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Araştırma Makalesi / Research Article

Recent Advances in Planning Farm Operations through Optimization Models

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Abstract

Operations Research applications in the agriculture sector have been a research area of high interest for over 50 years. Due to food security and sustainability concerns in the world, a lot of attention has been given to this area by OR researchers and practitioners recently. From distribution planning to performance evaluation, a variety of approaches and methods have been applied to a broad range of agricultural problems. Therefore, many review papers have been published from different points of view to serve both general and specific academic purposes. In this work, we present a review of the optimization approaches for the planning of farming operations which aims to optimize agricultural production systems. We use Scopus database to find relevant studies in three decision areas: crop planning, harvest planning and machinery management. Our review covers 54 papers published between 2002-2022.

Keywords: *OR in Agriculture, Agricultural Production, Farming Operations, Optimization.*

Optimizasyon Modelleri Yoluyla Çiftlik Operasyonlarının Planlanmasındaki Son Gelişmeler

Öz

Tarım sektöründe yöneylem araştırması tekniklerinin uygulanması, 50 yılı aşkın bir süredir yüksek ilgi gören bir araştırma alanı olmuştur. Dünyada gıda güvenliği ve sürdürülebilirlik endişeleri nedeniyle, son zamanlarda yöneylem araştırmacıları ve uygulayıcıları tarafından bu alana daha çok dikkat çekilmektedir. Dağıtım planlamasından performans değerlendirmesine kadar, çok çeşitli tarımsal problemlere uygulanan birçok farklı yaklaşım ve yöntem görülmektedir. Bu nedenle, hem genel hem de özel kapsamlarda akademik amaçlara hizmet edecek farklı bakış açılarıyla hazırlanmış birçok derleme makalesi yayınlanmıştır. Bu çalışmada, özellikle tarımsal üretim sistemlerinin iyileştirilmesini hedefleyen çiftlik operasyonlarının planlanması için geliştirilen optimizasyon yaklaşımlarının bir derlemesi sunulmaktadır. Mahsul planlama, hasat planlama ve makine yönetiminden oluşan üç karar alanındaki ilgili çalışmaları bulmak için Scopus veritabanı kullanılmıştır. Derlememiz 2002-2022 yılları arasında yayınlanmış toplam 54 makaleden oluşmaktadır.

Anahtar Kelimeler: *Tarımda Yöneylem Araştırması, Tarımsal Üretim, Çiftlik Operasyonları, Optimizasyon.*

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INTRODUCTION

As the human population grows rapidly, the need for efficient management of agricultural supply chains (ASC) increases so that healthy food is sufficiently provided with the least negative impact on the environment. The increasing demand for agricultural products with the public awareness of healthy consumption and sustainability leads to a trade-off between productivity and natural resource use. Being the second-largest emitter of greenhouse gas (GHG) emissions (Intergovernmental Panel on Climate Change (IPCC), 2014), the agriculture sector carries a lot of concepts to consider when planning the production and distribution of products. Aside from the sustainability and food security issues, there is a high level of complexity when planning operations of an agricultural system due to the limits on natural resources and time windows of each activity.

Mathematical programming approaches have been applied to agricultural operations since the 1950s (Behzadi et al., 2018). It can be seen that planning models vary in many different ways such as the product of interest, the planning scope, and the level of the supply chain being considered. As identified by Ahumada and Villalobos (2009), there are four functional areas of an ASC that planning models can be grouped into: *production*, *harvest*, *storage*, and *distribution*. The decisions such as land allocation, the timing of sowing, and resource allocation are production decisions whereas the scheduling of agricultural equipment, labor, and transportation equipment for harvesting activities are considered in the harvesting domain. Storage and distribution functions involve decisions like in the other supply chain planning problems except for the models that emphasize timeliness costs when perishable products are chosen (Ahumada & Villalobos, 2009).

The review in the current work is concentrated on research that focus on the production and harvesting areas of ASC both of which involve decisions related to the production of crops at the producer/farmer level. At this level, a coutious planning is necessary since agricultural production involves many time-sensitive operations like sowing, weeding, fertilizing and harvesting. Each of these operations creates a complex system requiring too many decisions and limitations to be considered simultaneously by the decision maker. Operations Research discipline certainly provides analytical tools to these decisions. The review presented in this paper provides an overview of the tools and problem areas in this domain.

The paper is organized as follows: Section 1 gives an overview of the previous review articles related to operations research applications in agriculture and states the scope of this review. In Section 2, descriptive information is given including the distribution of studies by year, methodology and decision area. Decision areas are explained in subsections of Section 3, giving detailed information regarding the problem types in the reviewed research.

1. OPERATIONS RESEARCH IN AGRICULTURE

The use of Operations Research (OR) methods in agricultural operations has a long history of research leading to many literature reviews conducted with various purposes. Planning models in the agriculture sector dates back to the 1950s as observed by Glen (1987) who made the first review in this domain. The work covers the papers published until 1985 which include farm planning models on crop and livestock production. The reviewing efforts have been carried out by other researchers with contributing topics such as farm planning models under uncertainty (Hardaker et al., 1991), multicriteria analysis for agricultural resource management (Hayashi, 2000), and modeling approaches for crop planning (Lowe & Preckel, 2004). A distinctive review by Lucas and Chhajed (2004) compiles the research with location analysis problems mainly for selecting warehouse and processing plant locations. As of the 1990s, the variety of agricultural problem types has increased due to the research stream becoming widespread. This trend has led to the pivotal work of Ahumada and Villalobos (2009) which presents the most comprehensive review of OR in agriculture to its date. As they pointed out, a shift toward supply chain planning models becomes more frequent in the literature compared to the previous trend of farm planning models. This new trend comes with the perishability concept due to the need for responsiveness to avoid food waste. However, they concluded that these models have a shortage of real-life applications mainly because of the complexity and the difficulty of coordination between ASC actors although having a high potential for savings in costs. A vast number of review papers have been published after 2010, but their primary focus is on supply chain management rather than farming operations which has more typical aspects of agricultural production. Another review brought by Bochtis et al. (2014) outlines the current advances in agricultural machinery management as a contribution to farming operations planning literature. The research covered by their review is categorized into five selected problem types which are capacity planning (strategic), task time planning (tactical), scheduling (operational), route planning (operational), and performance evaluation. All tasks except the performance evaluation models are related to the planning of production and harvest functions of an ASC. As far as we know, the most recent and extensive review is made by Nematollahi and Tajbakhsh (2020) covering 247 papers in the field of agricultural supply chain management with an emphasis on sustainability. They distinguish from the preceding review papers by their perspective on sustainability and underline that sustainability has become a main topic in most of the recent works. Even though their main keyword in the paper collection process is "supply chain", they found out a significant number of papers (84) deal with production-related problems alongside a research stream with a specific concentration on farming operations like crop rotation and harvest planning. Since there is an abundance of review papers examining the works that consider the agricultural supply chain as a whole, we present a different point of view representing the optimization models for farming operations related to production. Therefore, this study only covers the planning models for farm-level activities that require strategic, tactical, and operational decision-making.

2. DESCRIPTIVE INFORMATION ON THE REVIEW

In this study, we utilize the *Scopus* database for studies that focus on optimizing the production system of crops at the farm level. As discussed in Section 1, the previous reviews reveal that there are three main decision areas in the production level of agricultural supply chains which are crop planning, agricultural machinery management, and harvest planning. Based on that, the keywords used in the initial search are 'farm planning', 'farming operations', 'farm level operations', 'crop selection', 'crop rotation', 'agricultural machinery', 'harvest planning' with and without the word 'optimization'. In the collection process, studies that cover the planning of the agricultural supply chain and studies conducted only for evaluation and controlling the production system are excluded from the review. Additionally, we use forward, and backward snowball search techniques based on previous literature reviews and studies found in the initial search to find more papers in accordance with our scope. Finally, our review consists of 54 papers in total published between 2002 and 2022.

As shown in Fig. 1, the publication rate of farm-level Operations Research papers in the last five years are increasing especially in 2015, 2017, and 2021. This reveals that there is no shortage of research interest regarding the optimization of farm level production systems even though supply chain planning is becoming a more prominent research focus in the relevant literature. Farm-level production planning is mostly assessed for crop farming compared to livestock products due to the high variety in types of crops (Heidari et al., 2021). Also, the effects of crop rotation strategies, agricultural machinery performance, and fertilizing options are adding more complexity to the system in terms of yield. As a result, our review involves only crop production which focuses on the different aspects of agricultural production (crop, machinery, and harvest planning). The distribution of papers by decision areas is shown in Fig. 2. As the results reveal, crop planning is the most addressed issue as the crop types chosen for the problem are without any limitations by agricultural machinery usage or harvesting time windows.

Figure 1: Publications by Year

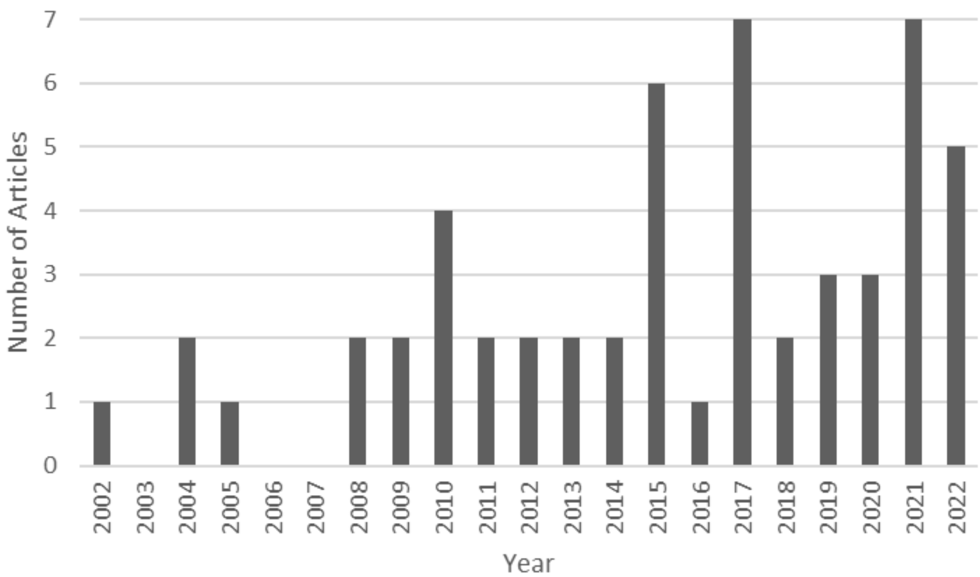
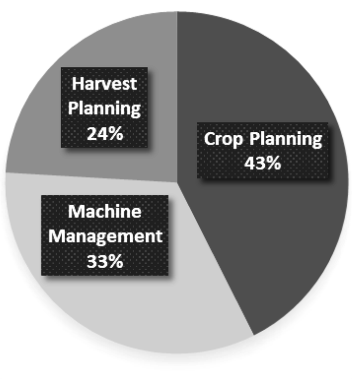
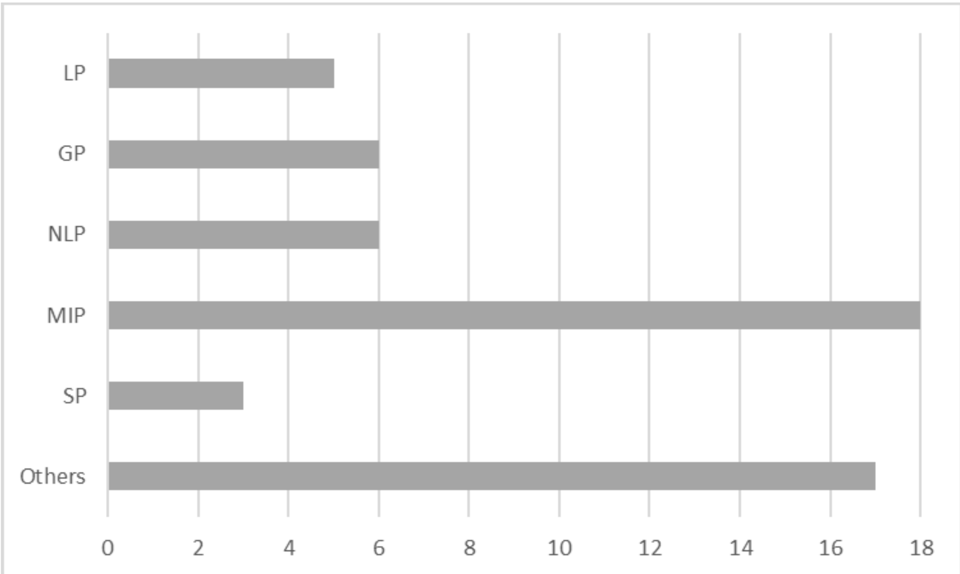


Figure 2: Publications by Decision Areas



In the reviewed papers, there is diversity in terms of methodology, objectives assessed in the problem, and uncertainty in the parameters. This difference is understandable mainly because of the unpredictable nature of the agricultural environment. Fig. 3 shows the distribution of optimization methods among the reviewed papers by numbers. The methods chosen for the study are mostly affected by the problem characteristics in terms of objective, uncertainty, and the variety of decision variables. Mixed-integer programming is the most used method in the studies (18), however high number of decisions considered in the problems increase the difficulty of solving them, which is associated with NP-hard problems in the literature. This led to the common use (17 studies) of relaxation methods, metaheuristics and evolutionary algorithms. In the case of uncertainty, the most preferred methods in the review are stochastic programming (Albornoz et al., 2019; Avanzini et al., 2021; Huh & Lall, 2013), non-linear programming (Cortignani & Severini, 2012; Harel et al., 2022) and mixed-integer programming (Filippi et al., 2017; Rădulescu et al., 2011). While most of the studies have a single objective in the problem, there is a significant number of papers (15) dealing with problems with multiple objectives. The most frequently used method found in this context is goal programming (Ahodo et al., 2019; Biswas & Pal, 2005; Fasakhodi et al., 2010; Lopez-Baldovin et al., 2017; Pal et al., 2009; Pal et al., 2010;), linear programming (Annetts & Audsley, 2002; Behera et al., 2015; Savin et al., 2014) and mixed-integer programming (Jami et al., 2021; Rădulescu et al., 2011; Wang & Huang, 2022a; Varas et al., 2020; Wang & Huang, 2022b).

Figure 3: Distribution by OR Methods



Abbreviations: *LP: Linear Programming; GP: Goal Programming; NLP: Non-linear Programming; MIP: Mixed Integer Programming; SP: Stochastic Programming; Others: Relaxation Methods, Metaheuristics and Evolutionary Algorithms.*

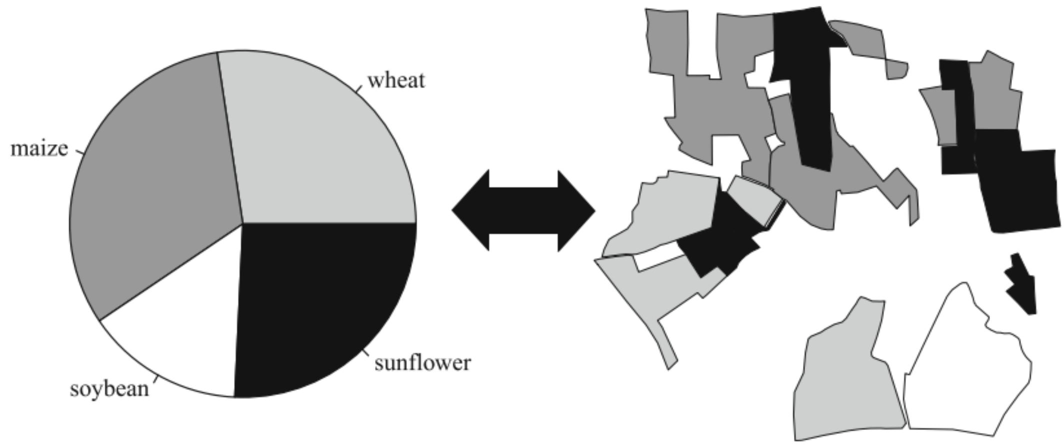
3. DECISION AREAS IN AGRICULTURAL PRODUCTION MANAGEMENT

As the previous literature reviews reveal, there are three main decision areas of farm-level operations that OR researchers have focused on: *crop-related decisions*, *agricultural machinery management*, and *harvest planning*. All these decision areas aim to improve the performance of an agricultural production system in different ways and different planning scopes. There are examples of strategic, tactical, and operational planning in studies assessing crop planning and machinery management, but harvest planning usually involves problems at the operational level. In the following sub-chapters, problem types in each decision area are explained with examples.

3.1. Crop Planning

Crop production planning is defined as the selection of crops to be grown and the area and resources to be allocated for each crop (Glen, 1987). Although this problem has a long history of research, there is no shortage of work regarding crop planning (23 papers) in our review with different aspects. Crop planning usually involves two types of problems at its core: *crop allocation* and *crop rotation. Crop allocation* is defined as the determination of the portion of land to be occupied by different crop types (Wijnands, 1999). This problem is caused by different soil types in land and the price fluctuations of crops in the market. On the other hand, *crop rotation* is a different issue which is defined as the selection of a crop sequence in the same piece of land for a fixed period (Leteinturier et al., 2006). This strategy is practiced mainly to protect yield and soil health by preventing pest infestation and crop diseases. Fig. 4 presents a crop plan with 4 crop types, each of which has its percentage of land as a result of a crop allocation problem. If the decision maker tries to create a cropping sequence, for example producing maize-soybean-wheat crop sequence after sunflower in the black areas, then it is a crop rotation problem. Generally, crop planning studies assess both problems together as also seen in our review (16 papers), there are exceptions solely on crop allocation (Albornoz & Zamora, 2020; Biswas & Pal, 2005; Filippi et al., 2017; Huh & Lall, 2013; Pal et al., 2009; Pal et al., 2010; Wishon et al., 2015), crop rotation (Annetts & Audsley, 2002; Capitanescu et al., 2017) and land-use crop planning in which Guan et al. (2017) model only to find the optimal allocation of land to sugarcane production while applying flow shop scheduling into agricultural production stages.

Figure 4: Representation of a Crop Plan



Source: Dury et al., 2012

Several studies deal with the timing of operations like cultivating, sowing, fertilizing, etc. with crop planning to avoid waste and to choose crops that fit the current schedule. These studies also involve machine-related decisions like the number of machines of different types (Ahodo et al., 2019; Annetts & Audsley, 2002), assignment of machines to operations (Biswas & Pal, 2005; Filippi et al., 2017; Pal et al., 2009; Pal et al., 2010), and reservation of machinery level to farmlands (Guan et al., 2017). In addition to machinery, the mentioned studies also aim to find the optimal level of labor while other studies assess labor requirements without machinery decisions (Bhatia & Rana, 2020; Fasakhodi et al., 2010; Montazar, 2011; Wishon et al., 2015).

There are different approaches considered for integrating the sustainability context in crop planning studies, but they can be grouped into two main branches: *crop maintenance* and *irrigation management*. Studies covering crop maintenance mostly involve minimizing chemical usages such as herbicides and pesticides and applying fertilizer at the right amount and the right time to avoid nitrate leaching (Ahodo et al., 2019; Annetts & Audsley, 2002; López-Baldovin, 2017). Nitrate leaching is known as the process of moving nitrate anion downwards in the soil which is caused by improper usage of chemical nitrogen fertilizers (Padilla et al., 2018). This phenomenon leads to the contamination of water resources which is avoided in the relevant studies. The availability of water resources is taken into account by other researchers by adding constraints to the models to keep water resources sufficient for multi-period agricultural production (Fasakhodi et al., Huh & Lall, 2013; 2010; Montazar, 2011). There are also examples of assessing both sustainability issues (Biswas & Pal, 2005; Pal et al., 2009; Pal et al., 2010;). These environmental restrictions are imposed by European Union's Common Agricultural Policy (CAP) along with other sustainability indicators seen in our reviews such as revenue inequality (Cortignani & Severini, 2012; Pakawanich et al., 2021) and crop diversification (Galán-Martín et al, 2015). All the articles that are interested in crop planning problems in our review are listed in Table 1.

Table 1: Research on Crop Planning

Research	Operation Scheduling	Crop Rotation	Crop Allocation	Labor Allocation	Machinery Decisions	Sustainability Issues	Optimisation Method
Annetts and Audsley, (2002)	+	+	-	+	+	Nitrate Leaching, Herbicide Use	Linear Programming
Biswas and Pal, (2005)	-	-	+	+	+	Fertilizer and Water Usage	Goal Programming
Pal et al. (2009)	-	-	+	+	+	Fertilizer and Water Usage	Goal Programming
Pal et al. (2010)	-	-	+	+	+	Fertilizer and Water Usage	Goal Programming
Fasakhodi et al., (2010)	-	+	+	+	-	Water Resources Sustainability	Goal Programming
Montazar, (2011)	-	+	+	+	-	Water Resources Sustainability	Non-linear Programming
Rădulescu et al., (2011)	-	+	+	-	-	Fertilizer and Pesticide Application Rate	Mixed-integer Programming
Cortignani and	-	+	+	-	-	Water Resources	Non-linear Programming

Severini, (2012)						Sustainability and Revenue Inequality	
Huh and Lall, (2013)	-	-	+	-	-	-	Stochastic Programming
Alfandari et al., (2015)	-	+	+	-	-	Land Space Consumption	Branch-price-and-cut Algorithm
Galán-Martín et al., (2015)	-	+	+	-	-	Crop Diversification and Preservation of Grassland	Linear Programming
Santos et al., (2015)	-	+	+	-	-	Land Space Consumption	Branch-price-and-cut Algorithm
Wishon et al., (2015)	-	-	+	+	-	-	Mixed-integer Programming
Capitanescu et al., (2017)	-	+	-	-	-	Greenhouse Gas Emissions and EU CAP	Mixed-integer Programming
Filippi et al., (2017)	+	-	+	-	+	-	Mixed-integer Programming
Guan et al., (2017)	+	-	-	+	+	-	Mixed-integer Programming
López-Baldovin, (2017)	-	+	+	-	-	Pesticide Use, Nitrate Leaching, Water Usage, Crop Diversification	Multi-criterie Programming
Ahodo et al., (2019)	+	+	+	-	+	Herbicide Use	Goal Programming
Albornoz et al., (2019)	-	+	+	-	-	-	Stochastic Programming
Albornoz and Zamora, (2020)	-	-	+	-	-	-	Decomposition-based Heuristic
Bhatia and Rana, (2020)	-	+	+	+	-	-	Linear Programming
Pakawanich et al., (2021)	-	+	+	-	-	-	Priority-based priority-based max-min Heuristic
Telles et al., (2021)	-	+	+	-	-	Land Space Consumption	Mixed-integer Programming

From the modelling perspective, it is seen that multi-objective programming methods are the most used modelling techniques in crop planning problems such as goal programming, linear programming, mixed-integer programming and multi-criteria programming. Because these problems involve strategic and tactical decisions of agricultural production which should consider multiple aspects of farming. In the studies using goal programming, profit maximization, land utilization and production achievement are the most addressed goals with some additions like machine-hour, manpower, water supply and fertilizer requirement. There are also some exceptions with the rest of these methods like minimization of environmental outcomes with linear programming (Annetts & Audsley, 2002), risk minimization with mixed-integer weighted goal-programming (Ahodo et al., 2019) and crop rotation goal with multi-criteria programming. In problems with single objective, mixed integer programming is the most widely used modelling approach since most of the goals mentioned earlier are addressed with no relaxation or analysed in multiple models. For example, Radulescu et al. (2011) compare the results of three separate MIP models with the objectives of environmental risk minimization, return maximization and financial risk minimization. In most studies, optimization software alternatives are enough to solve the MIP problem but there are some examples of strict models that have proven NP-hard. In these cases, branch-and-price-cut algorithms are mostly preferred (Alfandari et al., 2015; Santos et al., 2015) while other approaches like simulated annealing meta-heuristic is also used (Guan et al., 2017). In some studies, the methodology differs in accordance with uncertainty being considered. These studies tackle the issue of price and yield uncertainty with a stochastic programming approach (Huh & Lall, 2013; Albornoz et al., 2019).

3.2. Machinery Management

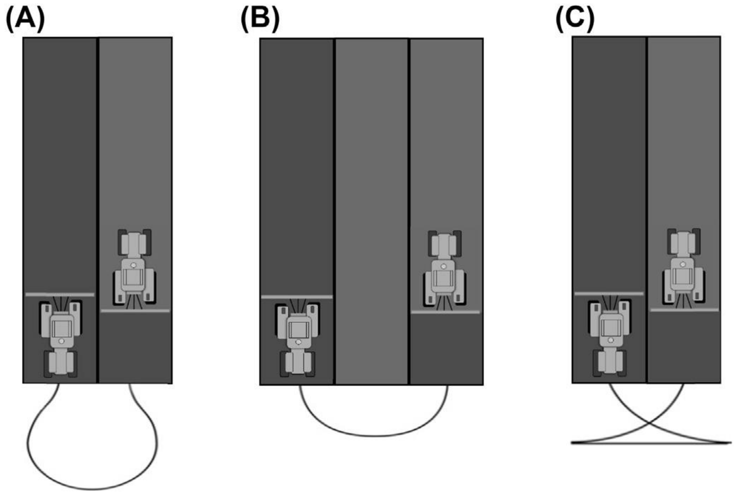
In a farm-level production system, agricultural machinery and equipment are essential in almost every stage of growing a crop from cultivating to harvesting. Being a significant part of any farm's annual costs, machinery investment is the second largest investment in farm planning following real estate investments (Kay et al., 2008). In the review, there are 18 papers dealing with problems involving agricultural machinery management, and they are presented in Table 2 with highlighting aspects. Unsurprisingly, different problem types can be seen in the studies due to different costs incurred by machinery such as investment costs, operating costs, and fuel costs. Regarding investment costs, selection problems are first seen according to the technical requirements of the problem considered. In the study of Camarena et al. (2004), we see a machinery selection model for a multi-farm system to match the machinery choices with different field sizes in order to complete all the operations in time. Similarly, Mohamed et al. (2017) takes the same problem for a multi-crop farm system with a different objective of minimizing the number of tractors as much as possible. In this research area, Sørensen et al. (2014) explore the problem of tillage system selection which requires different combinations of plowers and cultivators. They address environmental issues since each tillage system affects the soil differently and requires different tractor powers arising a need to consider GHG emissions.

Table 2: Research on Machine Management

Authors	Operation Scheduling	Harvesting Decisions	Problem Types	Sustainability Issues	Optimisation Method
Camarena et al. (2004)	+	+	Machinery Selection	-	Mixed-integer Programming
Søgaard and Sørensen, (2004)	+	+	Selection of Machinery Sizes	-	Non-linear Programming
Bochtis and Vougioukas, (2008)	-	-	Optimization of On-field Track Movements	-	Mixed-integer Programming
Verlinden and Van Oudheusden, (2009)	-	+	Infield Logistics Planning	-	Mixed-integer Programming
Bakhtiari et al., (2012)	-	-	Optimization of On-field Track Movements	-	Ant Colony Optimisation
Savin et al., (2014)	-	-	Maximization of Harvester Rentals	Waste Reduction	Linear Programming
Sørensen et al., (2014)	+	-	Tillage System Selection	Energy Inputs and GHG Emissions	Mixed-integer Programming
Amiama et al. (2015)	-	+	Routing and Machinery Selection	-	A New (Harvest Sillage) Decision Tool
Edwards et al., (2015)	+	-	Fleet Management	-	Tabu Search
Sethanan and Neungmatcha, (2016)	-	+	Infield Logistics Planning	-	Particle Swarm Optimization
Mohamed et al., (2017)	+	-	Machinery Selection	-	Mixed-integer Programming
Rodias et al., (2017)	-	-	Infield Logistics Planning	Energy Inputs and GHG Emissions	Clarke and Wright Savings Algorithm
Amaefule et al., (2018)	-	-	Tillage System Selection	-	Hunt-Wilson Model
Turner et al., (2019)	-	+	Infield Logistics Planning	-	Discrete Event Simulation
Jami et al., (2021)	-	+	Fleet Management	-	Mixed-integer Programming
Wang and Huang, (2022a)	-	-	Fleet Management	-	Mixed-integer Programming
Wang and Huang, (2022b)	+	+	Routing and Fleet Management	-	Mixed-integer Programming
Zhang et al., (2022)	+	-	Machinery Maintenance	-	Back Propagation Neural Network Algorithm

The objective of minimizing operating and fuel costs leads to another kind of problem group involving in-field logistics management. It encompasses the optimization of machinery movement on the field, routing decisions, and dispatching/allocating decisions. There are examples of on-field track movement optimization in the review (Bochtis & Vougioukas, 2008; Bakhtiari et al., 2012) and their main objective is to find the best headland pattern for the operating vehicles which minimize the total non-working distance traveled on the fields. These patterns represent the headland turnings of vehicles switching positions from one track to the next. Fig. 5 shows examples of headland-turning types of agricultural vehicles. We have reviewed some papers dealing with the in-field routing of vehicles to minimize the transportation costs between the fields and the depot. Amiama et al. (2015) deal with this problem along with the machinery selection decisions which affects the routing decisions. Verlinden and Van Oudheusden (2009) model the routing of combine harvesters for a crop-harvesting operation with penalty costs for additional turnings. They try to present a model that can be used for the programming of autonomous vehicles. Sethanan and Neungmatcha (2016) explore this problem for sugarcane field operations which gained a technological development turning manual harvesting into mechanical harvesting. In the study of Rodias et al. (2017), a field area coverage model is presented assessing the effects of automated navigation systems on the reduction of energy consumption to reduce the environmental effects of in-field logistics. The work by Turner et al. (2019) assesses the different harvest rates of wheat and corn for the routing of the same types of harvesters and transporters, which increases the complexity of the problem compared to a single crop type farm. In-field logistics planning also involves fleet management problems which deal with the dispatching of different machines to multiple consecutive tasks and multiple farms. Edwards et al. (2015) tackle this problem with the field readiness concept which requires vehicle dispatching done when fields are ready to be cultivated. This is an issue that is caused by different weather conditions and soil characteristics. Jami et al. (2021) manages a fleet of transporters in their study with resting time consideration which is dependent on the assigned job. Shared agricultural machinery also is a concept that draws attention lately in this context since multiple farms share a fleet of vehicles due to increasing costs of buying and operating costs of machines (Wang & Huang, 2022a; Wang & Huang, 2022b). Zhang et al. (2022) address a new kind of problem of scheduling maintenance operations of combine harvesters which is stated as critical for the timing of harvest and the yield.

Figure 5: Headland Turnings of Agricultural Vehicles



Source: Bochtis et al., 2019

Methodological pattern of machine management studies differs from crop planning mainly because of objective singularity. Due to this fact, there is no goal programming approach in the reviewed studies while mixed-integer programming is the most frequent (8) method for modelling. There are two bi-objective exceptions among them both of which try to minimize the total costs and the average completion time at the same time (Jami et al., 2021; Sethanan & Neungmatcha, 2016). A similar bi-objective system can be seen in the study of Savin et al., (2014) with a linear programming approach. There is a non-linear programming approach in the study of Søgaard and Sørensen, (2004) since they involve a non-linear cost function in the objective and non-linear constraints in the model. In the rest of the studies, we identified that more sophisticated methods are chosen as their problem focus is on operational planning like on-field route planning and dispatching agricultural vehicles in day-to-day operations. Methods in this context are ant colony optimization (Bakhtiari et al., 2012), Tabu Search (Edwards et al., 2015), particle swarm optimization (Sethanan & Neungmatcha, 2016), Clarke and Wright savings algorithm (Rodias et al., 2017) and back propagation (BP) neural network algorithm (Zhang et al., 2022) in our review.

3.3. Harvest Planning

Harvesting decisions are usually considered at an operational level due to being the last stage of the production process on the farm level but they also involve factors like scheduling and machinery capacity and allocation which are included in tactical decision-making. In the reviewed literature, we identified 13 articles mainly focused on harvest planning with some additional considerations related to crop planning and machinery management. The studies are listed in Table 3 with summarizing information.

The most frequently addressed problem in the studies is the scheduling of harvesting operations to achieve the best quality in the harvested product while minimizing the costs in the whole process. This issue is usually considered a problem in the case of high perishability rates, for example managing a vineyard or an apple orchard. In these studies, a quality/cost function is used as an objective which is expected to prevent waste in the yield. Expectedly, these problems are usually crop-specific since every crop has its quality loss function. In the works of Ferrer et al. (2008), Arnaout and Maatouk (2010), and Varas et al. (2020) there is a wine grape harvest planning problem which includes the scheduling of operations, labor allocation and the routing of harvesting units (manual workers, harvesters) decisions with the aim of achieving best wine quality at the least cost. Bohle et al. (2010) and Avanzini et al. (2021) deal with the same problem with the novelty of considering the deteriorating effect of weather uncertainty on labor productivity and grape quality. The same approaches can be seen in other products such as sugar cane (Jena & Poggi, 2013), olive oil (Herrera-Cáceres et al., 2017), wheat (He et al., 2018) and fruit production (Gómez-Lagos et al., 2021).

A different approach is presented by Albornoz et al. (2021), who explore the results of integrating harvest planning with zone delineation which is normally done before harvest planning to distinguish management zones. The authors state that the traditional approach to this problem is a hierarchical one, and by testing the integrated approach they report that the integrated approach gives better results in terms of total harvest cost. The integrated approach is also taken by Solano et al. (2022) for the decisions of crop planning, crop maintenance, and harvesting in banana production. Similarly, they report significant reductions in waste and production costs. Mechanization in harvesting methods creates different research topics as in the work of Harel et al. (2022) who compare the performance of human workers with the robotic harvesters in a sweet pepper harvesting operation. Their findings suggest that the capabilities of robotic harvesters are promising but still need improvements to reach the point of economic feasibility.

Table 3: Research on Harvest Planning

Authors	Scheduling	Labor Allocation	Routing	Machinery Decisions	Highlights	Optimisation Method
Ferrer et al. (2008)	+	+	+	+	Quality/cost Maximization in Wine Grape Harvesting	Mixed-integer Programming
Arnaout and Maatouk, (2010)	+	+	+	-	Quality/cost Maximization in Wine Grape Harvesting	New Heuristics
Bohle et al., (2010)	+	+	+	+	Uncertainty of Labor Productivity in Wine Grape Harvesting	Robust Optimization
Jena and Poggi, (2013)	+	+	+	-	Quality/cost Maximization in Sugar Cane Harvesting	Mixed-integer Programming
Herrera-Cáceres et al., (2017)	+	+	+	-	Quality/cost Maximization in Olive Harvesting	Mixed-integer Programming
He et al., (2018)	-	-	+	+	Minimization of Harvest Period in Wheat Production	Tabu Search
Varas et al., (2020)	+	+	+	+	Quality/cost Maximization in Wine Grape Harvesting	Mixed-integer Programming
Avanzini et al., (2021)	-	+	-	-	Effect of Weather on Labor and Grape Quality	Stochastic Programming
Albornoz et al., (2021)	+	+	-	-	Integration of Zone Delineation and Harvest Scheduling	Mixed-integer Programming
Gómez-Lagos et al., (2021)	+	+	+	+	Quality/cost Maximization in Multiple Orchards	GRASP Metaheuristic
Günder et al., (2021)	+	-	-	-	Quality/cost Maximization in a Multi-crop System	Evolutionary Algorithms
Harel et al., (2022)	+	+	+	+	Comparing Humans and Robots for Harvesting Fruit	Non-linear Programming
Solano et al., (2022)	+	+	-	-	Integration of Sowing, Crop Maintenance, and Harvesting	Non-linear Programming

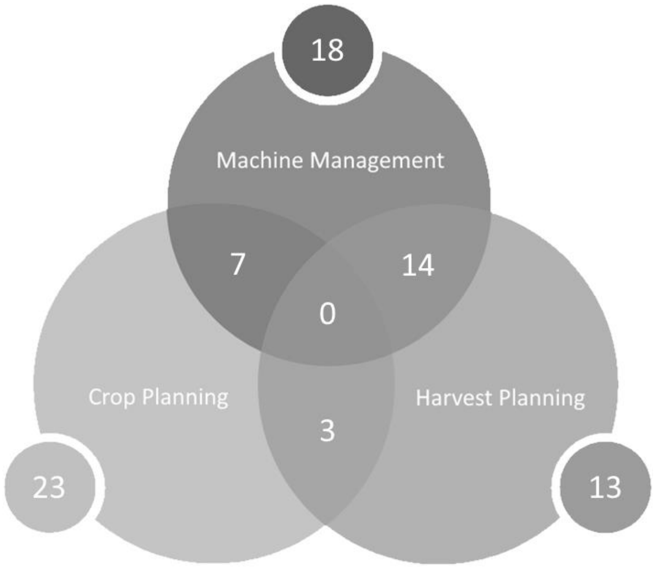
In harvest planning studies, there is a similar methodological framework when compared to machine management studies because of the similarity in planning scope and objective singularity. Mixed-integer programming again is the most preferred (5) among modelling methods with non-linear programming (Harel et al., 2022; Solano et al., 2022), stochastic programming (Avanzini et al., 2021) and robust optimization (Bohle et al., 2010) in the cases of uncertainty. MIP modelling has proven NP-hard in the rest of the papers; therefore, we see a new heuristic approach is proposed in the study of Arnaout and Maatouk (2010) along with other known approaches such as tabu search (He et al., 2018), GRASP metaheuristic (Gómez-Lagos et al., 2021) and evolutionary algorithms (Günder et al., 2021).

4. CONCLUSION

In this study, we present a different review of planning problems in the agricultural supply chain within the scope of Operations Research at farm-level. The papers reviewed exhibit specific characteristics of agricultural production at the farm level and focus on the details of crop production compared to the supply chain models which focus on the integration and coordination of actors from a broader perspective. We identify three main decision problem domains and explain their differences by giving details about the operations considered in each group.

An important finding that can be drawn from the review is that some research incorporates more than one decision area. Pairings like crop-machinery planning (Annetts & Audsley, 2002; Sørensen et al., 2014) and machinery-harvest planning (He et al., 2018; Sethanan & Neungmatcha, 2016) exist in the literature. Fig. 6 shows this intersection between decision problems by numbers. Findings show that the integration of machinery management and harvest planning is studied mostly while crop-machinery and crop-harvest pairings are studied less. To the best of our knowledge, there is no optimization approach for the integration of crop, machinery, and harvest decisions all together. As Ekman (2000) points out, there is an interaction between the machinery system and optimal crop rotation. In fact, the compatibility issue of agricultural machinery regarding soil type, fertilizing option, and crops to be sowed and harvested makes all these decisions interconnected. Therefore, integrated planning models involving multiple stages of production (cultivating, sowing, weed controlling, harvesting) and decision problems (crop and machinery selection) can get more attention in future work.

Figure 6: The Intersection of Decision Areas in the Review



We identify some product-related characteristics among the problem types because of their nature. For instance, while crop planning models have been implemented for both perishable and non-perishable product types, there is a tendency to choose perishable products (especially grapes) among researchers in developing harvest planning problems. On the other hand, machinery management models seem to be more applicable to non-perishable products since most agricultural machinery (especially harvesters) are needed for grain (wheat, barley, oat, etc.) and other crops (sugarcane, cotton, corn, etc.) that require special equipment. Nevertheless, the mechanization in all agricultural production stages increases rapidly which has a potential to lead to new opportunities in optimization models for the planning of more machine-oriented and more diverse crop production systems.

AUTHOR STATEMENT

Statement of Research and Publication Ethics

This study has been prepared in accordance with scientific research and publication ethics.

Author Contributions

The authors contributed equally to the study.

Conflict of Interest

There is no conflict of interest for the authors or third parties arising from the study.

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