment. Plessen (2019) investigated the problem of assigning crops to each field and routing of multiple harvesters to minimize costs.

For harvest and transportation planning, Higgins & Laredo (2006) presented a framework for sugar value chain and proposed two models. The transportation planning model decides the number and locations of the sidings while minimizing transportation costs. The harvest planning model assigns farms to harvest groups to minimize the total distance between them. Sutopo, Hisjam, & Yuniaristanto (2012) differentiated their study from the literature by including corporate social responsibility to a vegetable supply chain in order to enhance farmer's business skills. The model determines vegetable supply and allocation quantity and timing, training skills of farmers, and quality improvement percentage. The model maximizes farmer profit and retailer profit. da Silva, Marins, & Dias (2015) aimed to find a sugarcane harvest and transportation schedule to meet the model's goals which are to minimize the deviations on agricultural activity costs and on optimal sugarcane content.

Inventory planning was integrated into a harvest planning model by Widodo, Nagasawa, Morizawa, & Ota (2006) to design a short fresh product supply chain which includes the activities of harvesting at farms and meeting demands at retailers to maximize demand satisfaction. Nagasawa, Kotani, & Morizawa (2009) aimed to determine a harvest pattern for fresh produce in multiple farms in order to supply to multiple markets throughout periodical flowering. The model maximizes total daily consumption levels in markets.

Two of the articles focused on harvesting and processing decisions simultaneously. Differently from other studies, Jena & Poggi (2013) investigated harvest scheduling problem by creating two different models for operational and tactical decision levels. Models decide on routing of harvesting crews, harvest quantities, and which mill to process. Herrera-Cáceres, Pérez-Galarce, Álvarez-Miranda, & Candia-Véjar (2017) made a major contribution to the literature by proposing an olive harvest planning model for an olive oil mill. The model maximizes olive oil quantity from harvested olives. Moreover, different work teams with different resources, olives from other farmers, and bad weather conditions were incorporated into the model.

Jerić & Šorić (2010) proposed an optimization approach for the coordination of supplying olives from farmers in order to produce olive oil in one common mill. Furthermore, Jerić & Šorić (2019) improved their previous study by presenting a multi-objective programming version of their mathematical model. The first objective aims to maximize olive oil producer's profit, on the other hand, the second objective aims to minimize olive farmers' cost.

Some papers offered more comprehensive models with harvesting decisions. Grunow, Günther, & Westinner (2007) formulated two models for the optimization of supplying sugar cane to the sugar mill in order to produce raw sugar. The first model determines the cultivation planning and the second model provides a harvesting schedule with the allocation of crew and equipment. The objectives of the models are maximizing milling requirement coverage and minimizing total cost for production, respectively. The study of Costa, dos Santos, Alem, & Santos (2014) is distinguished from the literature by studying a vegetable crop rotation problem with the possibility of storing products in order to meet the demands. In order to evaluate spoiled products and hence to produce organic fertilizers, Cheraghalipour, Paydar, & Hajiaghaei-Keshteli (2018) addressed a closed-loop supply chain design model for citrus products. The model aims to minimize total cost and maximize responsiveness to satisfy customers. Roghanian & Cheraghalipour (2019) expanded the study of Cheraghalipour et al. (2018) by adding another objective function to consider sustainability in the supply chain.

Four articles only explored production planning. Kazaz (2004) presented a two-stage stochastic production planning problem for a four-year period in the olive oil industry with the objective of maximizing profit. In the first stage, the amount of olive trees to be leased is decided by the oil producer. In the second stage, depending on the olive yield and olive oil prices, the amount of olive to purchase from other farmers and how much olive oil to produce is decided. Kazaz & Webster (2011) extended the study of Kazaz (2004) to study yield dependent cost structure on pricing and olive oil production planning. Basso & Varas (2017) developed a model to determine the bottling schedule for wine products allocated to the production lines. Model minimize the delay of all orders, final completion time for each order, and final processing time for each job. Marchal, Gila, García, & Ortega (2018) designed a stochastic model to determine an olive oil production schedule regarding the received olive’s features.

Production and distribution planning problem was considered in several papers. Apaiah & Hendrix (2005) proposed a supply chain network design that targeted for Dutch market with the aim of minimizing total cost of producing pea-based protein. Included decisions determine locations to produce pea, production quantities of semi-finished and finished products, and transportation quantities. Paksoy, Pehlivan, & Özceylan (2012) studied an edible oil manufacturer’s production and distribution network which consists of supplying oil from suppliers, storing crude oil and processed oil, processing oil at the refinery, and filling bottles in order to supply demands. The model has two objective functions to minimize transportation costs. Focused on post-harvest losses, An & Ouyang (2016) explored a grain supply chain to include the decisions of harvest time, transportation, storage, grain purchase prices, and location selection. Due to the fact that sustainable AFSC design is challenging, Allaoui, Guo, Choudhary, & Bloemhof (2018) proposed a two-stage hybrid approach. In the first stage, potential supply chain partners are evaluated. In the second stage, according to partner evaluation, a generic AFSC design is presented. Yurt, Kota, Jarmai, & Aglamaz (2019) presented a production and distribution network optimization model for an olive oil company to produce bottled olive oil and to ship them to demand points.

Some models integrated inventory planning into the production and distribution decisions. Munhoz & Morabito (2001) proposed a model to study production, distribution, and warehousing of frozen concentrated orange juice. The goals of the model are to minimize the deviations of total cost and product quality. Higgins, Beashel, & Harrison (2006) examined an international sugar supply chain that consists of production, transportation, and storage of different sugar brands. Kostin, Guillén-Gosálbez, Mele, Bagajewicz, & Jiménez (2011) aimed to find the optimal sugarcane supply chain with strategic and tactical decisions. Technology selection, transportation mode selection, capacity planning, and production planning were investigated. Rong, Akkerman, & Grunow (2011) established an optimization approach for a generic fresh food production and distribution plan and made an important contribution to the literature by determining temperature levels during transportation and storage. For rice processing, Lim, Manan, Alwi, & Hashim (2013) investigated a rice mill complex design to optimize the production planning of rice products and by-products, technology selection for the complex, and distribution network. Supplying, storing, processing, and distributing unprocessed and processed grain products to domestic and external markets were investigated in the supply chain by Reis & Leal (2015). Gholamian & Taghanzadeh (2017) tackled the wheat-to-flour supply chain design to determine production, storage, and transportation quantities to meet domestic and external demands. Moreover, decisions on opening warehouses and selecting suppliers were considered. In order to investigate heterogeneity and freshness in the fruit supply chain, Grillo, Alemany, Ortiz, & Fuertes-Miquel (2017) considered sourcing fruits from one field to process in multiple packing facilities and distributing products to multiple customers. Model both maximize profit and freshness of products.

Varsei & Polyakovskiy (2017) developed a generic sustainable wine supply chain to select suppliers, to establish wineries, bottling plants, and distribution centers, and to determine production and transportation planning. Sazvar, Rahmani, & Govindan (2018) modeled a sustainable supply chain problem with a single supplier and multiple retailers to handle customer's demand for organic and conventional products. The model also investigates inventory planning and allows to substitute of conventional products with organic ones. Hosseini-Motlagh, Samani, & Saadi (2020) proposed a new integrated wheat supply chain network design considering sustainability and minimizing non-resiliency. The model components are domestic and external wheat suppliers, different wheat qualities, silos, flour factories, transportation modes, and demand zones.

Three papers considered cultivation planning and production planning and did not include particularly harvesting decisions. The paper presented by Accorsi, Cholette, Manzini, Pini, & Penazzi (2016) differs from the existing literature in terms of including renewable energy fields and plantings for carbon emissions with an interdisciplinary approach. In addition to this, agricultural lands, processing facilities, and warehouses are included as well. Miranda-Ackerman, Azzaro-Pantel, & Aguilar-Lasserre (2017) focused their work on designing a green supply chain only at a strategic level. The distinguishing elements of this study are incorporating decisions for organic and conventional raw materials, investigating green consumer behavior, and selecting technology for juice production. Jifroudi, Teimoury, & Barzinpour (2020) examined an integrated rice supply chain for planting, processing, and transportation planning. The highlights of this article are including fertilizer and pesticide suppliers, considering irrigation water consumption, and integrating different varieties of rice.

There are several comprehensive AFSC problems. A complex and detailed fruit supply chain tactical planning model which consists of many nodes and interactions was proposed by Masini, Blanco, Petracci, & Bandoni (2007). Essentially, the model determines the optimal quantities of fruit supplying, packaging, processing, storing, and transporting. Ahumada & Villalobos (2011b) proposed an operational model which consists of harvesting, packing, storing, and distributing multiple fresh produce to customers. Ahumada, Villalobos, & Mason (2012) presented an approach to tackle uncertainty and designed a two-stage stochastic model. In the first stage, planting decisions and labor requirements, in the second stage, harvesting and transportation decisions are studied. Suthar et al. (2019) extended the study of Ahumada & Villalobos (2011b) to make a significant contribution to the literature by including post-harvest losses, water, and energy consumption in the supply chain.

Munhoz & Morabito (2014) presented a robust optimization approach for a model that integrates harvesting and processing of oranges and storing of orange juice. Catalá, Moreno, Blanco, & Bandoni (2016) studied a tactical planning model which considers supplying fruits from owned and external farms, processing for juice production, packaging fresh produce, inventory management, and distributing to markets that have different quality requirements for products. The model aims to minimize fruit shortage and maximize total profit. Rocco & Morabito (2016a) addressed the annual planning of tomato processing with agricultural and industrial stages. The agricultural stage includes the decisions of harvesting different tomato varieties and transporting tomatoes for processing. The industrial stage contains production planning for semi-finished and final products, inventory management, transporting products to meet the demands. Furthermore, Rocco & Morabito (2016b) extended the abovementioned model to study uncertainties regarding tomato fruit. Another example of AFSC design was proposed by Ghezavati, Hooshyar, & Tavakkoli-Moghaddam (2017). They explored a distribution system among packing facilities, warehouses, cooling facilities, retailers, and processing plants.

Flores & Villalobos (2018) proposed a framework to plan agricultural activities according to fresh fruits' and vegetables' optimal growth conditions while maximizing total profit. The goal of the framework is to find an optimal solution for planting, harvesting, and shipping schedules. Cheraghalipour, Paydar, & Hajiaghaei-Keshteli (2019) offered a model for rice supply chain design with decisions on providing rice from farmers, processing rice at mills, and storing products to meet demands. Flores & Villalobos (2020) developed a two-stage stochastic programming model for a local agri-fresh supply chain based on the study of Flores & Villalobos (2018). In the first stage, selection of agricultural technologies and planting decisions are made. In the second stage, with stochastic parameters, harvest scheduling is determined to meet the market demands. The goals of the stages are minimizing costs and maximizing profit, respectively.

Regarding the consideration of all the decision variables of the AFSC, only two papers considered all of them. Ahumada & Villalobos (2011a) presented an integrated tactical planning for cultivation, harvest operations, packaging, storing, and transporting fresh products in the supply chain with the perspective of a grower. Jonkman, Barbosa-Póvoa, & Bloemhof (2019) proposed a multi-objective generic AFSC model which consists of planting, harvesting, processing, storing, and distributing at various locations.

2.4.1.2 Decision Levels

There are three decision levels: strategic as long-term decisions, tactical as medium-term decisions, and operational as short-term decisions. Activities such as technology selection, supply chain designs, crop rotation planning, capacity planning can be considered as strategic decisions. Tactical decisions can cover crop selection, planting, and harvest scheduling. Production planning, inventory, equipment scheduling can be considered as operational decisions (Ahumada & Villalobos, 2009).

Strategic decisions in 23 papers, tactical decisions in 55 papers, and operational decisions in 19 papers are considered. While 39 articles tackle with only one level decisions, 29 articles combined different level decision variables into their problems. For example, Vitoriano et al. (2003) included buying new equipment and harvest planning as strategic and operational decisions. Jena & Poggi (2013) considered tactical and operational decisions for harvest planning. Technology and capacity selection and production planning are incorporated as strategic and tactical decisions by Lim et al. (2013). Decision levels are indicated in Table 2.2.

2.4.1.3 Time Horizon

AFSCs can have different planning horizons according to the design of the supply chain (Esteso et al. 2018). Most of the models take into account multi-period planning horizon such as days (e.g. Ferrer et al., 2008) or weeks (e.g. Marchal et al., 2018). Single period planning horizon mostly used to make strategic decisions (e.g. Tan & Çömden, 2012). Multi-period planning horizon is considered by 54 papers, on the other hand, single-period planning horizon is taken into account by 14 papers.

2.4.1.4 Objective Functions

We also indicated the objectives of the models in Table 2.2. Most of the models either include minimization of cost or maximization of profit as objective. Only 8 articles did not include these objectives. Cost minimization is included in 29 articles and profit maximization is considered in 33 articles. Other objectives such as maximization of demand satisfaction (e.g. Nagasawa et al., 2009) and olive oil maximization (Herrera-Cáceres et al., 2017) are stated in problem scope discussion. In addition, sustainability related objectives are discussed in sub-section *2.4.2.1.6*.

Table 2.2 Classification according to problem scope

Authors	Decision variables					Decision levels	Time horizon	Objective function		
	CP	HP	PR	DT	IN			CM	PM	OT
Munhoz & Morabito (2001)			X	X	X	T	MP	X		X
Vitoriano et al. (2003)	X	X				S-O	MP	X		
Kazaz (2004)			X			S	SP		X	
Apaiah & Hendrix (2005)			X	X		S	SP	X		
Jiao et al. (2005)		X				T	MP			X
Caixeta-Filho (2006)		X				T	MP		X	
Higgins & Laredo (2006)		X		X		T	SP	X		X
Higgins et al. (2006)			X	X	X	T	MP	X		
Widodo et al. (2006)		X			X	T	MP			X
Grunow et al. (2007)	X	X		X	X	T-O	MP	X		X
Masini et al. (2007)		X	X	X	X	T	MP		X	
Ferrer et al. (2008)		X				T-O	MP	X		
Nagasawa et al. (2009)		X			X	T	MP			X
Piewthongngam et al. (2009)	X	X				T	MP			X
Arnaout & Maatouk (2010)		X				T-O	MP	X		
Bohle et al. (2010)		X				T-O	MP		X	
Jerić & Šorić (2010)		X	X		X	T-O	MP		X	
Ahumada & Villalobos (2011a)	X	X	X	X	X	T	MP		X	
Ahumada & Villalobos (2011b)		X	X	X	X	O	MP		X	
Kazaz & Webster (2011)			X			S	SP		X	
Kostin et al. (2011)			X	X	X	S-T	MP		X	
Rong et al. (2011)			X	X	X	T	MP	X		
Ahumada et al. (2012)	X	X	X	X		T	MP		X	
Paksoy et al. (2012)			X	X		T	SP	X		
Stray et al. (2012)		X				O	MP		X	
Sutopo et al. (2012)		X		X		T	MP		X	
Tan & Çömden (2012)	X	X				S	MP		X	
Jena & Poggi (2013)	X	X	X			T-O	MP		X	
Lim et al. (2013)			X	X	X	S-T	MP		X	
Costa et al. (2014)	X	X		X	X	S-T	MP		X	
Munhoz & Morabito (2014)		X	X		X	T-O	MP	X		
da Silva et al. (2015)		X		X		T	MP	X		X
González-Araya et al. (2015)		X				T-O	MP	X		
Reis & Leal (2015)			X	X	X	T	MP		X	
Thuankaewsing et al. (2015)		X				T	MP			X
Wishon et al. (2015)	X	X				T	MP		X	
Accorsi et al. (2016)	X		X	X		S	SP	X		
An & Ouyang (2016)			X	X		S-T	SP		X	
Catalá et al. (2016)		X	X	X	X	T	MP		X	X
Rocco & Morabito (2016a)		X	X	X	X	T	MP	X		
Rocco & Morabito (2016b)		X	X	X	X	T	MP	X		
Banasik et al. (2017)	X	X				T	MP		X	X
Basso & Varas (2017)			X			O	MP			X
Ghezavati et al. (2017)		X	X	X	X	S-T	MP		X	
Gholamian & Taghanzadeh (2017)			X	X	X	S-T	MP	X		
Grillo et al. (2017)			X	X	X	T	MP		X	X
Herrera-Cáceres et al. (2017)		X	X			O	MP			X
Miranda-Ackerman et al. (2017)	X		X			S	SP		X	X

Table 2.2 continues

Authors	Decision variables					Decision levels	Time horizon	Objective function		
	CP	HP	PR	DT	IN			CM	PM	OT
Varsei & Polyakovskiy (2017)			X	X	X	S-T	SP	X		X
Allaoui et al. (2018)			X	X		S-T	MP	X		X
Cheraghalipour et al. (2018)		X		X	X	S-T	MP	X		X
Flores & Villalobos (2018)	X	X	X	X		S-T	MP		X	
Marchal et al. (2018)			X			T	MP		X	
Sazvar et al. (2018)			X	X	X	T	MP	X		X
Banasik et al. (2019)	X	X				T	MP		X	X
Cheraghalipour et al. (2019)		X	X	X	X	S-T	MP	X		
He & Li (2019)		X				O	SP			X
Jerić & Šorić (2019)		X	X		X	T-O	MP	X	X	
Jonkman et al. (2019)	X	X	X	X	X	S-T	MP		X	X
Junqueira & Morabito (2019)		X				O	MP	X		
Plessen (2019)	X	X				T-O	SP	X		
Roghanian & Cheraghalipour (2019)		X		X	X	S-T	MP	X		X
Suthar et al. (2019)		X	X	X	X	T-O	MP		X	
Yurt et al. (2019)			X	X		T	SP		X	
Flores & 8Villalobos (2020)	X	X	X	X	X	S-T	MP	X	X	
Hosseini-Motlagh et al. (2020)			X	X	X	S-T	MP	X		X
Jifroudi et al. (2020)	X		X	X	X	S-T	SP		X	
Varas et al. (2020)		X				T-O	MP	X		X

CP: Cultivation planning, HP: Harvest planning, PR: Production planning, DT: Distribution planning, IC: Inventory planning, S: Strategic, T: Tactical, O: Operational, SP: Single period, MP: Multiple periods, CM: Cost minimization, PM: Profit maximization, OT: Other objectives

2.4.2 Model Characteristics

Model features and product specifications are discussed in this sub-section. Model features are time window constraints, perishability of products, resource limitations, uncertainty, product waste, and sustainability. Number of products and product types are indicated as well. AFSC characteristics are summarized in Table 2.3.

2.4.2.1 Model Features

Model features are addressed in detail below. Figure 2.4 presents the number of articles that consider various problem characteristics.

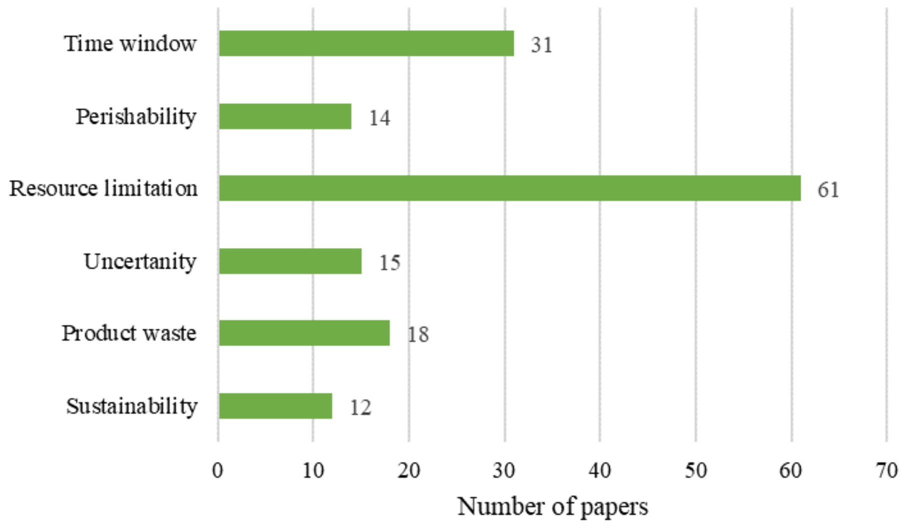

Figure 2.4 Number of papers regarding problem characteristics

2.4.2.1.1 Time Window. Time window constraints or limitations were applied to several cultivation and harvesting related papers. Figure 2.4 shows that 31 papers incorporated time windows into their model.

Time windows were used to limit the time periods for planting and harvesting activities in the planning horizon (e.g. Grunow et al., 2007; Plessen, 2019). Herrera-Cáceres et al. (2017) and González-Araya et al. (2015) considered time windows determined by decision-makers for olive harvesting and apple harvesting, respectively. In the case of wine grape harvesting, optimal harvesting dates were taken into account and a penalty for harvesting outside the optimal dates were included (e.g. Arnaout & Maatouk, 2010; Ferrer et al., 2008).

Flores & Villalobos (2018) and Flores & Villalobos (2020) took into account of planting and harvesting windows that effects vegetable yields because of different weather conditions. Differently from other studies, Tan & Çömden (2012) proposed an uncertain harvesting time window.

Some papers considered maturation curve to optimally harvest crops. Maturation curve was used for products such as orange (e.g. Caixeta-Filho, 2006), fresh produce (e.g. Nagasawa et al., 2009), and tomatoes (e.g. Rocco & Morabito, 2016a). An &

Ouyang (2016) considered early, preferred, and late harvesting periods and included early and late harvesting costs.

2.4.2.1.2 Perishability. Perishability of agricultural products was discussed in different ways and incorporated into the 14 models.

Widodo et al. (2006), Nagasawa et al. (2009), and Rong et al. (2011) considered deterioration curve to demonstrate perishability for post-harvest fresh produce. Ahumada & Villalobos (2011a; 2011b), Ahumada et al. (2012), Ghezavati et al. (2017), and Suthar et al. (2019) took into account perishability in terms of color changes throughout the post-harvest periods. Costa et al. (2014) used time-dependent variables and addressed that products can be stock for a certain period of time. Reis & Leal (2015) distinguished their research from other studies with the consideration of crop loss at farmers for the entire harvest season. Ghezavati et al. (2017) and Flores & Villalobos (2020) considered shelf life restrictions. Instead of including quality changes, Grillo et al. (2017) incorporated different selling prices according to remaining shelf life. Sazvar et al. (2018) addressed agri-food deterioration via holding cost function and a fixed deterioration rate. Jonkman et al. (2019) represented perishability with two alternatives: quality decay factor and shelf-life limitations.

Additionally, some papers took into account of the crop perishability via model configurations (e.g. Ferrer et al., 2008; Herrera-Cáceres et al., 2017). Authors designed their problem regarding daily processing capacity; thus, inventory of perishable crops were not allowed, and they assume quality loss did not occur. Due to the lack of specific additions to the models, these types of perishability considerations are not included in Table 2.3.

2.4.2.1.3 Resource Limitation. Almost all of the papers addressed the constraints on limited resources.

Most of the papers considered production/processing capacity (e.g. Banasik et al., 2017; Catalá et al., 2016; Hosseini-Motlagh et al., 2020; Junqueira & Morabito, 2019).

Some of the cultivation related papers used available land size as a limitation for planting crops (e.g. Costa et al., 2014; Wishon et al., 2015). Additionally, Apaiah & Hendrix (2005) proposed an uncapacitated and a capacitated model for pea cultivation.

Ahumada & Villalobos (2011a) and Ahumada et al. (2012) considered investment budget for cultivation, on the other hand, Flores & Villalobos (2018) and Flores & Villalobos (2020) considered a budget for farming technology selection. In addition, Flores & Villalobos (2020) allowed only limited amount of farming operations.

Harvesting related papers used multiple different harvesting resources. Harvesting resources with different capacities were taken into account by several papers (e.g. Herrera-Cáceres et al., 2017; Jena & Poggi, 2013). Besides that, as a harvesting resource, some papers limited the labor force (e.g. González-Araya et al., 2015; Suthar et al., 2019). Also, machine availability for harvesting was considered (e.g. Bohle et al., 2010; Varas et al., 2020).

Transportation capacity (e.g. Allaoui et al., 2018; Kostin et al., 2011) and storage capacity (e.g. Hosseini-Motlagh et al., 2020; Roghanian & Cheraghalipour, 2019) was included in some papers as well. Supplier capacity for raw materials was taken into account in some papers (e.g. Gholamian & Taghanzadeh, 2017; Jifroudi et al., 2020; Yurt et al., 2019).

Jonkman et al. (2019) and Marchal et al. (2018) differ from literature with the consideration of production quota for sugar beet and product selling capacity, respectively. Paksoy et al. (2012) discussed fuzzy numbers for production, supplier, and warehouse capacity. The distinguishing feature of the model proposed by Sutopo et al. (2012) is the consideration of budget for social corporate responsibility trainings and improvements.

2.4.2.1.4 Uncertainty. Various uncertainty elements of AFSCs were investigated in mathematical models.

Crop yield uncertainty was considered in Kazaz & Webster (2011), Ahumada et al. (2012), An & Ouyang (2016), and Jonkman et al. (2019). Demand uncertainty was incorporated into the models by Costa et al. (2014) and Jonkman et al. (2019). Kazaz (2004) and Banasik et al. (2019) considered both yield and demand uncertainties in the olive oil and mushroom production industries, respectively.

A number of uncertainties were incorporated into few models simultaneously. Tan & Çömden (2012) took into consideration of maturation time, harvest time, crop yield, and demand uncertainties, on the other hand, Hosseini-Motlagh et al. (2020) considered wheat supply, flour demand, transportation cost, and warehouse opening cost uncertainties. Paksoy et al. (2012) investigated production, supplier, and warehouse capacity, and demand uncertainties. da Silva et al. (2015) incorporated fluctuations in agricultural activity costs and sugar content.

Flores & Villalobos (2020) examined the variability of rainfall, temperature, and market prices in their study. Market prices were also discussed by Marchal et al. (2018) and Ahumada et al. (2012). Differently from other papers, Bohle et al. (2010) handled manual harvesting productivity as an uncertain element of the model.

Some papers investigated uncertainty in food properties. Munhoz & Morabito (2014) and Marchal et al. (2018) considered orange juice acidity and olive features, respectively. Rocco & Morabito (2016b) analyzed soluble solid content in tomatoes and crop yield uncertainties.

2.4.2.1.5 Product Waste. Product waste has been included in the models since the last decade according to Table 2.3.

Masini et al. (2007) evaluated product wastes for juice production. Kostin et al. (2011) considered waste from processing sugar waste. Wax, which is refinery waste from edible vegetable oil, was recycled to use in the cosmetic sector in the study of Paksoy et al. (2012). If the minimum quality level exceeded, products would become waste in Ghezavati et al. (2017), Jonkman et al. (2019), and Rong et al. (2011).

Reis & Leal (2015) included crop loss percentage due to transportation. Herrera-Cáceres et al. (2017) incorporated a prominent feature to the study by considering olive loss by the severe weather conditions. Post-harvest fresh produce waste was included in Costa et al. (2014) by incorporating product age. When products exceeded their remaining shelf life, Grillo et al. (2017) considered them as wastes.

When fruit quality level was not enough to sell as packaged fresh fruit due to damages or imperfections, they were considered as wastes and send for the juice production (Catalá et al., 2016). While Sazvar et al. (2018) considered deteriorated products at retailers, An & Ouyang (2016) considered post-harvest losses during transportation, storage, and processing.

Three papers developed closed-loop supply chains to recover product wastes. Banasik et al. (2017) considered recovering and reusing product waste. Cheraghalipour et al. (2018) and Roghanian & Cheraghalipour (2019) considered damaged products as wastes.

Banasik et al. (2019) considered substrate waste after using it for mushroom cultivation. Suthar et al. (2019) took into account product wastes at packing facility, repacking plant, and distribution center due to decay or disorder. Differently from other studies, Hosseini-Motlagh et al. (2020) considered wheat waste during transportation and minimized within the social objective function.

2.4.2.1.6 Sustainability. In this sub-section, we addressed the notable interest in sustainability concept, mostly growing in the recent years.

Only two articles considered the sustainability concept via constraints. Costa et al. (2014) provided a crop rotation plan with ecological constraints to sustain more productive land. Accorsi et al. (2016) restricted their model to have a zero-carbon emission ecosystem with constraints.

The inclusion of sustainability into the models was done by objective functions in the rest of the papers. Economic and environmental sustainability was considered mostly. Banasik et al. (2017) and Banasik et al. (2019) considered profit maximization and exergy loss minimization. Miranda-Ackerman et al. (2017) focused on global warming potential and minimizing costs, and therefore four objective functions were created to use in different scenarios. Objective functions are maximizing net present value, minimizing investment, minimizing average variable unit cost, and minimizing CO_2 emissions.

Total gross margin and CO_2 emissions of the supply chain were maximized and minimized, respectively in Jonkman et al. (2019). As an environmental objective, Roghanian & Cheraghalipour (2019) minimized CO_2 emissions created by different transportation vehicles which have different CO_2 production rates.

For sustainability, Hosseini-Motlagh et al. (2020) minimized total cost and negative impact of social corporate responsibility. Social objective function consists of job opportunities, waste generated during transportation, and loss workdays.

Economic, environmental, and social dimension of sustainability was included in three models. Sazvar et al. (2018) minimized total cost and greenhouse gas emissions and maximized public health. Public health objective was indicated as a function of individual health and environmental health. Allaoui et al. (2018) considered minimizing total cost, CO_2, and water footprint while maximizing created jobs. Varsei & Polyakovskiy (2017) minimized fixed and variable costs and CO_2 emissions from transportation and maximized social impact.

2.4.2.2 Number of Products

Some articles considered single product in their models, and some articles included multiple products or multiple different varieties of crops. Also, the concept of multiple products can show variability. 28 articles included only one product, whereas 40 articles covered multiple products.

Organic and conventional apples by Sazvar et al. (2018); different sizes of mushrooms by Banasik et al. (2019); different packaged olive oil products by Yurt et al. (2019); different olive oil combinations by Jerić & Šorić (2019); multiple brands of sugar by Higgins et al. (2006); different olive oil qualities by Marchal et al. (2018) and multiple vegetables by Flores & Villalobos (2018) were considered. Some papers used multiple varieties of crops to study (e.g. Herrera-Cáceres et al., 2017; Piewthongngam et al., 2009).

Although Accorsi et al. (2016) and Suthar et al. (2019) considered with multiple crops, they included only one crop in their case studies.

2.4.2.3 Agri-food Types

Fresh product characteristics was considered in 37 articles. Fresh product can be fresh vegetable (e.g. Ahumada et al., 2012), fresh fruit (e.g. González-Araya et al., 2015) or grain (e.g. An & Ouyang, 2016). Processed products were taken into account in 27 articles. For example, orange juice production (e.g. Munhoz & Morabito, 2001), olive oil production (e.g. Marchal et al., 2018), rice processing (e.g. Lim et al., 2013) or tomato processing (e.g. Rocco & Morabito, 2016a) were considered for processing crops.

The inclusion of both fresh and processed products was made by four articles. Masini et al. (2007) studied both fresh and processed fruits. Reis & Leal (2015) considered unprocessed and processed soybean products. Catalá et al. (2016) included fruit juice and packaged fresh fruit production. Ghezavati et al. (2017) examined supplying fresh tomatoes to retailers and process facilities. Figure 2.5 shows the percentage of agri-food types.

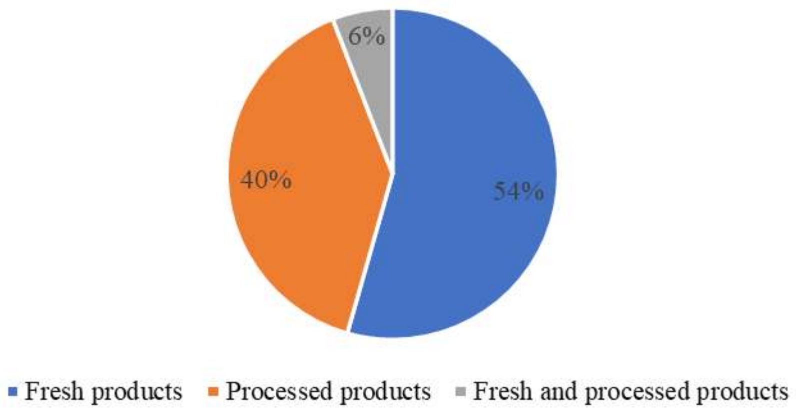

Figure 2.5 Agri-food types

Additionally, considered products are listed in Table 2.3.

Table 2.3 Classification according to model characteristics

Authors	Model features						No. of products	Agri-food type		Product
	TW	PE	RL	UC	PW	SU		Fresh	Processed	
Munhoz & Morabito (2001)			X				M		X	Orange
Vitoriano et al. (2003)	X		X				M	X		Multiple
Kazaz (2004)				X			S		X	Olive
Apaiah & Hendrix (2005)			X				S		X	Pea
Jiao et al. (2005)	X						S	X		Sugar cane
Caixeta-Filho (2006)	X		X				S		X	Orange
Higgins & Laredo (2006)			X				S	X		Sugar cane
Higgins et al. (2006)			X				M		X	Sugar
Widodo et al. (2006)	X	X					S	X		Unspecified
Grunow et al. (2007)	X		X				S	X		Sugar cane
Masini et al. (2007)	X		X		X		M	X	X	Fruit
Ferrer et al. (2008)	X		X				S	X		Grape
Nagasawa et al. (2009)	X	X					S	X		Unspecified
Piewthongngam et al. (2009)			X				M	X		Sugar cane
Arnaout & Maatouk (2010)	X		X				S	X		Grape
Bohle et al. (2010)	X		X	X			M	X		Grape
Jerić & Šorić (2010)			X				M		X	Olive
Ahumada & Villalobos (2011a)	X	X	X				M	X		Vegetable
Ahumada & Villalobos (2011b)	X	X	X				M	X		Vegetable
Kazaz & Webster (2011)				X			S		X	Olive
Kostin et al. (2011)			X		X		M		X	Sugarcane
Rong et al. (2011)		X	X		X		S	X		Pepper
Ahumada et al. (2012)	X	X	X	X			M	X		Vegetable
Paksoy et al. (2012)			X	X	X		M		X	Edible oil
Stray et al. (2012)	X						S	X		Sugarcane
Sutopo et al. (2012)			X				M	X		Vegetable
Tan & Çömden (2012)	X			X			S	X		Tomato
Jena & Poggi (2013)			X				S		X	Sugar cane
Lim et al. (2013)			X				M		X	Rice
Costa et al. (2014)		X	X	X	X	X	M	X		Vegetable
Munhoz & Morabito (2014)	X		X	X			M		X	Orange
da Silva et al. (2015)	X		X	X			S	X		Sugarcane
González-Araya et al. (2015)	X		X				M	X		Apple
Reis & Leal (2015)		X	X		X		M	X	X	Soybean
Thuankaewsing et al. (2015)			X				S	X		Sugarcane
Wishon et al. (2015)			X				M	X		Vegetable
Accorsi et al. (2016)			X			X	S	X		Potato
An & Ouyang (2016)	X		X	X	X		S	X		Grain
Catalá et al. (2016)	X		X		X		M	X	X	Pome fruit
Rocco & Morabito (2016a)	X		X				M		X	Tomato
Rocco & Morabito (2016b)	X		X	X			M		X	Tomato
Banasik et al. (2017)			X		X	X	M	X		Mushroom

Table 2.3 continues

Authors	Model features						No. of products	Product type		Product
	TW	PE	RL	UC	PW	SU		Fresh	Processed	
Basso & Varas (2017)	X		X				M		X	Wine
Ghezavati et al. (2017)	X	X	X		X		S	X	X	Tomato
Gholamian & Taghanzadeh (2017)			X				M		X	Wheat
Grillo et al. (2017)		X	X		X		M	X		Fruit
Herrera-Cáceres et al. (2017)	X		X			X	M		X	Olive
Miranda-Ackerman et al. (2017)			X			X	M		X	Orange
Varsei & Polyakovskiy (2017)			X			X	S		X	Wine
Allaoui et al. (2018)			X			X	M		X	Unspecified
Cheraghalipour et al. (2018)			X		X		S	X		Citrus
Flores & Villalobos (2018)	X		X				M	X		Vegetable
Marchal et al. (2018)			X	X			M		X	Olive
Sazvar et al. (2018)		X	X		X	X	M	X		Apple
Banasik et al. (2019)			X	X	X	X	M	X		Mushroom
Cheraghalipour et al. (2019)			X				M		X	Rice
He & Li (2019)	X		X				S	X		Grain
Jerić & Šorić (2019)			X				M		X	Olive
Jonkman et al. (2019)		X	X		X	X	M		X	Sugar beet
Junqueira & Morabito (2019)	X		X				S	X		Sugar cane
Plessen (2019)	X		X				M	X		Unspecified
Roghanian & Cheraghalipour (2019)			X		X	X	S	X		Citrus
Suthar et al. (2019)		X	X		X		S	X		Tomato
Yurt et al. (2019)			X				M		X	Olive oil
Flores & 8Villalobos (2020)	X	X	X	X			M	X		Vegetable
Hosseini-Motlagh et al. (2020)			X	X	X	X	S		X	Wheat
Jifroudi et al. (2020)			X				M		X	Rice
Varas et al. (2020)	X		X				S	X		Grape

Note: TW: Time window, PE: Perishability, RL: Resource limitation, UC: Uncertainty, PW: Product waste, SU: Sustainability, S: Single product, M: Multiple products

2.4.3 Modeling Approaches

In this sub-section, mathematical programming models, application types, and solution approaches are discussed, and Table 2.4 summarizes reviewed papers.

2.4.3.1 Model Types

We now discuss the mathematical modeling approaches applied to AFSC studies. Predominantly, single-objective optimization was considered by 48 articles, while multi-objective optimization was included by 18 articles. Differently from other studies, two articles considered bi-level optimization. Figure 2.6 shows the number of papers according to modeling types. We can see the interest in deterministic models.

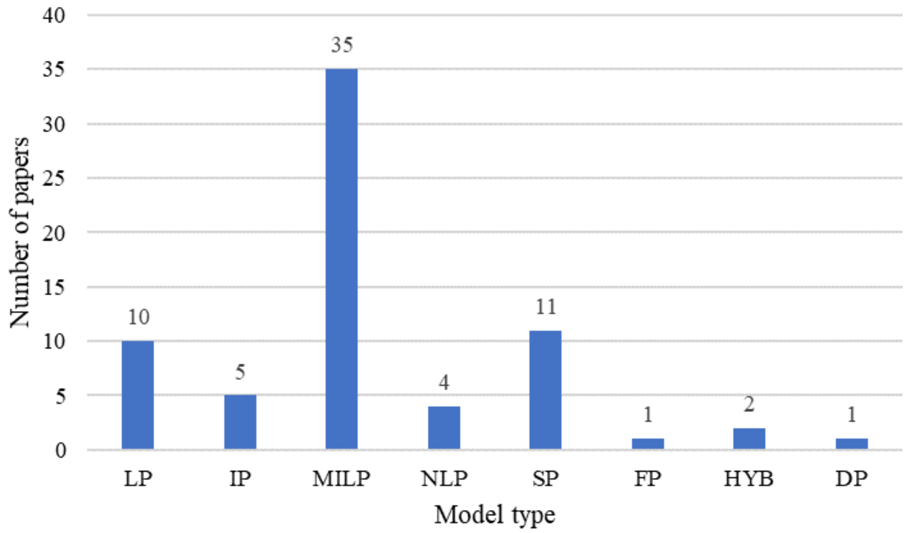

Figure 2.6 Number of papers according to model types

The most preferred modeling approach was MILP (e.g. Grunow et al., 2007; Jonkman et al., 2019). Notably, linear programming and integer programming models also used in planning models.

Differently from other papers, Vitoriano et al. (2003) specifically considered integer programming and mixed-integer programming models to demonstrate discrete time horizon and continuous time horizon.

Jiao et al. (2005) formulated an integer non-linear programming model to solve harvest scheduling. Miranda-Ackerman et al. (2017) presented a pure integer non-linear programming model to design a green AFSC. Sazvar et al. (2018) established a multi-objective mixed-integer non-linear programming model.

Bi-level optimization was considered by An & Ouyang (2016) to provide a robust optimization model and by Cheraghalipour et al. (2019) to model a non-linear programming model.

A number of papers applied the different concepts of stochastic programming to their models in order to tackle uncertainties in AFSCs. For example, two-stage stochastic programming by Kazaz (2004); robust optimization by Bohle et al. (2010) and scenario-based stochastic programming by Banasik et al. (2019) were considered. Moreover, Rocco & Morabito (2016b) proposed three robust optimization approaches to consider uncertain elements individually and simultaneously.

There are only two hybrid models. Allaoui et al. (2018) developed a multi-criteria method which is an integrated approach of Analytic Hierarchy Process method and Ordered Weighted Averaging to evaluate stakeholders and use its solution as an input parameter in the mathematical model. Hosseini-Motlagh et al. (2020) presented a novel hybrid stochastic fuzzy-robust programming, and moreover four other hybrid approaches were studied.

Widodo et al. (2006) used dynamic programming to model a fresh produce supply chain. Paksoy et al. (2012) proposed a multi-objective fuzzy programming model.

Some papers (e.g. Costa et al., 2014; Jonkman et al., 2019) also considered the stochastic version of their deterministic models to compare the deterministic and stochastic results.

2.4.3.2 Data Type

For the validation and illustration of their model, authors used either real case data or hypothetical data. 26 articles demonstrated the validation and practicability of their model with a real case study. Conversely, 42 articles used hypothetical case studies for the illustrations of their model.

2.4.3.3 Solution Methods

A variety of solution methods have been used to solve AFSC problems. We now discuss the prominent applied solution methods. Solution methodologies are listed in Table 2.4.

Most of the analyzed articles were solved by commercial software such as IBM ILOG (e.g. de Keizer et al., 2017), GAMS (e.g. Jonkman et al., 2019), and AMPL (e.g. Suthar et al., 2019).

Several heuristic and meta-heuristic methods were used to solve the considered problems. Higgins & Laredo (2006) solved the transportation planning model with a greedy randomized adaptive search procedure and the harvesting planning model with a tabu search. Higgins et al. (2006) used a general version of the tabu search and variable neighborhood search to demonstrate their model. They also compared the heuristics. Ferrer et al. (2008) solved the developed model in a shorter time with a decomposition heuristic approach than an exact branch and bound algorithm. Arnaout & Maatouk (2010) proposed two heuristics to solve the scheduling model. Kostin et al. (2011) used a decomposition method called rolling horizon. Stray et al. (2012) developed a tabu search approach. Jena & Poggi (2013) applied a number of solution techniques to solve the large operational planning model. Pre-processing, hot-start construction with heuristic solutions, valid inequalities, and a specialized algorithm were used to solve the model.

Thuankaewsing et al. (2015) and Basso & Varas (2017) used heuristics to solve large scale problems. Junqueira & Morabito (2019) solved their model with a mixed-integer programming based heuristic approaches which include aggregation process, relax-and-fix constructive heuristic, and fix-and-optimize improvement heuristic. He & Li (2019) solved the vehicle routing problem with a memetic algorithm which consists of a genetic algorithm and a local search procedure. Cheraghalipour et al. (2019) used genetic algorithm, particle swarm algorithm, and two hybrids of these algorithms. Roghanian & Cheraghalipour (2019) used a multi-objective version of tree growth algorithm as the main solution tool and compared the solutions with other evolutionary algorithms.

As an exact solution method, Costa et al. (2014) developed a column generation algorithm to solve both deterministic and stochastic models, while Ghezavati et al. (2017) solved the mixed-integer problem with a primal Bender's decomposition algorithm.

Several methods were used to solve multi-objective models. Notable solution methods, ϵ-constraint (e.g. Banasik et al., 2019; Jonkman et al., 2019) and augmented ϵ-constraint method (e.g. Catalá et al., 2016; Sazvar et al., 2018) were used in several articles. Jerić & Šorić (2019) and Miranda-Ackerman et al. (2017) solved their multi-objective model with a Non-Dominated-Sorting-Genetic algorithm. Also, Miranda-Ackerman et al. (2017) used a multi-criteria decision-making process with the aim of finding the best solution. Grillo et al. (2017) used the simple additive weighting method to maintain one global objective function.

Several step solution procedures were applied by Varas et al. (2020). Firstly, initial Pareto optimal solution are found with augmented weighted Tchebycheff method. If decision-makers do not accept the initial solution, then, Pareto optimal solutions are found in a local neighborhood through augmented ε-constraint method. Differently from other studies, Allaoui et al. (2018) solved the first stage of the problem by multi-criteria methods. Then, multi-objective model was solved with an approach based on the ε-constraint method. Cheraghalipour et al. (2018) developed a new population-based meta-heuristic algorithm called multi-objective Keshtel algorithm and then compared the solutions with other meta-heuristics. In addition, two articles used goal programming to solve multi-objective optimization (da Silva et al, 2015; Munhoz & Morabito, 2001).

Some methods were used to solve stochastic programming models. Monte Carlo simulation was used to solve robust optimization model by Bohle et al. (2010). As a different solution technique, Ahumada et al. (2012) used the stochastic version of

Bender's decomposition and multi-cut version of this algorithm. An & Ouyang (2016) proposed a Lagrangian relaxation algorithm to solve the stochastic model. Flores & Villalobos (2020) used two-stage stochastic decomposition approach to solve the stochastic model. Banasik et al. (2019) used sample average approximation based on Monte Carlo simulation to find better solutions. Moreover, Tan & Çömden (2012) solved their model with exact and approximate solutions and compared them.

Widodo et al. (2006) solved their model with an optimization algorithm which consists of decision rules. Plessen (2019) used integer programming based exact algorithms to solve the problem and proposed a heuristic for large scale problems.

Table 2.4 Classification according to modeling approaches

Authors	Model type				Data type	Solution methods
	SO	MO	BL			
Munhoz & Morabito (2001)		X		LP	HP	Goal programming
Vitoriano et al. (2003)	X			IP, MILP	HP	Exact
Kazaz (2004)	X			SP	HP	Exact
Apaiah & Hendrix (2005)	X			LP	HP	Exact
Jiao et al. (2005)	X			NLP	RC	Exact
Caixeta-Filho (2006)	X			LP	RC	Exact
Higgins & Laredo (2006)	X			IP	RC	Metaheuristics
Higgins et al. (2006)	X			MILP	HP	Metaheuristics
Widodo et al. (2006)	X			DP	HP	Exact
Grunow et al. (2007)	X			MILP	RC	Exact
Masini et al. (2007)	X			LP	HP	Exact
Ferrer et al. (2008)	X			MILP	RC	Heuristics
Nagasawa et al. (2009)	X			MILP	HP	Exact
Piewthongngam et al. (2009)	X			LP	HP	Exact
Arnaout & Maatouk (2010)	X			MILP	HP	Heuristics
Bohle et al. (2010)	X			SP	RC	Simulation
Jerić & Šorić (2010)	X			MILP	HP	Heuristics
Ahumada & Villalobos (2011a)	X			MILP	HP	Exact
Ahumada & Villalobos (2011b)	X			MILP	HP	Exact
Kazaz & Webster (2011)	X			SP	HP	Exact
Kostin et al. (2011)	X			MILP	HP	Heuristic
Rong et al. (2011)	X			MILP	HP	Exact
Ahumada et al. (2012)	X			SP	HP	Exact
Paksoy et al. (2012)		X		FP	RC	Exact
Stray et al. (2012)	X			IP	RC	Metaheuristic
Sutopo et al. (2012)		X		MILP	HP	Exact
Tan & Çömden (2012)	X			SP	HP	Approximate/Exact
Jena & Poggi (2013)	X			MILP	HP	Heuristic
Lim et al. (2013)	X			MILP	HP	Exact
Costa et al. (2014)	X			LP	HP	Exact
Munhoz & Morabito (2014)	X			SP	HP	Exact
da Silva et al. (2015)		X		LP	RC	Goal programming
González-Araya et al. (2015)	X			MILP	RC	Exact
Reis & Leal (2015)	X			LP	RC	Exact
Thuankaewsing et al. (2015)	X			MILP	RC	Heuristic
Wishon et al. (2015)	X			MILP	HP	Exact
Accorsi et al. (2016)	X			LP	HP	Exact
An & Ouyang (2016)			X	SP	HP	Heuristic
Catalá et al. (2016)		X		MILP	HP	Augmented ε-constraint
Rocco & Morabito (2016a)	X			LP	RC	Exact
Rocco & Morabito (2016b)	X			SP	RC	Exact
Banasik et al. (2017)		X		MILP	RC	ε-constraint
Basso & Varas (2017)	X			MILP	HP	Heuristic
Ghezavati et al. (2017)	X			MILP	RC	Exact
Gholamian & Taghanzadeh (2017)	X			MILP	RC	Exact
Grillo et al. (2017)		X		MILP	RC	MCDM
Herrera-Cáceres et al. (2017)	X			MILP	RC	Exact

Table 2.4 continues

Authors	SO	MO	BL	Model type	Data type	Solution methods
Miranda-Ackerman et al. (2017)		X		NLP	HP	Metaheuristics +MCDM
Varsei & Polyakovskiy (2017)		X		MILP	RC	Augmented ε-constraint
Allaoui et al. (2018)		X		HYB	HP	Exact
Cheraghalipour et al. (2018)		X		MILP	HP	Metaheuristics
Flores & Villalobos (2018)	X			MILP	HP	Exact
Marchal et al. (2018)	X			SP	HP	Exact
Sazvar et al. (2018)		X		NLP	RC	Augmented ε-constraint
Banasik et al. (2019)		X		SP	RC	ε-constraint + simulation
Cheraghalipour et al. (2019)			X	NLP	HP	Metaheuristics
He & Li (2019)	X			MILP	HP	Heuristic
Jerić & Šorić (2019)		X		MILP	HP	Metaheuristic
Jonkman et al. (2019)		X		MILP	HP	ε-constraint
Junqueira & Morabito (2019)	X			MILP	RC	Heuristic
Plessen (2019)	X			IP	HP	Heuristic
Roghanian & Cheraghalipour (2019)		X		MILP	HP	Metaheuristics
Suthar et al. (2019)	X			MILP	HP	Exact
Yurt et al. (2019)	X			IP	RC	Exact
Flores & 8Villalobos (2020)	X			SP	HP	Exact
Hosseini-Motlagh et al. (2020)		X		HYB	RC	Compromise programming
Jifroudi et al. (2020)				MILP	RC	Exact
Varas et al. (2020)		X		MILP	HP	Heuristic+ augmented ε-constraint

Note: SO: Single objective optimization, MO: Multi-objective optimization, BL: Bi-level optimization, LP: Linear programming, IP: Integer programming, MILP: Mixed-integer linear programming, SP: Stochastic programming, SM: Simulation, HYB: Hybrid, DP: Dynamic programming, FP: Fuzzy programming, RC: Real case, HP: Hypothetical, MCDM: Multi-criteria decision-making

2.5 Findings and Future Research Directions

In this section, we discuss the potential future research directions based on the evaluation made in section 2.5. Besides, we point out the following areas that are in need of greater investigation.

- There are only a few papers that include several decision variables and thus have a broader perspective in the AFCS context (e.g. Ahumada and Villalobos, 2011a). However, the vast majority of the models focused on certain parts of the supply chain. For instance, these parts can be harvesting (e.g. Ferrer et al., 2008) or production and distribution (e.g. Rong et al., 2011). Therefore, integrated supply chain designs are needed in order to make more efficient and effective decision-making processes. In line with the argument above, although previous reviews (e.g. Kusumastuti et al., 2016; Tsolakis et al., 2014) strongly put emphasis on the lack of the integrated harvest and production models, still very few articles exist on the subject. It is necessary to develop appropriate integrated harvesting and production models with the intention of coordinating harvest fields and production facilities.

- As a result of this review, we can conclude that almost all of the agricultural crops and products have different characteristics. Hence, there is a need to develop more specific models for AFSCs. Especially, fresh agri-food products have different quality requirements that need to be met in order to satisfy customers' demands.

- There are few studies that address product waste which can occur in the supply chain because of the inherent characteristics of agri-foods. Future research that studies integration of product waste is a crucial contribution for the literature.

- AFSCs are associated with several different topics. To exemplify, these topics can be economics, cultivation, geography, climate, food engineering, and logistics. So, interdisciplinary research approaches can be very useful for efficient and more specific supply chain designs.

- Sustainability is the least model feature included in the analyzed papers. Although in recent years sustainability has gained more interest by the academia, there still exists the need for developing and modeling sustainable AFSCs.

- Generally, real-life supply chains include multiple products. AFSC models should include more product variety and heterogeneity to explore real-world complexities.

- In contrast to the vast body of the literature dedicated to fresh product supply chain, there has been relatively less attention to the perishability. Perishability one of the prominent features of fresh products, therefore it would be more beneficial to include.

- The vast majority of the papers use deterministic models and there are few papers that consider uncertainty. Therefore, incorporating uncertain elements to the AFSC models is a promising research area.

- Relatively fewer papers validated their model with real-life case studies. If it is possible, more studies should implement real data sets to their model to show the practicability of their model.

- Although some previous review studies point out the need for the resiliency in AFSC studies, only one paper (Hosseini-Motlagh et al., 2020) included in their model. There is an urgent need for resilience strategies in the literature.

- Local farmers should be more included during research establishment in order to create real-life problem models that contain complexities that farmers challenge with. Thereby, local farmers and businesses can be supported in the decision-making process.

- Most of the models consider economic objectives (cost minimization and profit maximization). It can be beneficial to investigate AFSCs thoroughly to include more specific purposes.

- Recent developments in technology can create new opportunities for AFSC actors. Integrating digital technologies such as internet of things and sensor technologies have numerous potential research topics.

CHAPTER THREE
OLIVE OIL INDUSTRY

In this chapter, a brief information on olive fruit and olive oil is presented. Section 3.1 introduces olive fruit and addresses olive production. Section 3.2 addresses olive and olive oil production in the world. Section 3.3 demonstrates olive and olive oil production in Turkey. Section 3.4 briefly explains olive cultivation, olive harvesting, olive oil extraction, and olive oil storage conditions. Section 3.5 presents by-product management methods. Section 3.6 states olive oil quality factors. Section 3.7 specifies the differences between olive oil types.

3.1 Olive Production

Olive (*Olea europaea* L.) is an indigenous crop to the Mediterranean basin and its climate conditions (Food and Agriculture Organization of the United Nations, n.d.). Olive trees cannot be cultivated everywhere in the world because of the reasons such as climate and terrain conditions (Soyyiğit & Yavuzaslan, 2018).

Recent studies show that olive was native to the Southeastern Anatolia, specifically Mardin, Kahramanmaraş and Hatay area. Researchers estimate that olive trees were spread from Southeastern to West Anatolia and then, via Aegean islands to the Greece, Italy, and Spain (Yurtoğlu, 2019).

Olive farming is a widespread agricultural activity in Mediterranean region and crucial in rural areas as an economic resource, and furthermore, an important part of the culture and heritage (Zabaniotou, Rovas, Libutti, & Monteleone, 2015).

There are approximately 10-million-hectare olive fields in total 40 olive producer countries, and in these fields, on an average, 20 million tons of olives are produced. Mediterranean basin countries produce more than 90% of the world's olives. Spain is the biggest olive producer country every year, despite olive yield's fluctuations. Other major producer countries are all in the Mediterranean basin. Spain is followed by Italy, Greece, Turkey, Morocco, and Tunisia. And the rest of the olive production takes place in other 34 countries such as Australia, United States of America (USA), and Latin America countries (Agriculture Organization of the United Nations Statistics Division [FAOSTAT], 2020). Major olive producer countries' production volumes are presented in Table 3.1 and Figure 3.1.

Table 3.1 Olive production (tons) (FAOSTAT, 2020)

	2014	2015	2016	2017	2018
World	16,202,406	20,148,928	19,650,821	20,295,421	21,066,062
Spain	4,560,400	5,947,700	7,082,550	6,549,499	9,819,569
Greece	2,592,375	2,907,866	2,755,431	2,837,778	1,079,080
Italy	1,963,676	2,732,894	2,038,303	2,597,974	1,877,222
Turkey	1,768,000	1,700,000	1,730,000	2,100,000	1,500,467
Morocco	1,573,206	1,144,238	1,416,107	1,039,117	1,561,465
Tunisia	376,000	1,700,000	700,000	500,000	825,467

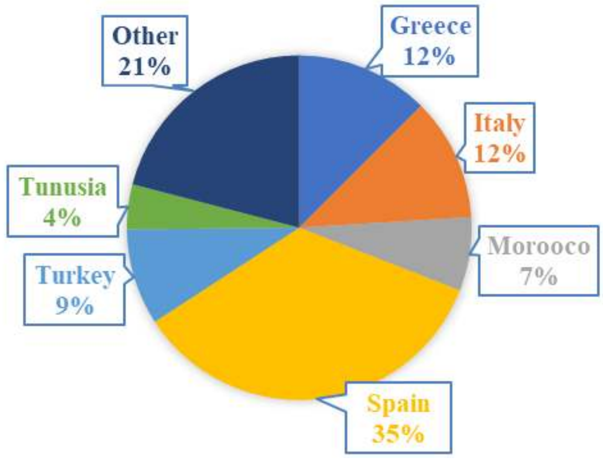

Figure 3.1 Average olive production between 2014-2018 (FAOSTAT, 2020)

Olive trees show a phenomenon called alternate bearing (periodicity or biennial cycle) which is the olive yield differentiation in every year. Therefore, a high yield year is an "on-year" and low yield year is an "off-year". The main reason of this phenomenon is the environmental conditions that olive trees exposed (Kour et al., 2018). The effects of this phenomenon can be seen in Table 3.1.

3.2 Olive Oil Production in the World

Olive oil is obtained from only applying mechanical and physical processes, without any chemical processes, to olive tree fruits. Olive oil is in a liquid form at room temperature, its color changes between clear green and yellow, and has a distinctive taste and smell (Özdoğan & Tunalioğlu, 2017).

World's major olive oil producer countries are shown in Table 3.2. Spain is the by far the major producer country in the world and followed by Italy, Greece, Turkey, and Tunisia.

Table 3.2 World olive oil producer countries (thousand tons) (International Olive Council [IOC], 2018)

Country	2014/15	2015/16	2016/17	2017/18*	2018/19**
World	2,458	3,176.5	2,561.5	3,314	3,131
Spain	842.2	1,403.3	1,290.6	1,260.1	1,598.9
Italy	222	474.6	182.3	428.9	265
Greece	300	320	195	346	225
Turkey	160	150	178	263	183
Tunisia	340	140	100	280	120
Morocco	120	130	110	140	200
Portugal	61	109.1	69.4	134.8	115
Syria	105	110	110	100	100
Argentina	69.5	82	63	82,5	76.5

* Estimates ** Forecasts

Exporter countries are presented in Table 3.3 and exportation volumes are aligned with their production volumes. Most of the larger producer countries are also the major exporter countries such as Spain, Italy, Tunisia, and Turkey.

Table 3.3 World olive oil exporter countries (thousand tons) (IOC, 2018)

Country	2014/15	2015/16	2016/17	2017/18*	2018/19**
World	929	788.5	782.5	945.5	844.5
Spain	236.8	297.8	291.2	292	320
Italy	199.6	208.1	199.5	186.4	185.8
Tunisia	304	102.5	89.5	200	130
Turkey	30	15	45	70	45
Portugal	47.6	40.5	39.5	58.3	50.2
Morocco	25	17	9	15	20
Argentina	12	31	16.5	36	11.5
Greece	16.8	19.3	18.7	18.6	10.2

* Estimates; ** Forecasts

Although Italy and Spain are the two biggest producer and exporter countries, they also import olive oil with a considerable amount. From Table 3.4, it can be seen that consumption of olive oil is increasing in non-producer countries such as USA, Brazil, Japan, and Canada.

Table 3.4 World olive oil importer countries (thousand tons) (IOC, 2018)

Country	2014/15	2015/16	2016/17	2017/18*	2018/19**
World	920.5	790.5	781.5	936	874.5
USA	294.5	314	305	310.5	310
Italy	96	40.6	35.9	64.1	85.4
Spain	104.7	47.3	41	99.4	25
Brazil	66.5	50	59.5	76.5	78
Japan	59	53.5	54.5	55.5	55
Canada	37.5	41	39.5	46.5	43
China	31	34	39	40	42
Australia	22	26	29	30	30
Saudi Arabia	22	22	23	23	24

* Estimates; ** Forecasts

In recent years, Mediterranean diet has gained interest due to the health benefits. It is stated that olive oil consumption has demonstrated health benefits for conditions such as cardiovascular diseases, cancer, diabetes, obesity, pregnancy, and aging (IOC, n.d.-a). Consequently, as an integral part of the Mediterranean diet, olive oil consumption has increased (Scheidel & Krausmann, 2011). Generally, as can be seen in Table 3.5, major olive oil consumer countries are also the producer countries.

Table 3.5 World olive oil consumer countries (thousand tons) (IOC, 2018)

Country	2014/15	2015/16	2016/17	2017/18*	2018/19**
World	2,916	2,979.5	2,726	3,008.5	2,950.5
Italy	571.7	598.1	438.9	566.1	500
Spain	492.2	494.5	442.9	475.1	525
USA	295	321	315	315	315.5
Turkey	125	116	150	176.5	163
Greece	130	140	105	130	130
Morocco	120	120	120	120	140
Syria	126	104	98	87	87
Brazil	66.5	50	59.5	76.5	78
Australia	37	42	45	46	47
Tunisia	30	35	21	33	30

* Estimates; ** Forecasts

3.3 Olive and Olive Oil Status in Turkey

3.3.1 Olive Production

Turkey is in the fourth place in the world regarding olive production. Figure 5.1 shows that between the years of 2014 and 2018, on an average, Turkey produced 9% of the world's olives. As can be seen in Table 3.6, olive tree areas and numbers are continuing to increase over the years in Turkey. Olives are used for either making table olives or olive oil. On average, 75% of the olives are used for oil production and the rest is used for table olive production.

Table 3.6 Olive production in Turkey (Turkish Statistical Institute [TURKSTAT], 2020)

Years	Area of Olive Trees (thousand hectare)	Number of Trees (thousand)	Olive Table (tons)	Olive for Oil (tons)	Olive Production (tons)
2010	784	156,448	375,000	1,040,000	1,415,000
2011	798	154,611	550,000	1,200,000	1,750,000
2012	814	157,061	480,000	1,340,000	1,820,000
2013	826	167,030	390,000	1,286,000	1,676,000
2014	826	168,997	438,000	1,330,000	1,768,000
2015	837	171,992	400,000	1,300,000	1,700,000
2016	846	173,785	430,000	1,300,000	1,730,000
2017	846	174,594	460,000	1,640,000	2,100,000
2018	864	177,843	426,995	1,073,472	1,500,467
2019	879*	182,076	415,000	1,110,000	1,525,000

*data is provisional

Olive trees are cultivated in five regions and they are: Aegean, Marmara, Mediterranean, South-eastern Anatolia and Black Sea. The major olive producer provinces are displayed in Table 3.7. Moreover, in these regions different olive cultivars can be grown. Main varieties are Ayvalık, Çekişte, Çelebi, Domat, Erkence, Gemlik, İzmir Sofralık, Memecik, Memeli, and Uslu (IOC, 2012).

Table 3.7 Olive production regarding provinces (tons) (TURKSTAT, 2020)

Province	2015	2016	2017	2018	2019
Aydın	297,240	259,237	455,378	200,889	384,027
Balıkesir	77,472	181,022	254,200	109,902	163,132
Hatay	177,703	135,900	147,194	91,001	136,203
Manisa	109,708	183,610	266,732	310,069	135,312
Mersin	170,698	143,275	142,869	69,993	98,216
Muğla	154,615	190,641	212,109	41,698	148,996
Çanakkale	71,076	112,193	69,425	44,288	36,749
İzmir	192,181	229,510	189,508	102,756	116,477

Figure 3.2 shows the alterations in olive production in every year. Generally, Aydın, İzmir, Balıkesir, and Muğla are the major olive producer provinces in Turkey.

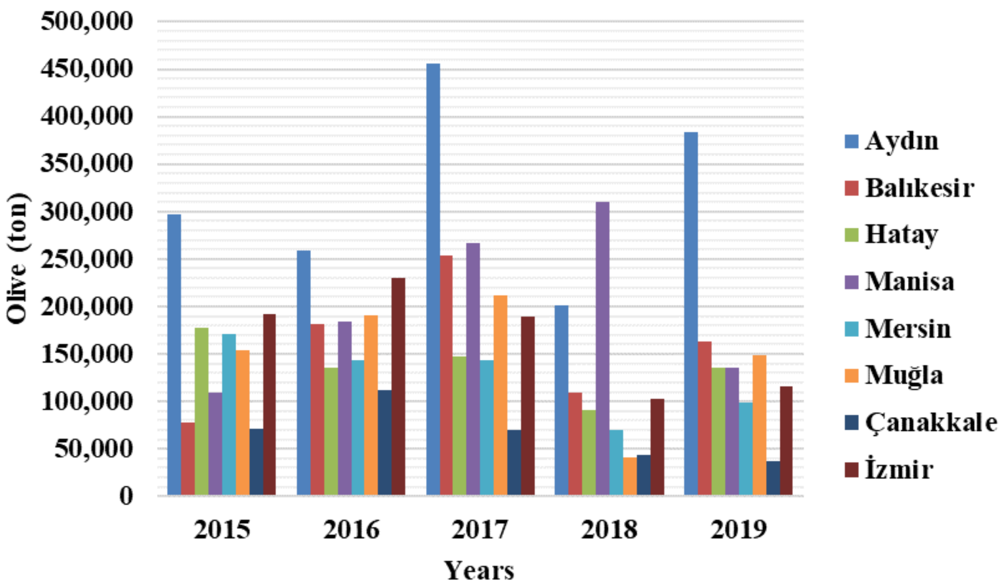

Figure 3.2 Olive production regarding provinces (TURKSTAT, 2020)

3.3.2 Olive Oil Production

Turkey is one of the leading olive oil producer countries in the world**.** Majority of the produced olive oil is consumed in the country and the rest of the amount is exported, as it can be seen in Figure 3.3. Also, according to analyzed data, Turkey do not import olive oil from other producing countries. Thus, it can be concluded that olive oil production industry in Turkey has an important place to provide demand that are particularly from domestic sources.

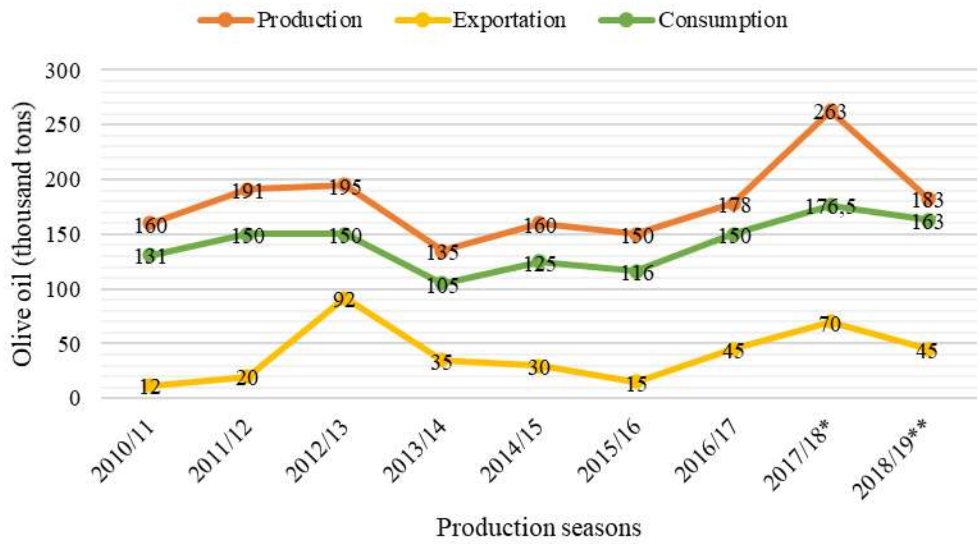

Figure 3.3 Olive oil production in Turkey (IOC, 2018) * Estimates ** Forecasts

3.4 Olive Oil Production

In this section, olive oil production stages from olive cultivation to olive oil storage are explained briefly.

3.4.1 Olive Tree Cultivation

In this sub-section, olive tree planting systems, cultivation activities, and organic farming activities are briefly presented.

Olive tree planting systems are distinguished into three types of olive groves: traditional, intensive and super intensive. The main differences between them are the number of olive trees that are planted on the same hectare and the distribution of the trees (Olive Oil Times, 2013). Traditional olive groves are widespread plantations and usually consist of low planting density which is between 30 and 180 trees per hectare (Sola-Guirado et al., 2014). Intensive olive grove systems have a density between 200 and 600 trees per hectare, on the other hand, super intensive systems have a density between 1,000 and 2,000 trees per hectare. Also, intensive and super intensive systems make possible to harvest entirely with machines (Olive Oil Times, 2013).

Pruning is the process of cutting olive tree branches. Light, medium, and severe pruning can be performed depending on tree age, fruit yield and cultivar variety in order to increase and maintain productivity. Irrigation is applied three times in general: before flowering, when fruits appear and at the time of ripeness. Irrigation prevents oil reduction in olive fruits, increases fruit yield, and enables to cope with alternate bearing (Kour et al., 2018).

Harvest, pruning, and leaf’s falls cause inadequacy in soil's minerals. Fertilization should be applied for desirable yield (Kour et al., 2018). Fertilization program should be decided regarding olive tree age, planting system, and variety (Fernández-Escobar et al., 2013).

Soil management is the soil tillage or harrowing activities for the olive grove surface areas and generally is made a few times a year (Mohamad et al., 2014). Weed control in the olive groves may reduce the harmful impacts of weeds on olive trees and can prepare the surface for the harvesting operations (Olive Oil Source, n.d.-a). There are several insects that can cause damages to fruits and trees such as olive fly. To prevent these damages pesticides are applied (Olive Oil Source, n.d.-b).

Organic olive farming is considered as sustainable or environmental farming option to the conventional farming. In organic farming, farmers use natural fertilizers such as manure, and compost. For conventional farming, farmers use synthetic fertilizers.

Besides that, organic farmers do not use any chemical for pest control, on the other hand, conventional farmers use pesticides. In addition, organic farmers are responsible for implementing the practices to prevent soil erosion, and for maintaining the soil organic matter levels (Berg, Maneas, & Salguero, 2018).

3.4.2 Olive Harvesting

Harvesting operations play a vital role in determining oil quality and quantity (Nasini & Proietti, 2014). Harvest timing differs regarding to geography and year. Harvest time is determined based on the ripeness of the olive fruits. Harvest is performed with manual workers or with the help of mechanical devices (Özdoğan & Tunalioğlu, 2017). The main reasons for mechanization are to reduce the number of workers, the production cost of olives, and harvest time (Amirante, Tamborrino, & Leone, 2012).

Harvesting systems can be classified as follows:

- Hand-picking
- Hand-held harvesting machines
- Trunk shakers
- Straddle harvesters (Nasini & Proietti, 2014).

Olive trees are harvested by long sticks or simply by hand and then fallen olives are collected from on the ground. Sometime ladder can be used to reach high points of the tree. Hand-picking can be applied to any kind of olive groves (size, slope etc.) (Nasini & Proietti, 2014). However, using long sticks can cause damages to the fruits and trees. These tools can affect the quality of the fruits and cause distinct variations of the biennial cycle (Yalçin, Alayunt & Çakmak, 2020). In traditional olive groves, harvesting is mostly performed with manual workers due to the complex and irregular structure of the trees (Sola-Guirado et al, 2014). Figure 3.4 shows the workers who pick olives with their hands.

Figure 3.4 Manual olive harvesting (Proietti & Regni, n.d.)

Harvesting with hand-held machines can be performed with different kinds of machines which vibrate the branches of the tree. Also, hand-held machines can be used in any olive groves (Sola-Guirado et al, 2014; Proietti & Regni, n.d.). Machines are operated by one worker, and other workers manage the nets on the ground (Proietti & Regni, n.d.). These machines can cause worker fatigue and can damage the branches of the tree (Nasini & Proietti, 2014). Figure 3.5 illustrates harvesting with a hand-held harvesting machine.

Figure 3.5 Harvesting with hand-held machine (Proietti & Regni, n.d.)

Before the harvesting begins, nets are placed under tree branches. After, shaker attached tractor grips the trunk of the tree and then vibrates. Following the few seconds of vibration olives are fallen (Wiesman, 2009, chap. 8) as can be seen in Figure 3.6. Trunk shaker can be used in both traditional and intensive olive groves (Fernández-Escobar et al., 2013). The usage of trunk shakers can cause damages on trunk bark (Proietti & Regni, n.d.).

Figure 3.6 Tractor with a trunk shaker (Sola-Guirado et al., 2014)

Straddle harvesters are used in super-intensive olive groves with dwarf cultivar olive trees. (Nasini & Proietti, 2014). Outer spaces of the trees are covered by these machines and by means of several beating heads, trees are harvested (Hafezalkotob, Hami-Dindar, Rabie & Hafezalkotob, 2018). Figure 3.7 shows the continuous form of straddle harvesters. However, olive tree cultivars are limited, and high investment costs are necessary (Nasini & Proietti, 2014).

Figure 3.7 Straddle harvester (Hafezalkotob et al., 2018)

The productivity of the harvesting systems increases regarding to the machine technology. Hand-picking has the least productivity among harvesting systems. After that, with the hand-held harvesting machines, productivity increases. Trunk shakers can harvest more olives than hand-held machines. Ultimately, straddle harvesters have the highest productivity due to continuous form and super-intensive olive groves (Proietti & Regni, n.d.)

3.4.3 Olive Oil Extraction Systems

There are two main olive oil extraction processes: traditional and continuous methods. Although, traditional method has been used for many centuries, during the last decades, modern methods have been applied for oil production mostly (Roig, Cayuela, & Sánchez-Monedero, 2006).

Continuous systems were developed thanks to the technological improvements that have been occurred during the last decades. Majority of the olive mills are operating with continuous systems nowadays (Khdair, Ayoub, & Abu-Rumman, 2015).

3.4.3.1 Traditional Method

For the traditional olive oil extraction process, pressing technique is used. Firstly, olives are washed, then crushed with stones or granite wheels. The obtained olive paste is spread onto disks which are placed on top of each other. Pressurization makes solid and liquid phases to be separated. Lastly, olive oil is separated from wastewater by vertical centrifugation or decanting (Azbar et al., 2004; Kalogianni, Georgiou, & Hasanov, 2019). Figure 3.8 shows the stages in traditional method.

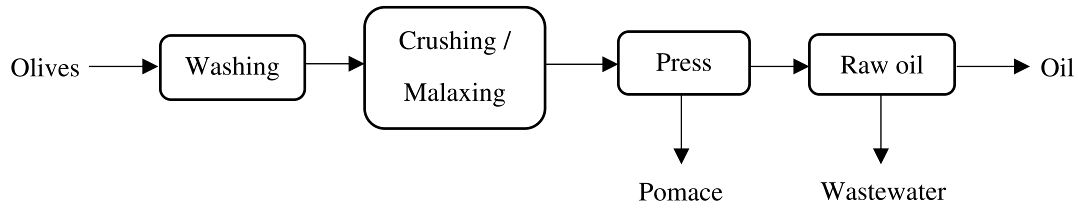

Figure 3.8 Traditional method for olive oil production (Azbar et al., 2004)

3.4.3.2 Modern Methods

In modern methods, horizontal centrifugation systems make it possible to have a continuous process (Azbar et al., 2004).

At first, olives are cleaned and washed in order to remove leaves, stones, dust, soil debris, and any impurities. Then, cleaned olives are crushed and malaxed. Afterwards, the obtained olive paste is placed into decanter where phases are to be separated. Horizontal centrifugation systems are used in the decanters and two decanter systems are available: three-phase and two-phase (Kalogianni et al., 2019).

Three-phase system has some benefits when it is compared to the traditional method. It produces better oil quality, needs smaller areas, and offer complete automation (Roig et al., 2006). Figure 3.9 depicts the stages of three-phase system.

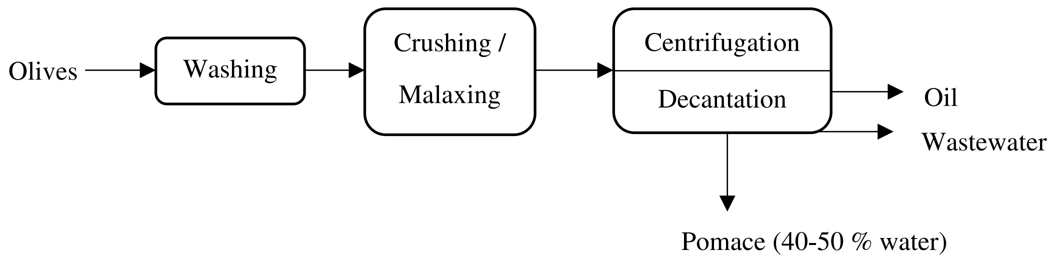

Figure 3.9 Three-phase continuous process (Azbar et al., 2004)

In 1992, a new centrifugation system was developed to reduce water usage and called two-phase because of two fractions which are olive oil and wet pomace (Roig et al., 2006). Figure 3.10 shows the two-phase system.

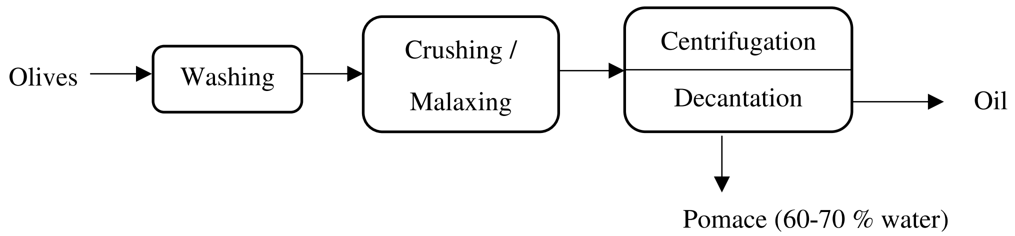

Figure 3.10 Two-phase continuous process (Azbar et al., 2004)

3.4.4 Olive Oil Storage

After extraction process, obtained olive oil should be stored in stainless steel for one to three months in order to settle down sediment and any remaining matter (Vossen, 2007).

Most of the producers consider 12-18 months of storage period. However, produced olive oil is usually consumed before the next harvest and production season (Morelló, Motilva, Tovar & Romero, 2004).

3.5 By-product Management

Olive oil production generates an important quantity of residues that are needed to be managed. However, management of these residues are a difficult task to overcome from economic and environmental perspectives (Christoforou & Fokaides, 2016).

Traditional pressing and three-phase process systems generates three residues: olive pomace, olive oil, and olive mill wastewater. On the other hand, two-phase process system generates two residues: wet pomace and olive oil (Christoforou & Fokaides, 2016; Roig et al., 2006).

Olive oil mill wastewater has severe effects on environment because of the widespread disposal application to the aquatic receivers (Goula & Lazarides, 2015). Chemical treatment, biological treatment, and coupled treatment have been applied to olive mill wastewater to eliminate harmful elements. Therefore, olive mill wastewater can be converted to several products such as bio fertilizer, animal feed, and food supplement (Wiesman, 2009, chap. 10).

Olive pomace consists of olive skins, flesh, seeds, and stones and contains different amount of process water regarding the olive oil extraction process. In addition, generated olive pomace is most likely hazardous to the environment. Thus, after threating olive pomace, it can be used as fuel (Rodrigues, Pimentel & Oliveira, 2015).

Outputs of the olive oil processing systems are shown in Table 3.8.

Table 3.8 Olive oil and waste quantities regarding production processes (Azbar et al., 2004)

Production Process	Input	Amount of input	Output	Amount of output (kg)
Traditional pressing	Olives	1 ton	Oil	~200
	Washing water	0.1-0.12 m^3	Solid waste	~400
			Wastewater	~600
Three–phase process	Olives	1 ton	Oil	200
	Washing water	0.1-0.12 m^3	Solid waste	500-600
	Fresh water for decanter	0.5-1 m^3	Wastewater	1000-1200
Two–phase process	Olives	1 ton	Oil	200
	Washing water	0.1-0.12 m^3	Solid + water waste	800-950

3.6 Olive Oil Quality

There are many factors that affect olive oil quality and some of them are olive cultivar, harvest time, extraction method, olive field's geographic characteristics, and weather conditions during olive growth period (Baccouri et al., 2007).

There are three main analysis for quality determination: physical, chemical, and sensory analysis. Physical analysis is the cleaning of olives from foreign objects like dust and stones when they arrive to the olive oil mill. Because these foreign objects can affect the quality of olive oil. Chemical analysis is done in accredited laboratories and free fatty acids (FFA), peroxide value, and UV absorption characteristics (K232, K270) are evaluated (Özdoğan & Tunalioğlu, 2017). Sensory analysis is done by expert tasters who taste and smell olive oil and rate the different samples (Jiménez, Sánchez-Ortiz, Lorenzo, & Rivas, 2013).

3.7 Types of Olive Oils

There are three main category of olive oils: virgin oil, refined olive oil and olive oil.

3.7.1 Virgin Oil

These types of oils are obtained from olive tree fruits by applying only mechanical and/or physical methods with a thermal condition that do not change the natural qualities of fruits. FFA, expressed as a percentage of oleic acid, are below 3.3 grams per 100 grams. Only processes that fruits can have are washing, decantation, centrifugation, and filtration. Virgin olive oil types and their free acidity levels are presented as follows:

- Extra virgin olive oil

  FFA content is less than 0.8 grams per 100 grams.
- Virgin olive oil

  FFA content is less than 2.0 grams per 100 grams.
- Ordinary virgin olive oil

  FFA content is between 2 and 3.3 per grams per 100 grams.
- Lampante

  FFA content is more than 3.3 grams per 100 grams. This olive oil type is not suitable for human consumption unless it is refined (IOC, n.d.-b; Marmarabirlik, n.d.; Tariş, n.d.).

3.7.2 Refined Olive Oil

It is an olive oil type that is obtained from refining virgin olive oil which contains high acidity level or bad taste and smell. And also, these refining methods do not alter the natural glyceridic structure of the virgin olive oil. FFA content is less than 0.3 grams per 100 grams (IOC, n.d.-b; Marmarabirlik, n.d.; Tariş, n.d.).

3.7.3 Olive Oil

This olive oil is a blend of refined olive oil and virgin olive oil. Its FFA content is less than 1.0 grams per 100 grams (IOC, n.d.-b; Marmarabirlik, n.d.; Tariş, n.d.).

CHAPTER FOUR
PROBLEM DEFINITION AND MATHEMATICAL MODEL

In this chapter of the thesis, studied problem is described and a mathematical model is presented for the solution. Section 4.1 addresses related research gaps and thesis' position in the literature. Section 4.2 explains the considered problem. Section 4.3 presents the proposed model, its assumptions, and the related notations.

4.1 Research Gaps and Thesis' Position

As demonstrated by the amount of recent contributions on harvest and production planning in the AFSC literature presented in Chapter 2, this field has gained a remarkable momentum in the last two decades. Although there is an increasing interest in the optimization applications on agri-food products, there is only a small number of optimization-based studies that have focused on olive oil production. The summary of the reviewed literature on olive oil production is presented in Table 4.1. A number of observations can be made from the reviewed articles.

Harvest planning was considered in three papers (Herrera-Cáceres et al., 2017; Jerić & Šorić, 2010; Jerić & Šorić, 2019). However, Jerić & Šorić (2010; 2019) decide only the periods which farmers should harvest. They did not consider a detailed farmer level harvest planning such as Herrera-Cáceres et al. (2017) who also allocated the harvest crews for the optimal schedule. Nevertheless, harvest planning for the entire harvest season has not been studied yet.

All papers considered production planning for olive processing, except Yurt et al. (2019) who examined olive oil bottling operations and distribution planning. Inventory planning was studied for storing olives to prevent deterioration before the processing stage by Jerić & Šorić (2010; 2019). Herrera-Cáceres et al. (2017) also took into account the perishability of the olives and did not allow the storing of olives. Differently from the other papers, specific time windows for harvesting operations in the olive groves were studied only by Herrera-Cáceres et al. (2017).

Supplier selection decisions were not taken into account in the previous studies. However, Kazaz (2004) and Kazaz & Webster (2011) considered purchasing olives from external sources and yet did not specify the suppliers. So, selecting external farmers to procure olives for oil production has not been considered thus far.

Furthermore, quality levels of olives were addressed by Marchal et al. (2018) to point out the differences in the olive fruit structure throughout the harvest season. Although olive oil quality is an important element of trading, it has not been studied sufficiently. Industrial yield or oil concentration, which is a significant factor for production planning, was incorporated by Herrera-Cáceres et al. (2017) and Marchal et al. (2018) to demonstrate the oil increase in the fruit.

Management of by-products has been neglected by the previous studies. By-products can be used as raw materials to generate different products and thus, can contribute to the other businesses while preventing damages to the environment that are caused by by-products.

There are three papers which incorporated uncertain elements of AFSCs. Kazaz (2004) examined oil demand and olive yield uncertainties, on the other hand, Kazaz & Webster (2011) considered only olive yield uncertainty for oil production. Differently, Marchal et al. (2018) studied the uncertainty in the olive fruit features which affect the quality of olive oil.

In addition, some papers considered various concepts for product differentiation. Jerić & Šorić (2010; 2019) took into account of different olive oil mixes, Herrera-Cáceres et al. (2017) considered multiple olive varieties. Marchal et al. (2018) and Yurt et al. (2019) examined products with different olive oil qualities and packaging methods.

Among examined olive oil studies, green consumers' preference products are not included in any form. Green consumers show a willingness to consume products such as organic, energy-efficient, or recyclable at higher prices (Luzio & Lemke, 2013). In parallel with this argument, incorporating different farming systems into an olive oil supply chain for organic and conventional raw materials has not been studied yet. Ultimately, producing green consumers' preference products can be profitable for producers.

All of the developed models have the same objective, which is maximizing total profit, except Herrera-Cáceres et al. (2017) who aimed to maximize the oil quantity from the harvested olives.

Model types and their solution methods of the addressed studies are also listed in Table 4.1.

Table 4.1 Previous quantitative studies on olive oil production

Authors	Decisions						Features							Objective	Model type	Solution method
	HP	HR	PR	IN	DT	SS	TW	PE	QL	IY	BM	FS	UC			
Kazaz (2004)			X										X	Max. profit	SP	Exact
Jerić & Šorić (2010)	X		X	X				X						Max. profit	MILP	Heuristic
Kazaz & Webster (2011)			X										X	Max. profit	SP	Exact
Herrera-Cáceres et al. (2017)	X	X	X				X	X		X				Max. olive oil	MILP	Exact
Marchal et al. (2018)			X						X	X			X	Max. profit	SP	Exact
Jerić & Šorić (2019)	X		X	X				X						Max. profit	MILP	Meta-heuristic
Yurt et al. (2019)			X		X									Max. profit	IP	Exact
This study	X	X	X			X	X	X	X	X	X	X		Max. profit	MILP	Exact

Not: HP: Harvest planning, HR: Harvest resource allocation, PR: Production planning, IC: Inventory planning, DT: Distribution planning, SS: Supplier selection, TW: Time window, QL: Quality, IY: Industrial yield, BM: By-product management, FS: Farming systems, UC: Uncertainty, SP: Stochastic programming, MILP: Mixed-integer linear programming, IP: Integer programming

The main purpose of this thesis is to develop MILP model for olive harvest and olive oil production planning within AFSC. The developed model may assist small olive oil producers in the decision-making process.

In light of the previous research studies, the contributions of this developed model to the literature are four-fold.

- Integrated harvest and production planning for the entire harvesting season both at the tactical and operational levels is considered.
- Organic and conventional farming systems are adopted for the first time into an olive oil supply chain network study to address green consumers' preferences.
- Olive supplier selection is undertaken to procure olives at higher prices to meet demands.
- By-product management is included to handle the by-products that are hazardous to the environment and contribute to the economy.

4.2 Problem Statement

In this thesis, a harvest and production planning problem is studied with the perspective of a small producer in the olive oil industry. The MILP model is developed based on some of the small producer's operations and restrictions in Ayvalık, Turkey. Olive oil supply chain network consists of several internal (i.e. owned) olive groves, several candidate external olive suppliers (i.e. olive farmers), and one olive oil mill. A multi-period, multi-product olive oil supply chain network is designed both at tactical and operational levels. Olive oil supply chain network problem is shown in Figure 4.1.

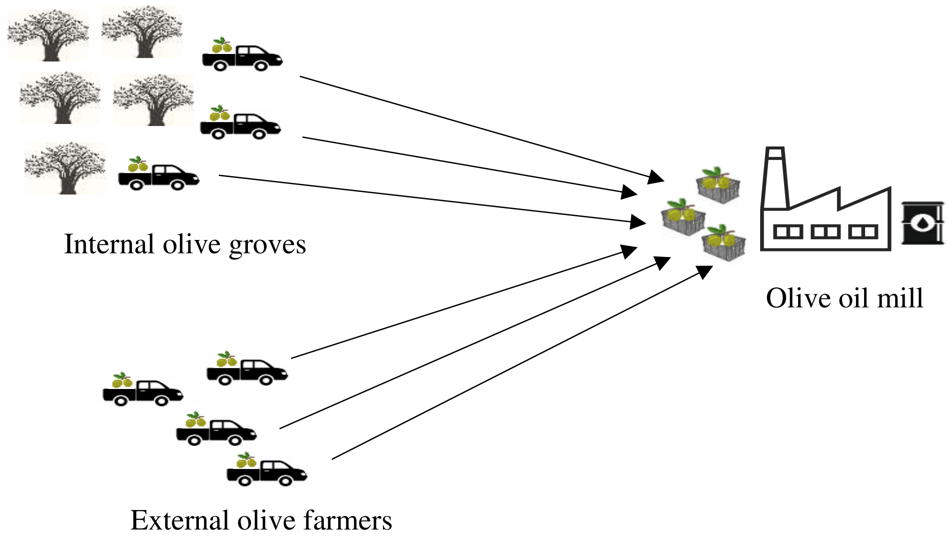

Figure 4.1 Harvest and production network for olive oil

Following short descriptions may help to better understand the problem:

- An *olive grove* is a place where olive trees are planted and grown.
- A *harvesting mode* is a method to harvest olive trees.
- An *olive oil mill* is a plant where olives are processed, and olive oil is obtained.
- A *harvesting window* is the feasible periods for harvesting operations in the olive grove.
- A *harvest crew* is a group of workers who harvest olive trees with appointed resources.
- A *quality level* is the FFA% level.
- A *farming system* is a set of activities performed by farmers.
- A *product* is the olive oil that is classified according to the quality of the oil or processed olives' farming system.
- A *by-product* is a secondary product obtained from processing olives.
- The *planning horizon* is the time interval between the beginning of the harvest season and the end of the harvest season.

This problem considers an olive oil producer who has several traditional olive groves and a two-phase olive oil mill. So, this producer is an olive farmer and also an olive oil producer at the same time. Before the harvesting season begins, olive groves are inspected and expected olive yield is observed. After a while, according to the olive ripeness, the producer decides the beginning of the harvest season.

When harvesting is started, the producer carries out harvesting operations in the internal olive groves. Harvest crews are hired daily, and different harvesting resources, which are owned by the producer, are allocated to the olive groves for operations. Also, a harvest crew can work only in one olive grove per period. Moreover, in an olive grove, only one harvest crew can perform harvesting operations. Generally, harvest crews work with a harvesting machine or without any machine. Capacities of the harvest crews differ because of machine usage and the number of workers. The utility of the resources may be restricted in the olive groves for different reasons. For example, low yield and sloping land can limit the application. In addition to the constraints, the producer limits the harvesting operations to a harvesting window in the olive groves.

The producer aims to harvest all of the expected olives in the internal olive groves. However, internal olive groves' yield may not be adequate for satisfying demands. Thus, the producer may procure harvested olives from external olive farmers who apply organic or conventional olive farming methods to their olive groves. These farmers are small farmers who harvest their olive groves in a short period of time and in small quantities. There are several farmers who sell their harvested olives to several producers to maximize their profits.

Harvested and purchased olives are transported to the olive oil mill in order to convert olives into olive oil products. In the olive oil mill, olive processing is not carried out every day, so production is assigned to certain days in the planning horizon. Hence, harvesting days and purchasing days are coordinated according to production days. Assigned production days also require a minimum quantity of olives for processing to justify using resources at the mill. In addition, harvested olive and purchased olive quantities are determined according to the mill's capacity. The producer does not allow the storing of olives to prevent deterioration and decrease in quality.

After processing olives, products are classified regarding the farming systems and quality levels. Olive oil products mainly differ with respect to acidity levels. At the same time, olive oil obtained from organic raw materials is labeled as organic. On the other hand, olive oil obtained from conventional raw materials is not particularly labeled as conventional olive oil. Maximum demand is determined as the maximum selling capacity for the next one-year period.

Also, simultaneously, wet pomace is produced as a by-product of olive oil in the two-phase olive oil mill. With the intention of by-product management, wet pomace is sold to a pomace factory where it is treated and produced fuel from it.

Olive oil producer aims to maximize the profit which contains several components. Revenue is gained from selling olive oil and wet pomace. Cost components are harvesting cost for internal olive groves, purchasing cost for external olives, variable processing cost, and fixed processing cost. Transportation cost for external olives is included within the purchasing cost. Although olive oil is not immediately sold in the planning horizon, the producer seeks to maximize profit by mostly selling produced olive oil.

After olive oil is produced, the filtration process can take up to a month. Usually, olive oil is stored in drums and then bottled as it is sold. Ultimately, produced olive oil can be sold for two years. Because of the abovementioned reasons, bottling operations and distribution planning are excluded from this study. In addition, olive oil is stored after production, but it does not require any additional storage cost.

For olive oil production, several different configurations exist. Some producers do not purchase olives from other farmers, they process only owned olives at their owned olive oil mill. Some producers only have an olive oil mill, but not olive groves, so they produce olive oil from purchased olives. Some producers only have olive groves, but not an olive oil mill. Thus, they produce olive oil at another producer’s mill. The considered problem is an example of the existing various olive oil supply chain configurations.

A deterministic MILP model is proposed to simultaneously plan the harvest and production operations for the entire harvest season to assist small producers in maintaining profitable and sustainable production. The model contains both tactical and operational level decision variables. These decisions are described as follows:

- Scheduling harvesting operations in the olive groves
- Determining olive quantities to harvest
- Olive supplier selection for purchasing external olives
- Determining olive quantities which will be purchased from external suppliers
- Selecting the harvest and production periods
- Production planning of olive oil
- Determining by-product quantities

4.3 Mathematical Model

A novel MILP model is formulated to solve the olive harvest and olive oil production problem described in the previous section. The model manages both harvest and production operations in the olive oil industry.

The model considers the following assumptions:

- Single olive variety is considered.
- Candidate external olive farmers, their selling capacity, and harvesting windows are known.
- Organic and conventional olives are produced in the olive oil mill separately.
- There are enough storage units for the produced olive oil.
- Fallen olives due to over-ripeness are not taken into account.
- It is presumed that internal and external olives have the same quality levels.

Indices and sets:

$j \in \mathrm{J}$:	Set of internal olive groves
$a \in \mathrm{A}$:	Set of farming systems for candidate olive farmers' olive groves (organic and conventional)
$f \in \mathrm{F}$:	Set of candidate external olive farmers
$F_a \subseteq F$:	Subset of candidate external olive farmers with farming system *a*.
$m \in \mathrm{M}$:	Set of harvesting modes
$k \in K$:	Set of harvest crews
$K_m \subseteq K$:	Subset of harvest crews that belong to the same harvesting mode
$q \in \mathrm{Q}$:	Set of quality levels
$o \in O$:	Set of organic products
$c \in C$:	Set of conventional products
$p \in P$:	Set of products $O \cup C = P$
$t \in T$:	Set of time periods (days)

Parameters:

L_j :	Expected quantity of olives (yield) at olive grove *j* at the beginning of the planning horizon (ton)
OC_t :	Oil concentration of olives at period *t* (percentage)
HP_{jt} :	Harvesting window parameter indicating whether olive grove *j* can be harvested during period *t*. 1, if the harvesting possible, and 0 otherwise
PD_k :	Maximum harvesting capacity of harvest crew *k* per period (ton)
V_k :	Minimum harvesting capacity of harvest crew *k* per period (ton)
QC_{qt} :	Quality parameter indicating that quality level *q* is provided at period *t*. 1, if olives provide quality level *q* at period *t*, and 0 otherwise
N_t :	Minimum olive quantity required at period *t* if production exists in that period (ton)
B_{jm} :	1, if olive grove *j* can be harvested with harvesting mode *m*, and 0 otherwise
TP :	Total processing capacity of the mill per period (ton)

R_m : Minimum quantity of olives to be harvested with harvesting mode *m* during planning horizon (ton)

MC_{ft} : Maximum quantity of olives that candidate olive farmer *f* can sell at period *t* (ton)

G_{ft} : Minimum quantity of olives that candidate olive farmer *f* can sell at period *t* (ton)

$Wmin_p$: Minimum quality level for product *p*

$Wmax_p$: Maximum quality level for product *p*

$Dmax_p$: Maximum demand for product *p* (ton)

PR : Wet pomace conversion rate (percentage)

CM_k : Cost of harvest crew *k* (TL/ton)

FP_f Cost of buying external olives from olive farmer *f* (TL/ton)

PC : Variable cost for processing olives at the mill per period (TL/ton)

FC : Fixed cost for processing olives (TL)

S_p : Selling price for product *p* (TL/ton)

BP_p : Selling price for wet pomace (TL/ton)

M : A "big M" value

Decision variables:

x_{jtk} : Quantity of olives harvested from olive grove *j* at period *t*, with harvest crew *k* (ton)

h_{jtk} : 1, if olive grove *j* harvested during period *t* with harvest crew *k*, 0 otherwise

VF_{ft} : Quantity of olives purchased from olive farmer *f* at period *t* (ton)

w_t : 1, if harvesting exists in the period *t*, 0 otherwise

E_{ft} : 1, if olives are purchased from olive farmer *f* at period *t*, 0 otherwise

OP_{qt}^{a} : Olive oil quantity produced with quality *q* from farming practice *a* at period *t* (ton)

Z_{pt} : Amount of product *p* produced at period *t* (ton)

WP_t : Amount of wet pomace produced at period *t* (ton)

Objective function:

$Maximize : TR - TC$

$$TR = \sum_{p}\sum_{t} S_p * Z_{pt} + \sum_{t} BP_t * WP_t \tag{4.1}$$

$$\begin{aligned} TC = \sum_{j}\sum_{t}\sum_{k} CM_k * x_{jtk} + \sum_{f}\sum_{t} FP_f * VF_{ft} + \sum_{t} FC * w_t \\ + PC * (\sum_{j}\sum_{t}\sum_{k} x_{jtk} + \sum_{f}\sum_{t} VF_{ft}) \end{aligned} \tag{4.2}$$

The objective function aims to maximize total profit. Maximization of profit consists of two components: total sales revenue and total cost. Equation 4.1 and Equation 4.2 present total sales revenue and total cost, respectively. Total sales revenue is obtained from olive oil and wet pomace sales, respectively. Equation 4.2 represents the total cost. The total cost is composed of four components. These are harvesting cost, purchasing cost, fixed processing cost, and variable processing cost, respectively.

Constraints:

The constraints of the mathematical model are provided with several categories as follows.

Harvest planning constraints:

$$h_{jtk} \leq B_{jm} \qquad \forall j \in J, \forall t \in T, \forall m \in M, \forall k \in K_m \tag{4.3}$$

Constraint (4.3) allows that the olive groves can only be harvested with the feasible harvesting mode which belongs to the olive grove.

$$h_{jtk} \leq HP_{jt} \qquad \forall j \in J, \forall t \in T, \forall k \in K \tag{4.4}$$

Constraint (4.4) permits that harvesting activities take place only within the harvesting window.

$$\sum_{j} \sum_{k} h_{jtk} \leq w_t * M \qquad \forall t \in T \tag{4.5}$$

Constraint (4.5) ensures that harvesting exists in that period if harvesting takes place in the olive groves.

$$\sum_{j} h_{jtk} \leq 1 \qquad \forall t \in T, \forall k \in K \tag{4.6}$$

Constraint (4.6) imposes that a harvest crew can only work in at most one olive grove per period.

$$\sum_{k} h_{jtk} \leq 1 \qquad \forall j \in J, \forall t \in T \tag{4.7}$$

Constraint (4.7) guarantees that each olive grove can only be harvested by at most one harvest crew at each period.

Harvest capacity constraints:

$$x_{jtk} \geq V_k * h_{jtk} \qquad \forall j \in J, \forall t \in T, \forall k \in K \tag{4.8}$$

Constraint (4.8) specifies that harvested quantity must be greater or equal than the minimum harvesting capacity.

$$x_{jtk} \leq PD_k * h_{jtk} \qquad \forall j \in J, \forall t \in T, \forall k \in K \tag{4.9}$$

Constraint (4.9) guarantees that harvested quantity of olives cannot be greater than the harvest crew's maximum harvesting capacity.

$$\sum_{j}\sum_{t}\sum_{k\in K_m} x_{jtk} \geq R_m \qquad \forall m \in M \tag{4.10}$$

Constraint (4.10) ensures the minimum utilization of each harvesting mode for the planning horizon.

$$\sum_{t}\sum_{k} x_{jtk} = L_j \qquad \forall j \in J \tag{4.11}$$

Constraint (4.11) ensures that the total harvested quantity of olives must be equal to the total expected quantity for each olive grove.

Production planning constraints:

$$\sum_{j}\sum_{k} x_{jtk} + \sum_{f} VF_{ft} \geq w_t * N_t \qquad \forall t \in T \tag{4.12}$$

Constraint (4.12) provides that total harvested quantity and purchased olives from external farmers must be equal or greater than the required minimum quantity from the mill per period if harvesting and production exist.

$$w_t \geq E_{ft} \qquad \forall f \in F, \forall t \in T \tag{4.13}$$

Constraint (4.13) imposes that external olives can only be purchased if harvesting exists in that period.

$$VF_{ft} \leq MC_{ft} * E_{ft} \qquad \forall f \in F, \forall t \in T \tag{4.14}$$

Constraint (4.14) ensures that if olives are purchased from external olive farmers, purchased olive quantity should be equal or less than their capacity.

$$VF_{ft} \geq G_{ft} * E_{ft} \qquad \forall f \in F, \forall t \in T \tag{4.15}$$

Constraint (4.15) guarantees that if olives are purchased from external olive farmers, purchased olive quantity should be equal or greater than their lower bound.

$$\sum_{j}\sum_{k} x_{jtk} + \sum_{f} VF_{ft} \leq TP \qquad \forall t \in T \tag{4.16}$$

Constraint (4.16) enforces that total olive quantity should be equal or less than the processing capacity of the mill per period.

Production constraints:

$$\sum_{f \in F_{org}} VF_{ft} * QC_{qt} * \ OC_t = OP_{qt}^{a=org} \qquad \forall q \in Q, \forall t \in T \tag{4.17}$$

Constraint (4.17) calculates organic olive oil quantity produced from external olives according to the quality levels.

$$(\sum_{j}\sum_{k} x_{jtk} + \sum_{f \in F_{conv}} VF_{ft}) * QC_{qt} * OC_t = OP_{qt}^{a=conv} \qquad \forall q \in Q, \forall t \in T \tag{4.18}$$

Constraint (4.18) calculates the quantity of olive oil from conventionally grown olives.

$$\sum_{Wmin_p \leq q \leq Wmax_p} OP_{qt}^{org} = Z_{pt} \qquad \forall p \in O, \forall t \in T \tag{4.19}$$

Constraint (4.19) defines organic olive oil products.

$$\sum_{Wmin_p \leq q \leq Wmax_p} OP_{qt}^{conv} = Z_{pt} \qquad \forall p \in C, \forall t \in T \tag{4.20}$$

Constraint (4.20) represents the olive oil products produced from conventionally grown olives.

$$WP_t = \left(\sum_j \sum_k x_{jtk} + \sum_f VF_{ft} \right) * PR \qquad \forall t \in T \tag{4.21}$$

Constraint (4.21) calculates the generated wet pomace quantity.

Demand constraints:

$$\sum_t Z_{pt} \leq Dmax_p \qquad \forall p \in P \tag{4.22}$$

Constraint (4.22) restricts the maximum production quantity for each product.

Type of decision variables constraints:

$$h_{jtk}, E_{ft}, w_t \in \{0,1\} \quad \forall j \in J, \forall t \in T, \forall k \in K, \forall f \in F \tag{4.23}$$

$$\begin{gathered} x_{jtk}, VF_{ft}, OP_{qt}^{a}, Z_{pt}, WP_t \geq 0 \\ \forall j \in J, \forall t \in T, \forall k \in K, \forall p \in P, \forall f \in F, \forall a \in A, \forall q \in Q \end{gathered} \tag{4.24}$$

Constraints (4.23) and (4.24) correspond to the integrality and non-negativity on the decision variables, respectively.

CHAPTER FIVE
COMPUTATIONAL EXPERIMENTS

In this chapter, a hypothetical case study is provided to validate the developed model. Besides, computational results of the scenario analysis and sensitivity analysis are evaluated. This chapter is organized as follows. Section 5.1 presents a case study inspired by real life. Section 5.2 presents the computational results of the case study. Section 5.3 examines an extended version of the developed model that includes severe climatic damages. Section 5.4 addresses the sensitivity analysis to show the impacts of changes in several parameters. Section 5.5 summarizes the computational experiments.

5.1 Case Study

In this section, a hypothetical case study is presented to validate and demonstrate the applicability of the proposed model. In order to provide a better understanding of the problem, a case study inspired by the olive oil producers in Ayvalık, Turkey is considered.

An AFSC network that consists of an olive oil producer who owns 12 traditional olive groves and one olive oil mill is considered. Conventional farming methods are used in the olive groves. All of the olive groves are located in Ayvalık county. Olive groves' yields are ranging between 8.8 and 42.3 tons. Two of the olive groves are on sloping land, so trunk shaker cannot be operated properly. Moreover, two of the olive groves have yielded less than 20 tons, so the producer does not allow machine usage in these olive groves. The producer permits any machine usage in the olive groves with more than 20 tons of olives. The planning horizon of harvest and production operations is determined between November 4 and December 29, 2019, in a total of 56 days. In addition, the producer allows the harvesting operations in the olive groves at different time intervals. Olive groves' yields, permitted harvesting modes, and harvesting windows are presented in Table 5.1.

Table 5.1 Internal olive grove specifications

Olive grove	Expected yield (tons)	Harvesting mode	Harvesting window (days)
1	28	1-2-3	[15-42]
2	36.5	1-2-3	[1-35]
3	20.3	2-3	[15-56]
4	42.3	1-2-3	[1-14]
5	8.8	3	[22-56]
6	40.3	1-2-3	[22-49]
7	33.4	2-3	[8-42]
8	35	1-2-3	[22-49]
9	39.6	1-2-3	[29-56]
10	40	1-2-3	[22-56]
11	25	1-2-3	[1-21]
12	18.3	3	[29-42]

The producer owns several harvesting machines and hires harvest crews daily to carry out harvesting operations in the olive groves. For this problem, three types of harvesting modes are considered, namely, trunk shaker, hand-held shaker, and manual mode. There are four harvesting crews. First harvest crew has 5 workers and a trunk shaker as a harvesting machine. Firstly, olive trees are vibrated with a trunk shaker by one worker, and then fallen olives are collected from the ground by four workers. Second crew has 10 workers with two hand-held harvesting machines. Two workers use the machines to vibrate the branches of the trees, and other workers collect the fallen olives from the ground. Third and fourth crews do not have any machine, so they harvest trees with their hands and sticks. Approximately, a worker collects a minimum of 100 kg of olives and a maximum of 120 kg of olives daily. Based on this information, estimated harvesting capacities are calculated. Harvesting costs are calculated based on the daily average cost, which is 80 TL. Data related to harvest crew configurations, minimum and maximum harvesting capacities, and harvesting costs are presented in Table 5.2.

Table 5.2 Harvest crew specifications

Harvest crews		Harvesting mode	Minimum harvest quantity (tons)	Maximum harvest quantity (tons)	Cost (TL/ton)
hc1	Trunk shaker + 5 workers	1	10	14	50
hc2	2 hand-held machines + 10 workers	2	4	6	225
hc3	20 workers	3	2	3	800
hc4	15 workers	3	1.5	2.25	800

The producer requests a minimum harvested olive quantity from each harvesting mode for the planning horizon in order to justify the utilization. Minimum harvesting quantities are 80 tons for harvesting mode 1, 60 tons for harvesting mode 2, and 40 tons for harvesting mode 3.

When internal olive groves' yield is not adequate for production requirements, the producer may purchase olives from external olive farmers. Generally, olive farmers harvest their olive groves in a short period of time and may sell their olives to several oil producers. External farmers' olive groves are also located in Ayvalık county and in very close areas. Six olive farmers apply organic farming methods and 12 farmers apply conventional farming methods to their olive groves. Each farmer may sell olives between a lower and an upper bound at previously determined harvesting periods. Generally, organic farmers have less olive grove spaces and therefore, produce less olive fruits than conventional olive farmers. Also, each farmer has a specific cost per ton of olives. Organic olive farmers have higher selling prices than conventional olive farmers due to the organic farming methods' higher costs. In addition, organic farmers harvest olive trees in November to prevent quality decay. Organic extra virgin olive oil is considerably more demanded than organic virgin olive oil by the market. Therefore, organic olive farmers sell their olives in November, thereby organic extra virgin olive oil can be produced. Candidate external olive farmers' features are demonstrated in Table 5.3.

Table 5.3 Candidate external olive farmers specifications

External olive farmers	Farming system	Minimum selling quantity (ton/period)	Maximum capacity (ton/period)	Cost (TL/ton)	Periods
1	Organic	0.5	2	6200	[8-21]
2	Organic	0.5	1	6100	[1-7]
3	Organic	0.5	3	6300	[1-7]
4	Organic	0.4	1	6250	[8-14]
5	Organic	0.6	2	6400	[15-21]
6	Organic	1	3	6600	[8-21]
7	Conventional	1	3	5000	[1-7]
8	Conventional	1	4	5050	[8-14]
9	Conventional	1	5	5150	[15-21]
10	Conventional	1	6	5200	[22-28]
11	Conventional	1	5	4800	[29-35]
12	Conventional	2	7	4850	[36-42]
13	Conventional	1	6	5450	[8-14]
14	Conventional	1	5	4950	[43-49]
15	Conventional	1	3	4900	[43-56]
16	Conventional	1	5	5250	[22-28]
17	Conventional	1	5	5000	[8-21]
18	Conventional	1	4	5040	[22-35]

Variable and fixed processing costs are considered. Variable processing cost addresses electricity and water consumption which are necessary for the processing of olives. Electricity and water consumption and their corresponding costs are shown in Table 5.4.

Table 5.4 Electricity and water required for processing operations

	Value	Source
Electricity consumption	37.785 kWh/ton olive	Pattara, Salomone, & Cichelli (2016)
Electricity cost	0.809789 TL/kWh	Enerji Atlası, (2020)
Water consumption	0.25 m^3/ton olive	Borja, Raposo & Rincón (2006)
Water cost	12.71 TL/m^3	ASKİ, (2019)

Fixed processing cost includes the extra personnel cost who are hired for the processing operations and maintenance cost for olive processing machines. Permanent worker cost is not included, because this cost is independent from the production operations. Variable and fixed costs are indicated in Table 5.5.

Table 5.5 Variable and fixed costs

	Value	Source
Variable processing cost (TL/ton)	32.1026 TL	Table 5.3
Fixed processing cost (TL/day)	3000 TL	Assumption

Processing capacity of olive oil mill is set to 20 tons per day. Concurrently, if harvesting and purchasing take place, producer requests at least 10 tons of olives to process for more efficient use of the mill.

Oil concentration (i.e. industrial yield) and FFA% values are generated according to several studies (Bustan et al., 2014; Dag et al., 2011; Garcia, Seller, & Perez-Camino, 1996; Gündoğdu, 2018). Previous studies, which study on olive fruits and its features, usually calculated these values on a weekly or on a monthly basis, however, this case study considers daily information. An analysis carried out on oil concentration and then, daily oil concentration values are derived. However, FFA% levels are determined on a weekly basis because of the small decimal numbers. Figure 5.1 shows the oil quantity in the olives for each period.

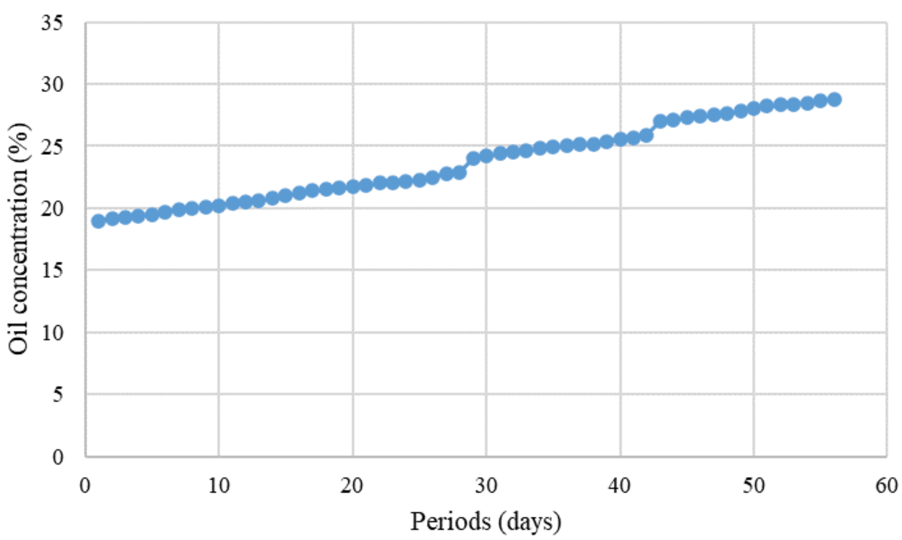

Figure 5.1 Oil concentration throughout the planning horizon

It is presumed that FFA% levels are the same for 7-day periods. As can be seen in Figure 5.2, FFA% levels are increasing as time progresses.

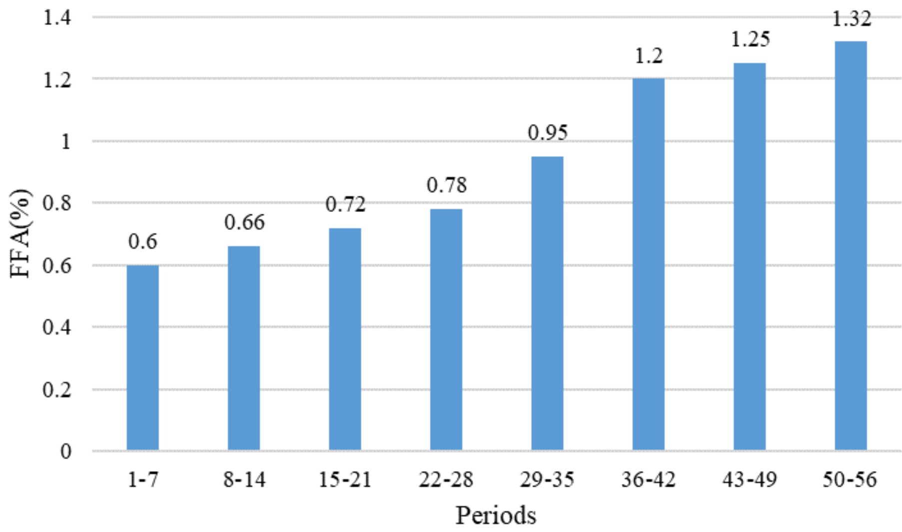

Figure 5.2 FFA% levels throughout planning horizon

Produced olive oil is categorized according to olive grove farming methods and acidity levels. Only organic product is organic extra virgin olive oil. Conventional products are extra virgin olive oil and virgin olive oil. From Figure 5.2, we can conclude that extra virgin olive oil products can be produced until the end of the period 28, and virgin olive oil products can be produced between the periods 29 and 56.

Demand is the maximum selling capacity for each product that can be sold in a one-year period. Prices are addressed for each ton of olive oil products. Demand and prices are assumptions from the market observations. Quality requirements, product demand, and prices are shown in Table 5.6.

Table 5.6 Olive oil product specifications

	Olive oil	Quality (FFA%)	Demand (tons)	Price
Product 1	Organic extra virgin olive oil	$\leq$ 0.8	8	65,000 TL/ton
Product 2	Extra virgin olive oil	$\leq$ 0.8	72	32,000 TL/ton
Product 3	Virgin olive oil	0.8 – 2.0	40	22,000 TL/ton

Concurrently, wet pomace is produced as a by-product of olive oil in the two-phase olive oil mill. Wet pomace conversion rate and selling price to the pomace factory are shown in Table 5.7.

Table 5.7 Wet pomace specifications

	Value	Source
Wet pomace conversion rate	875 kg/ton olive	Azbar et al. (2004)
Wet pomace price	100 TL/ton	Assumption

5.2 Results of the Case Study

The MILP model formulation has been implemented and solved using IBM ILOG CPLEX Optimization Studio 12.10 software on AMD A9-9420 CPU @3-3.6 GHz and 4 GB RAM personal computer.

The model consists of 4,872 continuous variables, 3,752 binary variables, 16,034 constraints, and which was solved in approximately 27 seconds.

Optimum results of the case study are presented in the following tables. The optimal value of the objective function is 2,822,842.845 TL. Revenue and cost related results are presented in Table 5.8 and Table 5.9, respectively.

Objective function: Total Revenue (TR) - Total Cost (TC) = 2,822,842.845 TL

Table 5.8 Revenues of the harvest and production network

Total revenue (TL)	Olive oil revenue (TL)	Wet pomace revenue (TL)
3,748,841.543	3,704,000	44,841.543

Table 5.9 Costs of the harvest and production network

Total cost (TL)	Harvesting cost (TL)	Variable processing cost (TL)	Fixed cost (TL)	Purchasing cost (TL)
925,998.698	58,875	16,451.773	81,000	769,671.925

The color assignments of the harvest crews for differentiation are demonstrated in Table 5.10. Allocated harvest crews to the olive groves are demonstrated in Table 5.11. Harvesting window of each olive grove is shaded in grey in this table and harvest crews are stated in different colors.

Table 5.10 Color assignments of the harvest crews

hc1	hc2	hc3	hc4

27 periods out of 56 periods are used for harvesting and processing activities. Harvest and production operations start in period 10 and end in period 56. Organic extra virgin olive oil is produced between periods 10 and 21. Extra virgin olive oil is produced between periods 10 and 28. On the other hand, virgin olive oil is produced between periods 47 and 49 and between periods 52 and 56. Since oil accumulation in the olive fruits is increasing over the planning horizon, olive oil products are produced at periods in which oil yield is higher.

37.9 tons of organic olives are purchased from external olive farmers to produce 8 tons of organic extra virgin olive oil. 107.07 tons of conventionally grown olives are purchased to meet the maximum selling capacity of extra virgin olive oil and virgin olive oil. In 25 periods out of 27 active periods, external olives are purchased from olive farmers to produce more olive oil. Organic olives are purchased from farmers 1, 3, and 5 with ranging volumes. Conventionally grown olives are purchased from farmers 8, 14, 15, 17, 18. For organic olives, the least purchased quantity is 5 tons from farmer 4 and the most purchased quantity is 24 tons from farmer 1. For conventional olives, the least purchased quantity is 4.84 tons from farmer 8 and the most purchased quantity is 58.15 tons from farmer 17. Purchasing olives from external olive farmers are mostly decided according to their selling capacities and harvesting windows. Details of the purchased olive quantities are shown in Appendix 2 and external olive farmers' harvesting windows are shaded in grey.

Purchasing from external olive farmers are dependent on the selling capacity. If the producer decides the produce less olive oil, purchasing olives from external farmers may not exists. Otherwise, if the producer decides to produce more olive oil, more olives can be purchased from external olive farmers.

In total, 512.47 tons of olives are processed in the olive oil mill. 367.5 tons of olives are from internal olive groves and 144.97 tons of olives are from external olive groves. That is to say, for the entire production season, 45.75% of the processing capacity is utilized. In Turkey, olive oil mills work considerably under their capacity limits (Hocaoğlu, Baştürk, Haksevenler & Aydöner, 2017). Therefore, it can be concluded that the data used is realistic. Moreover, only in 4 periods, olive oil mill does not process at full capacity.

Additionally, generated wet pomace quantities are also shown in Table 5.11.

Table 5.11 Optimal harvest and production plan for case study (All quantities are expressed in tons)

	Planning horizon																				
Olive grove	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1																			10		
2																				11	11.5
3																					
4											12	12	6	12.3							
5																					
6																	12.4	11.75			
7										1.5					2						
8													2.25								
9																					
10																					
11															11	12.5			1.5		
12																					
Internal										1.5	12	12	8.25	12.3	13	12.5	12.4	11.75	11.5	11	11.5
External (org.)										3	3	3	3	3	2	2.6	2.6	3.7	4	4	4
External (conv.)										6.09	5	5	8.75	4.7	5	4.9	5	4.55	4.5	5	4.5
Total										10.59	20	20	20	20	20	20	20	20	20	20	20
Product 1										0.606	0.612	0.615	0.618	0.624	0.42	0.5512	0.5564	0.7934	0.864	0.868	0.872
Product 2										1.534	3.468	3.485	3.502	3.536	3.78	3.6888	3.7236	3.5066	3.456	3.472	3.488
Product 3										-	-	-	-	-	-	-	-	-	-	-	-
Wet pomace										9.2698	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5

Table 5.11 continues

Olive grove	Planning horizon																				
	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
1				12.6	5.4																
2		14																			
3																					
4																					
5																					
6		2.15	14																		
7	6		6	4.45	1.6	5.85	6														
8																					
9																					
10	10				10	10	10														
11																					
12	3	2.85		1.95	3	3	3														
Internal	19	20	20	19	20	18.85	19														
External (org.)	-	-	-	-	-	-	-														
External (conv.)	1	1	-	1	-	1.15	1														
Total	20	20	20	20	20	20	20														
Product 1	-	-	-	-	-	-	-														
Product 2	4.4	4.42	4.44	4.46	4.5	4.56	4.58														
Product 3	-	-	-	-	-	-	-														
Wet pomace	17.5	17.5	17.5	17.5	17.5	17.5	17.5														

Table 5.11 continues

	Planning horizon														
Olive grove	43	44	45	46	47	48	49	50	51	52	53	54	55	56	Total
1															28
2															36.5
3										6	6	4	4.3		20.3
4															42.3
5										1.5	2.3	2		3	8.8
6															40.3
7															33.4
8					10.18	12	10.57								35
9											1.9	11	12.7	14	39.6
10															40
11															25
12							1.5								18.3
Internal					10.18	12	12.07			7.5	10.2	17	17	17	367.5
External (org.)					-	-	-			-	-	-	-	-	37.9
External (conv.)					8	8	7.93			3	3	3	3	3	107.07
Total					18.18	20	20			10.5	13.2	20	20	20	512.47
Product 1					-	-	-			-	-	-	-	-	8
Product 2					-	-	-			-	-	-	-	-	72
Product 3					4.9997	5.52	5.56			2.9715	3.7488	5.7	5.74	5.76	40
Wet pomace					15.9081	17.5	17.5			9.1875	11.55	17.5	17.5	17.5	448.4154

Total harvested olive quantities and the number of activity periods of harvest crews are shown in Table 5.12. All of the yields of the olive trees are harvested. The mostly used harvest crew is hc1, because of the bigger harvesting capacity and lower harvesting cost. In addition, requested minimum olive quantities from harvesting modes 2 and 3 are provided, but considerably more olives are harvested by harvesting mode 1.

Table 5.12 Harvest crew utilizations

Harvest crews		Harvesting mode	Harvested olives (tons)	No. of activity periods
hc1	Trunk shaker + 5 workers	1	267.5	23
hc2	2 hand-held machines +10 workers	2	60	11
hc3	20 workers	3	24.15	9
hc4	15 workers	3	15.85	9

5.3 Scenario Analysis for Severe Climate Conditions

The harvest season of olive trees is within the wintertime in Turkey, therefore severe weather conditions can affect the olive fruits and can cause damages for producers. Heavy rain and wind can damage the branches of the trees, and olive fruits can detach from the branches. Ultimately, olives could be lost under those conditions. This approach was used by Herrera-Cáceres et al. (2017) and we also consider the relevant parts of their mathematical model to examine severe weather situations.

For the climate condition scenarios, an initial day is included for the new decision variable. Also, the total expected olives cannot be harvested under these conditions, so constraint (4.11) is changed to permit olive loss and to ensure model's accuracy. New set and index, parameter, decision variable and constraints are presented as follows:

Set and index:

$t \in T$ Set of time periods (days). An initial day is considered as 0, then T′= {0,1…. T}

Parameter:

OL_{jt} : Olive loss by the weather conditions in olive grove j at period t (percentage)

Decision variable:

FO_{jt} : Quantity of olives left in the olive grove j at the end of period t. (ton) $t \in \mathrm{T}'$

Olive availability constraints:

$$FO_{j0} = L_j \qquad \forall j \in J \tag{5.1}$$

Constraint (5.1) indicates that olive quantities left in the olive groves at the start of the planning horizon are equal to the expected olive quantities. Let us remind that L_j represents the olive quantities in the olive groves at the beginning of the planning horizon.

$$FO_{jt} = FO_{j(t-1)} * \left(1 - OL_{jt}\right) - \sum_{k} x_{jtk} \qquad \forall j \in J, \forall t \in T \tag{5.2}$$

Constraint (5.2) determines the quantity of olives left at the olive groves.

$$\sum_{t}\sum_{k} x_{jtk} \leq L_j \qquad \forall j \in J \tag{5.3}$$

Constraint (5.3) is the necessary change of constraint (4.11).

$$FO_{jt} \geq 0 \quad \forall j \in J, \forall t \in \mathrm{T}' \tag{5.4}$$

Constraint (5.4) enforces to correspond to decision variable.

For the scenario analysis, the model presented in section 4.3 has been extended by adding the new constraints (5.1) - (5.4). Note that constraint (4.11) was replaced by the constraint (5.3). Two scenarios are created in order to test and demonstrate the applicability of the extended model where threatening weather conditions take place at earlier and later periods in the planning horizon.

5.3.1 Scenario 1

For scenario 1, severe climate conditions are considered between periods 21 and 25. Figure 5.3 shows the olive loss as the percentage of olives left in the olive groves. Also, it is assumed that climate conditions affect several olive groves, but not all of them. For scenario 1, olive groves 1, 2, 3, 6, 7, 10, 11, and 12 are affected.

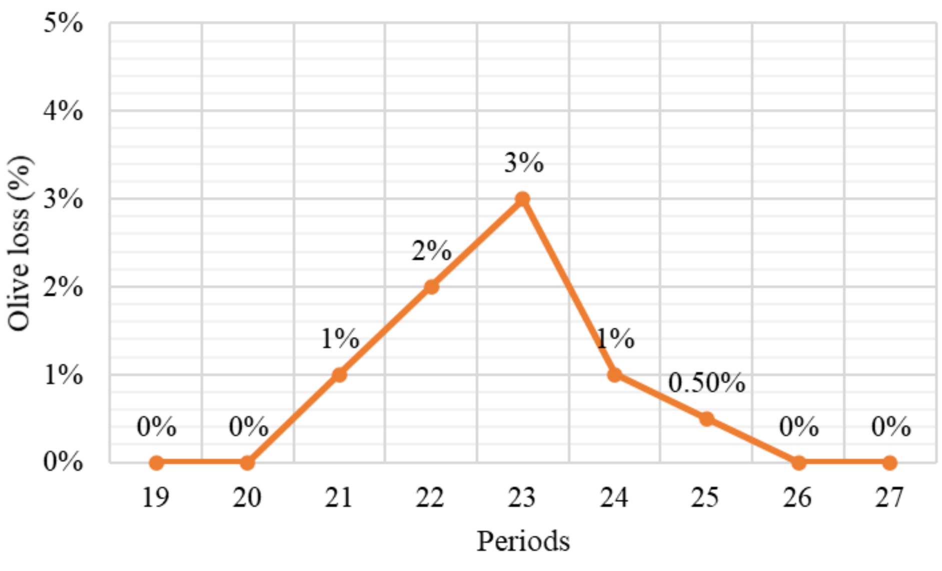

Figure 5.3 Olive loss for scenario 1

According to computational results for scenario 1, again, there are 27 active periods for harvesting and processing operations, but olive supply network and the allocation of the harvest crews have been changed compared to the base case, which is the case study results presented in section 5.2. Revenues and cost related outcomes are presented in Table 5.13 and Table 5.14, respectively. Objective function is decreased by 1.01% and found as 2,783,145.511 TL. Because of the decreased olive quantity in the internal olive groves, purchased olive quantity is increased by 4.17%. 151.02 tons of olives have been purchased to produce the maximum demand, accordingly, purchasing cost is increased. Wet pomace revenue, variable processing cost, and harvesting cost also changed.

Table 5.13 Revenues of scenario 1

Total revenue (TL)	Olive oil revenue (TL)	Wet pomace revenue (TL)
3,748,871.522	3,704,000	44,871.522

Table 5.14 Costs of scenario 1

Total cost (TL)	Harvesting cost (TL)	Variable processing cost (TL)	Fixed cost (TL)	Purchasing cost (TL)
965,726.011	58,589.866	16,462.772	81,000	809,673.373

Organic extra virgin olive oil is produced between periods 10 and 21 and extra virgin olive oil is produced between periods 10 and 28. On the other hand, virgin olive oil is produced between periods 46 and 49 and between periods 53 and 56.

Harvesting operations in the olive grove 2 have been changed and completed before the olive loss could occur, thereby olive loss did not happen. In other olive groves except olive grove 11, harvesting operations have been carried out in the later periods, consequently, olive loss is incurred. In the results of the base case and scenario 1, olives have been harvested before the olive loss could take place in the olive grove 11. Olive loss occurred in the olive groves are indicated in Table 5.15 and olive groves affected by the weather conditions are shaded in grey. Optimal harvest and production network for scenario 1 is presented in Table 5.16. Harvest crews have already been displayed in Table 5.10.

Table 5.15 Olive loss for scenario 1

Olive grove	Olive loss (%)
1	2.93
2	0
3	6.51
4	0
5	0
6	1.07
7	0.87
8	0
9	0
10	4.98
11	0
12	4.65

Table 5.16 Optimal harvest and production plan for scenario 1 (All quantities are expressed in tons)

	Planning horizon																				
Olive grove	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1																		14			
2											12.33	14							10.17		
3															2.25						
4										11.05	1.5	2.75	13	14							
5																					
6															11.87					14	
7													4	3	4	4	5.75		5.83		
8																					
9																					
10																					13.85
11																14	11				
12																		2.25		2	2.15
Internal										11.05	13.83	16.75	17	17	18.12	18	16.75	16.25	16	16	16
External (org.)										3	3	3	3	3	1.88	2	3.25	3.75	4	4	4
External (conv.)										-	-	-	-	-	-	-	-	-	-	-	-
Total										14.05	16.82	19.75	20	20	20	20	20	20	20	20	20
Product 1										0.606	0.612	0.615	0.618	0.624	0.395	0.424	0.696	0.806	0.864	0.868	0.872
Product 2										2.233	2.821	3.433	3.502	3.536	3.805	3.816	3.584	3.494	3.456	3.472	3.488
Product 3										-	-	-		-	-	-	-	-	-	-	-
Wet pomace										12.2971	14.7256	17.2779	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5

Table 5.16 continues

	Planning horizon																				
Olive grove	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
1		13.18																			
2																					
3																					
4																					
5																					
6	14																				
7	4.53						2														
8						5.59															
9																					
10			10	4.16	10																
11																					
12		2.82		1.5			3														
Internal	16.53	16	10	5.66	10	5.59	5														
External (org.)	-	-	-	-	-	-	-														
External (conv.)	1.47	4	10	14.34	10	14.41	15														
Total	20	20	20	20	20	20	20														
Product 1	-	-	-	-	-	-	-														
Product 2	4.4	4.42	4.44	4.46	4.5	4.56	4.58														
Product 3	--	-	-	-	-	-	-														
Wet pomace	17.5	17.5	17.5	17.5	17.5	17.5	17.5														

Table 5.16 continues

Olive grove	43	44	45	46	47	48	49	50	51	52	53	54	55	56	Total
	Planning horizon														
1															27.18
2															36.5
3											6	4.73		6	18.98
4															42.3
5					2.8						3		3		8.8
6															39.87
7															33.11
8					5.41	12	12								35
9											2.25	12.27	14	11.08	39.6
10															38.01
11															25
12				2	1.73										17.45
Internal				2	9.94	12	12				11.25	17	17	17.08	361.8
External (org.)				-	-	-	-				-	-	-	-	37.88
External (conv.)				8	8	8	8				3	3	3	2.92	113.14
Total				10	17.94	20	20				14.25	20	20	20	512.82
Product 1				-	-	-	-				-	-	-	-	8
Product 2				-	-	-	-				-	-	-	-	72
Product 3				2.74	4.933	5.52	5.56				4.047	5.7	5.74	5.76	40
Wet pomace				8.75	15.6959	17.5	17.5				12.4688	17.5	17.5	17.5	448.7153

Since olive loss takes place between periods 21 and 25, the number of harvesting operations is decreased after period 21. The number of harvesting operations before period 21 is increased. In the results of the case study, purchased olive quantities between the periods 21 and 28 are very small. On the other hand, external olive quantities are considerably higher in the results of scenario 1.

5.3.2 Scenario 2

For scenario 2, severe climate conditions occur in the later parts of the planning horizon. Olive loss percentages are shown in Figure 5.4.

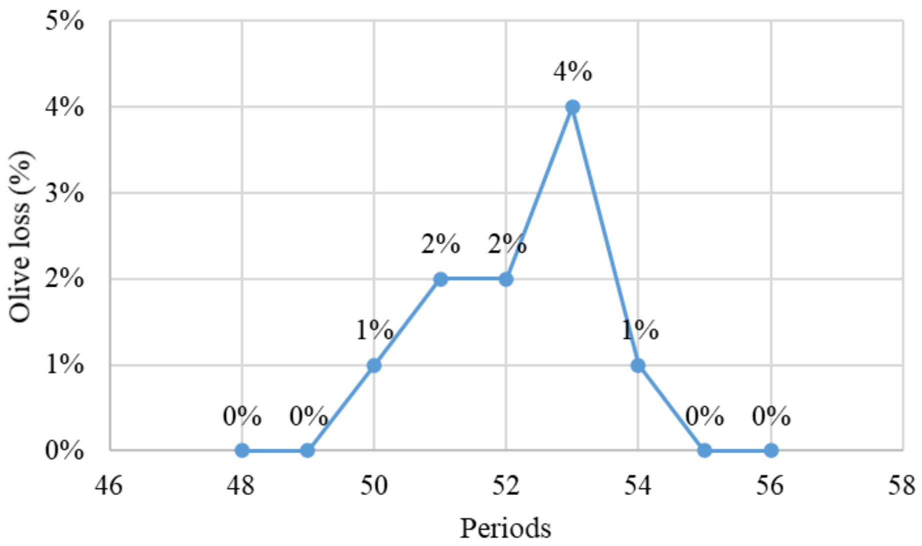

Figure 5.4 Olive loss for scenario 2

Note that, for scenario 2, affected olive groves are different than affected olive groves in scenario 1, and their numbers are 2, 3, 5, 6, 7, 8, 9, 10. For this scenario, the number of active periods is 27, and again, olive supply network and the allocation of the harvest crews have been changed. Revenue and cost related outcomes are presented in Table 5.17 and Table 5.18, respectively. The objective function is decreased by 1% and found as 2,806,974.099 TL.

Purchased olive quantity is increased by 2.33% compared to the base case. 148.32 tons of olives are purchased, and accordingly, purchasing cost is increased. Additionally, olive oil products are produced at maximum demand quantities.

Table 5.17 Revenues of scenario 2

Total revenue (TL)	Olive oil revenue (TL)	Wet pomace revenue (TL)
3,749,042.364	3,704,000	45,042.364

Table 5.18 Costs of scenario 2

Total cost (TL)	Harvesting cost (TL)	Variable processing cost (TL)	Fixed cost (TL)	Purchasing cost (TL)
942,068.265	58,822.193	16,525.451	81,000	785,720.620

Again, organic extra virgin olive oil is produced between periods 10 and 21 and extra virgin olive oil is produced between periods 10 and 28. However, virgin olive oil is produced earlier in this scenario, between periods 45 and 52. In olive grove 3, harvesting operations have been carried out earlier than the base case and still, olive loss occurred. Moreover, in olive grove 5, although harvesting activities have taken place earlier, there are harvesting periods that coincide with those time periods 51 and 52. Therefore, olive loss occurred in the olive grove 5. In olive grove 9, harvesting operations have been carried out earlier than the base case, and still, olive loss happened in period 50 and 51.

Affected olive groves and their olive loss quantities by percentage are listed in Table 5.19 and affected olive groves are shaded in grey. The optimal plan for scenario 2 is presented in Table 5.20. The color assignments of the harvest crews have already been displayed in Table 5.10.

Table 5.19 Olive loss for scenario 2

Olive grove	Olive loss (%)
1	0
2	0
3	1.88
4	0
5	2.39
6	0
7	0
8	0
9	1.17
10	0
11	0
12	0

Table 5.20 Optimal harvest and production plan for scenario 2 (All quantities are expressed in tons)

	Planning horizon																				
Olive grove	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1															13						
2																			11		
3																					2.25
4											12	10	10.3	10							
5																					
6										2.25											
7													1.7								5.75
8																					
9																					
10												2.25		2			10.62	11.13			
11																13				12	
12																	1.5				3
Internal										2.25	12	10.25	12	12	13	13	12.12	11.3	11	12	11
External (org.)										3	3	3	3	3	2	2	2.88	4	4	4	4
External (conv.)										5.34	5	4.75	5	5	5	5	5	4.87	5	4	5
Total										10.59	20	20	20	20	20	20	20	20	20	20	20
Product 1										0.606	0.612	0.615	0.618	0.624	0.42	0.424	0.617	0.86	0.864	0.868	0.872
Product 2										1.534	3.468	3.485	3.502	3.536	3.78	3.816	3.663	3.44	3.456	3.472	3.488
Product 3										-	-	-	-	-	-	-	-	-	-	-	-
Wet pomace										9.2698	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5

Table 5.20 continues

	Planning horizon																				
Olive grove	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
1			12.33				2.67														
2					14		11.5														
3			4.85																		
4																					
5																					
6	14	12.15		11.9																	
7	6			5.62	6	4	4.33														
8																					
9		6																			
10						14															
11																					
12		1.85	2.82			2	1.5														
Internal	20	20	20	17.52	20	20	20														
External (org.)	-	-	-	-	-	-	-														
External (conv.)	-	-	-	2.48	-	-	-														
Total	20	20	20	20	20	20	20														
Product 1	-	-	-	-	-	-	-														
Product 2	4.4	4.42	4.44	4.46	4.5	4.56	4.58														
Product 3	-	-	-	-	-	-	-														
Wet pomace	17.5	17.5	17.5	17.5	17.5	17.5	17.5														

Table 5.20 continues

	Planning horizon													
Olive grove	43	44	45	46	47	48	49	50	51	52	53	54	55	56	Total
1															28
2															36.5
3								4.82	4	4					19.92
4															42.3
5			1.55	2					2.04	3					8.59
6															40.3
7															33.4
8			4.63	10	10	10.37									35
9							10	12.18	10.96						39.14
10															40
11															25
12					2	1.63	2								18.3
Internal			6.18	12	12	12	12	17	17	7					366.45
External (org.)			-	-	-	-	-	-	-	-					37.88
External (conv.)			8	8	8	8	8	3	3	3					110.44
Total			14.18	20	20	20	20	20	20	10					514.77
Product 1			-	-	-	-	-	-	-	-					8
Product 2			-	-	-	-	-	-	-	-					72
Product 3			3.87	5.48	5.5	5.52	5.56	5.6	5.64	2.83					40
Wet pomace			12.4038	17.5	17.5	17.5	17.5	17.5	17.5	8.75					450.4236

Harvesting operations have been carried out mostly between periods 10 and 28, therefore in scenario 1, more olives are lost than scenario 2. Besides, between periods 21 and 25, extra virgin olive oil is produced and has the highest demand among olive oil products. Hence, before period 28, most of the olive oil products have been produced. Virgin olive oil has less demand than extra virgin olive oil, thus, fewer olives are needed and harvested in periods 29 and 56. As a consequence, less olive loss occurred in scenario 2. Due to the olive loss, purchased olives quantities are increased in both of the scenarios in order to guarantee the demand. In addition, oil accumulation in the olive fruits is constantly increasing over the planning horizon, so olive oil has been produced in the later periods despite the olive loss. We can conclude that internal olive groves' yields are harvested as much as possible to prevent a cost increase in purchasing cost. Nevertheless, olive loss has been taken place in the internal olive groves.

Table 5.21 shows the cost related results, purchased olive quantities, and total olive loss in the internal olive groves.

Table 5.21 Comparison of base case, scenario 1, and scenario 2 results

	Base case	Scenario 1	Scenario 2
Profit (TL)	2,822,842.845	2,783,145.511	2,806,974.099
Olive oil revenue (TL)	3,704,000	3,704,000	3,704,000
Wet pomace revenue	44,841.543	44,871.522	45,042.364
Harvesting cost (TL)	58,875	58,589.866	58,822.193
Variable processing cost (TL)	16,451.773	16,462.772	16,525.451
Fixed cost (TL)	81,000	81,000	81,000
Purchasing cost (TL)	769,671.925	809,673.373	785,720.620
External olive quantity (tons)	144.97	151.02	148.32
Olive loss (tons)	-	5,7	1,05

5.4 Sensitivity Analysis

In this section, sensitivity analysis has been performed to analyze the impacts of the important parameters' changes on the computational results.

5.4.1 Effects of Changes in Demand

Fluctuations in demand parameter may cause several changes in the supply chain. In order to observe the changes, demand value is set to 5% and 10% lower and higher than the base case data. When demand is higher, more olive oil products are produced to obtain more profit. Therefore, more external olives have been purchased for processing operations, so variable and fixed processing costs and purchasing costs have been increased. Also, the number of active production periods have been altered according to processed olive quantity. It can be seen that profit is positively correlated with demand change. Table 5.22 shows the changes when demand values fluctuate.

Table 5.22 Impacts of demand changes

	-10%	-5%	Base case	+5%	+10%
Profit (TL)	2,728,243.852	2,777,498.194	2,822,842.845	2,866,636.466	2,909,827.621
Purchasing cost (TL)	499,934.810	630,495.876	769,671.925	909,599.416	1,047,100.614
Variable processing cost (TL)	14,750.309	15,574.009	16,451.773	17,333.252	18,198.065
Fixed processing cost (TL)	72,000	75,000	81,000	84,000	90,000
External olives (ton)	91.97	117.63	144.97	172.43	199.37
No. of periods	24	25	27	28	30
Product 1 (ton) Covered (%)	100	100	100	100	100
Product 2 (ton) Covered (%)	100	100	100	100	100
Product 3 (ton) Covered (%)	100	99.52	100	100	100

5.4.2 Effects of Changes in Processing Capacity

Changes in processing capacity in the olive oil mill affect fixed processing costs and the number of active periods. When processing capacity is increased more olives could be processed, so the number of active periods is decreased. Likewise, when processing capacity is decreased more active periods are needed for the production.

Also, profit has been fluctuated according to capacity changes. Table 5.23 shows the profit's trends when processing capacity changes by 10% and 20% lower and higher.

Table 5.23 Impacts of capacity changes

	-20%	-10%	Base case	+10%	+20%
Profit (TL)	2,771,832.900	2,800,653.289	2,822,842.845	2,838,232.622	2,847,453.828
Fixed processing cost (TL)	102,000	90,000	81,000	72,000	66,000
No. of periods	34	30	27	24	22

Figure 5.5 presents the impacts of capacity changes through the number of active periods on the profit.

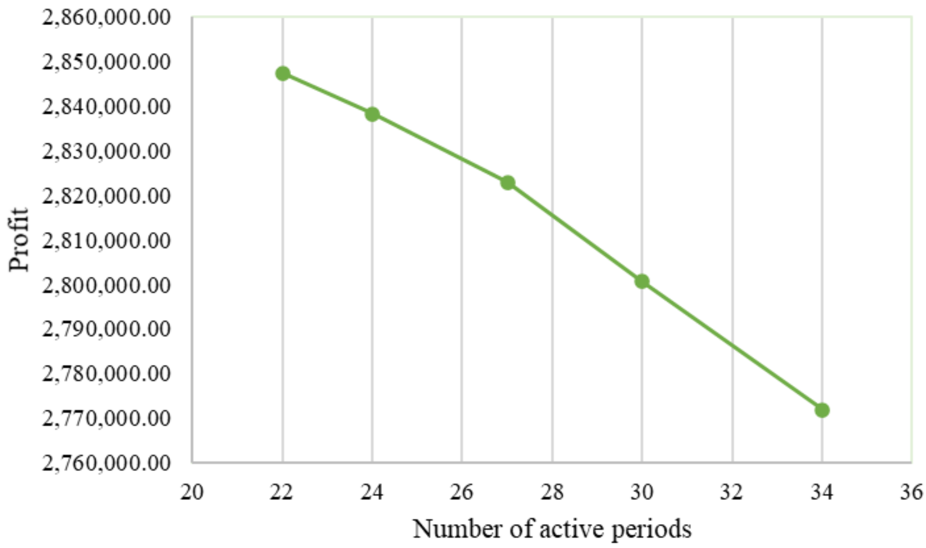

Figure 5.5 Effects of processing capacity changes

5.4.3 Effects of Changes in Olive Yield

In the course of determining olive quantities in the olive groves, before the harvest season, there could be some mistakes with the assessments. According to Table 5.23, changes in yield have a direct effect on purchased olives. For instance, when olive yield has been determined lower in the internal olive groves, purchased olive quantity has been increased in order to ensure demand satisfaction. In every scenario, the maximum demand quantities of olive oil products have been produced to maximize the profit. The effects of yield changes in the olive groves are presented in Table 5.24.

Table 5.24 Impacts of yield changes

Fluctuations	Profit (TL)	Purchasing cost (TL)	Purchased olives (ton)	Harvested olives (ton)
-10%	2,637,982.425	956,390.511	182.097	330.75
-8%	2,674,902.945	919,101.313	174.726	338.1
-6%	2,711,804.286	881,830.328	167.337	345.45
-4%	2,748,320.463	844,946.908	159.992	352.8
-2%	2,785,967.692	806,917.077	152.369	360.15
Base case	2,822,842.845	769,671.925	144.974	367.5
2%	2,859,778.686	732,366.261	137.582	374.85
4%	2,896,452.136	695,322.981	130.190	382.2
6%	2,933,040.728	658,364.834	122.803	389.55
8%	2,969,732.760	621,301.945	115.393	396.9
10%	3,006,104.794	583,997.333	107.914	404.25

Figure 5.6 shows the profit changes when olive yield fluctuates.

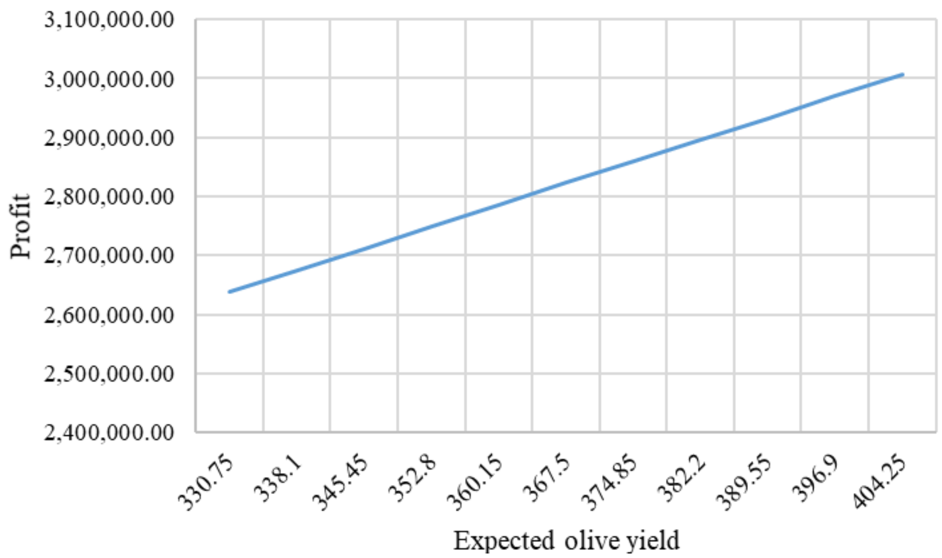

Figure 5.6 Profit vs expected olive yield trends

Based on the findings from the sensitivity analyses, some suggestions are made to help decision-makers in the planning process. Findings are presented as follows:

- Olive yield fluctuations have a major effect on the supply chain network and total profit. Therefore, olive oil producers should be prepared for the changes in the olive yield. Also, producers may consider performing the necessary operations to increase the olive trees' yield.

- Demand changes also affect the optimal chain network and total profit. Producers should be alert to the demand changes and investigate the market needs in order to be a responsive producer in the market.

- Processing capacity changes have a significant impact on fixed costs and the number of active periods in the olive oil mill, therefore on the total profit. It may be efficient to examine processing capacity by producers.

5.5 Results

In this study, a realistic case study has been presented to validate the applicability of the developed model. According to the results of this model, harvest crews are optimally allocated to the olive groves, external olives are purchased to satisfy demands, several olive oil products are produced, contribution to the economy is made by selling by-products of olive oil, and green consumer's preference products are provided.

With the case study, we illustrate the optimal harvest and production plan for olive oil producer who has multiple olive groves and one olive oil mill. Because the producer has only conventional olive groves, organic olives are completely purchased from external olive farmers. Also, conventional olives are purchased when it is needed. The maximum demand quantities of olive oil products are produced to maximize the total profit. Concurrently, generated wet pomace is sold to a pomace factory where it is converted into fuel.

Two scenarios are generated to analyze severe climatic conditions which can take place during the harvest season of olive trees. First scenario examines the severe weather conditions at the earlier times in the planning horizon, on the other hand, second scenario studies severe conditions at the later times in the planning horizon. Considering realistic situations such as olive loss caused by climatic conditions makes the extended model more applicable to real-world situations.

The sensitivity analysis results illustrate the effects of related parameter changes on the objective function. This analysis may assist the decision-makers to understand the system more thoroughly. It can be concluded that demand and yield changes are the parameters that affect the supply chain strongly. Also, capacity changes according to market needs can be more efficient for olive oil mill operations.

Olive oil producers can benefit from this study to plan their harvest and production plan optimally. Also, the model can be modified according to other producers' constraints and requirements. This research study can be useful to make positive impacts on local producers' businesses. Therefore, it can be concluded that the outcomes of this study can contribute to Turkey's economy.

CHAPTER SIX
CONCLUSION

6.1 Summary of the Thesis

AFSCs, which are comprised of several stakeholders such as farmers, processors, distributors, retailers, and costumers, have been extensively studied mostly in recent years. The overall objective of AFSC models is to find solutions to the complex problems such as harvest scheduling for crops, production planning for packaging or processing of agri-foods, and distribution planning according to quality requirements.

In this thesis, in order to identify trends and gaps in the literature, a systematic literature review study has been conducted. In this comprehensive review, firstly, previous review studies are analyzed. The objectives of the review papers and suggested future research directions have been specifically examined to discover opportunities in order to make contributions to the literature. Therefore, mathematical programming models which consist of at least one harvest or production decision variables on food crops have been investigated. In light of the previous reviews, a new classification scheme has been developed to better comprehend the previously studied harvest and production planning models. The proposed framework has classified the articles according to problem scope, model characteristics, and modeling approaches. Based on the findings of the conducted literature review, a new research study for this thesis has been developed.

An attempt has been made to study an integrated harvest and production planning problem with the perspective of a small olive oil producer. A MILP model which considers olive harvesting and olive oil production operations is proposed. The novelty of the developed model is four-fold. Firstly, integration of harvest and production operations for the entire harvest and production season is established. Secondly, organic and conventional farming systems are included to produce differently labeled organic and conventional products. Thirdly, external olive supplier selection is incorporated to purchase organically and conventionally grown olives. Fourthly, as a by-product management method, selling generated wet pomace to a pomace factory is considered. The model aims to maximize total profit which comprises of olive oil revenue, wet pomace revenue, harvesting cost, purchasing cost, variable processing cost, and fixed processing cost. Several constraints such as harvest crew capacity, olive oil mill capacity, scheduling, and demand constraints are taken into account.

Applicability of the mathematical formulation has been demonstrated by considering a realistic case study. The computational results of the case study provide an optimal harvest and production plan for the entire harvest and production season. Model outputs may assist the producers with the questions of when, how much, and where to harvest, which harvest resource to utilize, when and how much to purchase organically and conventionally grown olives, and when and how much to produce olive oil.

Then, scenario analysis has been developed to examine the olive loss that may occur because of the severe climatic conditions. In the first scenario, olive loss is incurred in the earlier periods whereas, in the second scenario, olive loss takes place in the later periods of the planning horizon. Two scenarios generate different optimal plans regarding the olive loss. These scenarios may help to determine harvest and production plans under severe weather conditions.

Lastly, sensitivity analysis has been conducted to determine and observe the changes in important parameters which can affect the total profit and the entire plan. The results suggest that changes in olive yield and olive oil demand are significant on both total profit and optimal network.

6.2 Future Research Directions

This thesis provides a new perspective to the olive harvesting and oil production problems. According to the results obtained, the proposed mathematical model is effective for the decision-making process. Based on the presented research study, several future directions are suggested as follows:

- Proposed model can be applied to the similar problems with some modifications. Producers can modify the model according to their problem specifications and find optimal solutions for their problems. Besides that, table olive production can be included to the study.

- Strategic decisions can be incorporated to the model such as purchasing organic and/or conventional olive groves. Multi-criteria decision-making methods can be utilized for the selection process.

- One research direction would be considering stochastic parameters. Olive yield, olive oil demand, or olive loss by climate conditions could be taken into account as stochastic parameters.

- Moreover, this model can be converted into other similar harvest and production planning problems of other crops such as grape and sugarcane with some modifications according to crops' characteristics.

- For large-size problems, commercial software may not find the optimal solutions. Thus, heuristics and/or meta-heuristics can be developed for this problem.

- This model and its extensions according to other producers' problems can be converted into a decision support system to optimize harvest and production activities for local olive oil producers.

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APPENDICES

APPENDIX-1: Literature review articles' journal and country list

Authors	Journal	Country
Munhoz & Morabito (2001)	Operational Research Society of India	Brazil
Vitoriano et al. (2003)	Production, Manufacturing and Logistics	Spain
Kazaz (2004)	Manufacturing & Service Operations Management	USA
Apaiah & Hendrix (2005)	Journal of Food Engineering	The Netherlands
Jiao et al. (2005)	Computers and Electronics in Agriculture	Australia
Caixeta-Filho (2006)	Journal of the Operational Research Society	Brazil
Higgins & Laredo (2006)	Journal of the Operational Research Society	Australia
Higgins et al. (2006)	Journal of the Operational Research Society	Australia
Widodo et al. (2006)	European Journal of Operational Research	Japan
Grunow et al. (2007)	International Journal of Production Economics	Multiple
Masini et al. (2007)	Book chapter: Process Systems Engineering: Supply Chain Optimization. Part II	Argentina
Ferrer et al. (2008)	International Journal of Production Economics	Chile
Nagasawa et al. (2009)	Journal of the Operations Research Society of Japan	Japan
Piewthongngam et al. (2009)	Agricultural Systems	Thailand
Arnaout & Maatouk (2010)	International Transactions in Operational Research	Lebanon
Bohle et al. (2010)	European Journal of Operational Research	Chile
Jerić & Šorić (2010)	Croatian Operational Research Review	Croatia
Ahumada & Villalobos (2011a)	Annals of Operations Research	USA
Ahumada & Villalobos (2011b)	International Journal of Production Economics	USA
Kazaz & Webster (2011)	Manufacturing & Service Operations Management	USA
Kostin et al. (2011)	Computers and Chemical Engineering	Multiple
Rong et al. (2011)	International Journal of Production Economics	Multiple
Ahumada et al. (2012)	Agricultural Systems	USA
Paksoy et al. (2012)	Applied Mathematical Modelling	Turkey
Stray et al. (2012)	Computers and Electronics in Agriculture	South Africa
Sutopo et al. (2012)	Makara Journal of Technology	Indonesia
Tan & Çömden (2012)	European Journal of Operational Research	Turkey
Jena & Poggi (2013)	European Journal of Operational Research	Brazil
Lim et al. (2013)	Computers and Chemical Engineering	Malaysia
Costa et al. (2014)	Annals of Operations Research	Brazil
Munhoz & Morabito (2014)	Computers and Electronics in Agriculture	Brazil
da Silva et al. (2015)	Applied Mathematical Modelling	Brazil
González-Araya et al. (2015)	Book chapter -Handbook of Operations Research in Agriculture and the Agri-Food Industry	Chile
Reis & Leal (2015)	Journal of Transport Geography	Brazil
Thuankaewsing et al. (2015)	Computers and Electronics in Agriculture	Thailand
Wishon et al. (2015)	International Journal of Production Economics	USA

APPENDIX-1: continues

Authors	Journal	Country
Accorsi et al. (2016)	Journal of Cleaner Production	Multiple
An & Ouyang (2016)	Transportation Research Part E	USA
Catalá et al. (2016)	Computers and Electronics in Agriculture	Argentina
Rocco & Morabito (2016a)	Computers and Electronics in Agriculture	Brazil
Rocco & Morabito (2016b)	International Journal of Production Research	Brazil
Banasik et al. (2017)	International Journal of Production Economics	The Netherlands
Basso & Varas (2017)	Computers & Industrial Engineering	Chile
Ghezavati et al. (2017)	Central European Journal of Operations Research	Iran
Gholamian & Taghanzadeh (2017)	Computers and Electronics in Agriculture	Iran
Grillo et al. (2017)	Applied Mathematical Modelling	Spain
Herrera-Cáceres et al. (2017)	Computers and Electronics in Agriculture	Chile
Miranda-Ackerman et al. (2017)	Computers & Industrial Engineering	Multiple
Varsei & Polyakovskiy (2017)	Omega	Australia
Allaoui et al. (2018)	Computers and Operations Research	Multiple
Cheraghalipour et al. (2018)	Applied Soft Computing	Iran
Flores & Villalobos (2018)	Agricultural Systems	USA
Marchal et al. (2018)	Journal of Process Control	Spain
Sazvar et al. (2018)	Journal of Cleaner Production	Multiple
Banasik et al. (2019)	Journal of Cleaner Production	The Netherlands
Cheraghalipour et al. (2019)	Computers and Electronics in Agriculture	Iran
He & Li (2019)	Applied Soft Computing	China
Jerić & Šorić (2019)	Ekonomski Vjesnik	Croatia
Jonkman et al. (2019)	European Journal of Operational Research	Multiple
Junqueira & Morabito (2019)	International Journal of Production Economics	Brazil
Plessen (2019)	Artificial Intelligence in Agriculture	-
Roghanian & Cheraghalipour (2019)	Journal of Cleaner Production	Iran
Suthar et al. (2019)	Postharvest Biology and Technology	USA
Yurt et al. (2019)	International Journal of Sustainable Agricultural Management and Informatics	Multiple
Flores & 8Villalobos (2020)	European Journal of Operational Research	USA
Hosseini-Motlagh et al. (2020)	Computers and Electronics in Agriculture	Iran
Jifroudi et al. (2020)	Decision Science Letters	Iran
Varas et al. (2020)	Computers & Industrial Engineering	Chile

APPENDIX-2: Purchased olive quantities from external farmers for case study (all quantities are expressed in tons)

	Planning horizon																											
Farmers	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1										2	2	2	2	2	2	2	2	2	2	2	2							
2																												
3																												
4										1	1	1	1	1														
5																0.6	0.6	1.7	2	2	2							
6																												
7																												
8										1.09			3.75															
9																												
10																												
11																												
12																												
13																												
14																												
15																												
16																												
17										5	5	5	5	4.7	5	4.9	5	4.55	4.5	5	4.5							
18																						1	1		1		1.15	1
Organic										3	3	3	3	3	2	2.6	2.6	3.7	4	4	4	-	-		-		-	-
Conventional										6.09	5	5	8.75	4.7	5	4.9	5	4.55	4.5	5	4.5	1	1		1		1.15	1

APPENDIX-2: continues

Farmers	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
	Planning horizon																											
1										2	2	2	2	2	2	2	2	2	2	2	2							
2																												
3																												
4										1	1	1	1	1														
5																0.6	0.6	1.7	2	2	2							
6																												
7																												
8										1.09			3.75															
9																												
10																												
11																												
12																												
13																												
14																												
15																												
16																												
17										5	5	5	5	4.7	5	4.9	5	4.55	4.5	5	4.5							
18																						1	1		1		1.15	1
Organic										3	3	3	3	3	2	2.6	2.6	3.7	4	4	4	-	-		-		-	-
Conventional										6.09	5	5	8.75	4.7	5	4.9	5	4.55	4.5	5	4.5	1	1		1		1.15	1