A Literature Review of Mathematical Programming Applications in the Fresh Agri-Food Supply Chain

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1 Introduction

The agricultural business, or agribusiness, includes a range of farm-related industries, especially food manufacturing and food services. It covers activities as farming, production, marketing, and management of rural commodities, such as livestock and crops. A plenty of food and beverage manufacturing plants are engaged in transforming raw agricultural materials into products for intermediate or final consumption.

The term **agri-food supply chain** (ASC) has been coined to describe the activities from production to distribution that bring agricultural or horticultural products from farm to the table. ASC is formed by the organizations responsible for production (farmers), distribution, processing, and marketing of agricultural products to the final consumers [2, 6].

In addition to the problems common to most supply chains, ASCs must also deal with factors such as food quality, safety, and weather-related viability. Also, they may manage issues related to limited shelf life, which restricts the amount of time that most products can spend in storage and therefore the capacity of holding inventory as a buffer for variability. Furthermore, compounding the issues of variability and

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perishability, we have very long lead times from the moment that planting is made, until harvest [19, 22, 27].

As will be seen in the following sections, models and solution methods for ASC problems are relatively abundant. Due to NP-hardness of supply chain problems [7] and the large sized data in the real world, meta-heuristics such as genetic algorithm and particle swarm optimization, have been widely used. However, as well as in other optimization problems, the solution technique of **mixed integer programming** (MIP) models, or mixed integer linear programming, can be employed in supply chain problems. As none of the reviews works reported here (in the Sect. 3) focused specifically mathematical programming formulations, our aim is to investigate the published research addressing MIP models for agri-food supply chain problems and the respective constraints considered.

2 Fresh Agri-Food Supply Chain Problem

Due to issues related to public health, in practice agricultural products attracts a great deal of attention, subject to stringent regulations and closer monitoring. This implies that traditional supply chain practices may be under revision and change [2]. In order to address the global challenges and to keep up with the changes occurring in agricultural supply chains, greater efficiency must be achieved by all parties involved. It is because of this strong need to increase the efficiency of the supply chain that planning models will become of increasing importance to farmers, intermediaries, and final distributors of agricultural commodities. Planning tools and information technology for each of these key players must become increasingly refined and applied, in tor to drive non-value-adding costs out of the value chain [22].

Among the specific issues of ASC problem, perishability, in particular, is very critical for horticultural products, whose shelf life is significantly lower than that of traditional crops, like grains, fruits, and other vegetables. Moreover, it is important to consider the greater economic context of the farm business and the position of farmers who are subject to the forces of the market. Also, they have little control over prices, the exact timing and the yields of their crops, all of this while working with relatively small profit margins. Complexity is further compounded when the supply chain has a large amount of stakeholders at various echelon (such as farmers, shippers, and distributors) that must coordinate their actions to avoid losses caused by a mismatch of supply and demand [17, 19, 22].

Nevertheless, Siddh et al. [29] state that the fresh agri-food segment is a profitable venture of all farming activities as it provides ample employment opportunities and scopes to raise the income of the agricultural community. In the last decade, there were dramatic changes in the supply chain of agri-fresh products, which compose a significant position of the world economy as well as they are the supplies for various food processing industries. Inside fresh agri-food supply chains, raw foodstuffs are transformed through packing, distribution, and related services. In this process, it is very important that not only the product quality is ensured but the supply chain quality should be maintained as well.

The agri-food supply chain network typically is a multi-echelon supply chain network with multiple products, including four stages: primary production (of raw products by farmers), production of semi-product by plants, production of finished products and distribution (transporting finished products to the distribution center or consumers). Broadly speaking, the problem can be to determine the optimal number, location, and capacity of the production plants and product type produced by each plant. It also can select transportation mode (by railway, by sea or by truck) and the corresponding amount of items shipping from supplier to plants, between two plants and from plants to distribution centers. The decisions are made given the market demand, such that the total costs (comprising the production and transportation costs) are minimized [37].

Even for local organic food supply chains, designing and managing are complex, and face socially bound uncertainties such as poor collaboration, communication, and information sharing. Moreover, there are aspects such as ethics, sustainability and human values that influence decision making and supply chain activities. Local organic food supply chains are mainly composed of small-scale enterprises that face limitations in implementing complex mathematical models and sophisticated software used in quantitative supply chain design and management. Viable and well-established approaches to reduce the inherent uncertainty are lacking and need to be developed [32].

As pointed out by Mason et al. [22], the technology and tools for increasing the efficiency of ASC have been researched in the past; however, their implementation has been very limited to their mathematical formulation, which contrasts with the intuition of traditional decision-makers, their limitations on capturing the whole system dynamics, and the added complexity inherent of integrated models. Therefore, this work aims to focus on research in fresh agri-food supply chains which employ mixed integer programming models as a solution approach to investigate its improving potential especially in the efficiency of the products delivery.

3 A Tertiary Study of ASC Planning

There are many literature reviews of solution approaches for agri-food supply chain planning. Thereby, this section presents a short tertiary study of this subject matter, i.e., a review of literature reviews. As pointed out by Abedinnia et al. [1], the main objective of tertiary studies is to investigate core themes that have been studied in a particular research area by reviewing and analyzing secondary works (i.e., literature reviews), providing a compact and comprehensive overview of the state of knowledge and unveil general deficiencies of published literature reviews on the subject under consideration. Thus tertiary studies are valuable sources for finding potential areas for future research. Thereafter, we have conducted a secondary study on the (primary) literature specifically about MIP models for ASC problems (in Sect. 4).

Siddh et al. (2017) provided a structured a review of fresh ASC quality over a period of 23 years (1994 to mid-2016) and a platform for practitioners and researchers that identifies the existing state of work, gaps in current research, and future directions in that field. A critical review of ASC management was presented by Ganeshkumar et al. [13], with the gaps to be explored about practices which may be used by researchers to enrich theory construction and practitioners may concentrate on establishing the extent and frontiers of ASC management.

A comprehensive and structured review on recent studies in the field of agribusiness planning models, aiming to optimize fresh ASC, with a focus on loss minimization in the fruits and vegetables was presented by Pamm et al. [23]. From the literature, it is concluded that the importance of food loss minimization is increasing. However, in most of the reviewed papers, food loss minimization is considered as a secondary scope with the main scope of cost decrease or profit increase.

The development of approaches used to identify and assess the risks that occurred in the ASC have mapped by Septiani et al. [28]. The papers found were classified into three stages: risk identification, assessment, and mitigation. Kusumastuti [18] have reviewed the literature on crop-related agri-chains focusing on the integration, or lack thereof, harvesting and processing planning and related inventory control issues. The research highlighted the importance of minimizing food waste and maximizing food quality since crops are particularly prone to deterioration after harvesting and before processing.

The ASC coordination was aimed by Handayati et al. [15], presenting the spectrum of coordination mechanism taken to deal with different levels of interdependencies and quality requirements. Mason et al. [22] published a brief historical overview of planning and optimization models in ASC, with an analysis of the new tendencies of the market. Tsolakis et al. [33, 34] proposed a taxonomy of the literature and practices that apply to all major issues that stakeholders need to address for the design and management of ASC. They presented the generic system components along with the unique characteristics of ASC that differentiate them from conventional supply chain networks.

Operations research and management science applications in the specialty crop industry (fruits, vegetables, grapes, nuts, berries, and dried fruits) were reviewed by Zhang and Wilhelm [36], with the goal of providing a perspective of models available to assist growers and distribution managers as decision support aids and a vision of research needs to stimulate academic research. A variety of models have been devised to support decisions that maximize profit, improve operation efficiency, balance risks, and integrate systems components much more effectively than human decision maker can without them.

Ahumada and Villalobos [2] presented the state-of-the-art for that moment of successfully implemented models for production and distribution of agricultural crops. They classified the models according to relevant features, such as the optimization approaches used, the type of crops modeled and the scope of the plans, among many others. Through the analysis of the current state of the research, they diagnosed some of the requirements for modeling the supply chain of agri-foods.

Lowe and Preckel [19] addressed the main modeling approaches used in crop planning in the context of agribusiness, highlighting some potential areas for research in the area. Lucas and Chhajed [20] considered the location analysis applied to agriculture, covering applications related to the location of warehouses and processing plants. They exposed the complexity and challenges of strategic production–distribution models applied to the agricultural industry and emphasized the emerging use of these models by large corporations. Glen [14] performed an extensive search of the literature previous of the year of 1985, focusing on the mathematical models for farm planning.

4 Publications with MIP Models for ASC Problems

According to the literature reviews presented previously (in Sect. 3), the use of mathematical models and operations research tools for agricultural planning is not a new concept. Instead, optimization models for applications in crop planning can be found since the early 1950 years, even in a tenuous way. This solution technique became more widespread during the decade of 1980, with growing interest in the 1990s. In particular, the perishability of fresh products and risk management are two themes which have quickly gained importance and visibility among the academic community [2, 14, 22]. This last fact highlights the relevance of the present study.

As stated by Zhang and Wilhelm [36], mathematical models have remained relatively small and within the reach of commercial solvers. However, as the industry grows and problems become larger (with more stakeholders, locations, and further collaboration), basic research will become increasingly important to ensure solvability. This review emphasizes the published papers which consider mixed integer programming models as a solution approach for fresh agri-food supply chain problems.

Searches were made at databases Science Direct, ISI and Scopus, from January to March 2018, with the following keywords, isolated and combined: *agri-food*, *fresh food delivery*, *mip models*, *mixed integer programming*, and *mathematical models*. The sample was formed with a manual selection of articles agreeing with the theme of this research. Only papers from indexed journals, peer-evaluated and written in English were considered (excluding publications for scientific events, chapters of books and academic publications such as thesis, dissertations, and monographs).

For each paper reviewed, Table 1 presents in reverse chronological order its reference (author/s and year of publication), the journal (to identify the main research sources of this problem), description of the problem and the case study considered, the objective function of the MIP model, and the kind of numerical input data.

For better visualization of the sample distribution, Fig. 1 presents the number of papers by publication year, from the most pioneering (1991) to the most recent (2017). As can be seen, there are many periods with no published papers: 1992–1996, 1999–2003, 2007, 2009, and 2013–2016. The years with more publications are 2011, 2010, and 2005.

Table 1 Publications reviewed with MIP models for fresh ASC problem

Reference	Journal	Description	Case study	Objective function	Data
Soto-Silva et al. [30]	Computers and Electronics in Agriculture	Optimization models that deal with three related decisions in horticulture: purchasing, transporting and storing fresh produce	Apple dehydration plant in Chile	Minimizing costs of purchasing and maintenance; minimizing costs of transportation and storage	Real data
Stay et al. [31]	Computers and Electronics in Agriculture	An optimization-based seasonal sugarcane harvest scheduling decision support system	Syndicate of four sugarcane growers and their manager at South Africa	Maximizing the total harvesting operational profit	Real data
Ahumada and Villalobos [3]	Annals of Operations Research	An integrated tactical planning model for production and distribution of fresh produce. Logistic decisions associated with the distribution of the crop	Hypothetical producer of green bell peppers and vine ripe tomatoes	Maximizing the expected revenue, given by expected market prices, amount of each crop to be planted, when to harvest and sell them, the labor resources to contract and transportation mode to user to deliver	Hypothetical data

(continued)

Table 1 (continued)

Reference	Journal	Description	Case study	Objective function	Data
Ahumada and Villalobos [4]	Intonational Journal of Production Economics	An operational model that generates short term planning decisions for fresh-produce industry. Profitability is affected by management of labor costs, preservation of the value of perishable crops and use of transportation modes	Hypothetical producer of tomatoes and bell peppers	Maximizing the income, given a choice of customers, the prices and the costs incurred deliver	Hypothetical data
Rong et al. [26]	International Journal of Production Economics	Integrate food quality in decision making on production and distribution in a food supply chain	Supply chain for bell peppers	Minimizing the total costs, given by production, cooling, transportation, storage, and waste disposal costs	Generated instances
Rong et al. [26]	International Journal of Production Economics	Integrate food quality in decision making on production and distribution in a food supply chain	Supply chain for bell peppers	Minimizing the total costs, given by production, cooling, transportation, storage, and waste disposal costs	Generated instances

(continued)

Table 1 (continued)

Reference	Journal	Description	Case study	Objective function	Data
Blanco et al. [8]	Networks and Spatial Economics	An agricultural cooperative which uses harvesters for harvesting the crop and trucks for carrying it from the smallholdings to the landowners' silos	Cooperative of northwest Spain which manages the harvesting of grass and com	Minimizing the total working time of machinery (time of harvesters' activity plus the delays by waiting for trucks to unload)	Generated instances
Carpente et al. [11]	Top	An agricultural cooperative that has a big number of partners, each of them having one or more smallholdings. The cooperative has to crop all the smallholdings by using harvesters	Cooperative of northwest Spain which manage the harvesting of grass and com	Minimizing the total traveling time used by the harvester	Generated instances
Ferrer et al. [12]	International Journal of Production Economics	Scheduling wine grape harvesting operations taking into account both operational costs and grape quality	Vineyard in the central zone of Chile	Minimizing costs and maximizing quality	Generated instances
Higgins [16]	European Journal of Operational Research	Scheduling transport of sugarcane to the mill focusing on reducing vehicle queue times	Sugar mill region in Australia	Minimizing a combination of queue time and idle time	Real data

(continued)

Table 1 (continued)

Reference	Journal	Description	Case study	Objective function	Data
Apraiah and Hendrix [5]	Journal of Food Engineering	A supply chain network with a goal to manufacture a pea-based novel protein food	Data of the Netherlands, France, Ukraine, and Canada	Minimizing the sum of the production and transportation costs	Real data
Blanco et al. [9]	Journal of Food Engineering	Operations management of a packaging plant in the fruit and concentrated juice industry	Fresh fruit industry (apples and pears) and concentrated juice from Argentina	Maximizing total profit (sales income minus raw material, labor and cooling costs)	Real data
Rantala [25]	Silva Fennica	A capacitated MIP model for solving an integrated production distribution system design problem in the seedling supply chain management	Multi-unit Finnish nursery company	Maximizing the sum of production, storage, and transport costs	Real data
Broekmeulen [10]	International Transactions in Operational Research	Tactical decision problem of improves the effectiveness of the operations of a distribution center of vegetables and fruits	A wholesaler of vegetables and fruits in the Netherlands	Maximizing a cost function (the fraction of the quality that is lost every day)	Generated instances (based on real data)

(continued)

Table 1 (continued)

Reference	Journal	Description	Case study	Objective function	Data
Maia et al. [21]	International Journal of Production Economics	Selection of technology routes for fruit and vegetable crops between harvest and market	Small cooperative of banana producers in the southwest of Brazil	Maximizing the expected profit	Real data
Zuo et al. [38]	The Journal of the Operation Research Society	A large-scale agricultural production and distribution problem, involving allocation of products to available production plants and transportation to the customers	Large seed com production company	Maximizing the sum of production and transportation costs	Generated instances

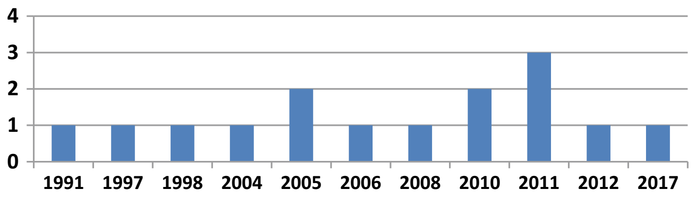

Fig. 1 Number of published papers by year

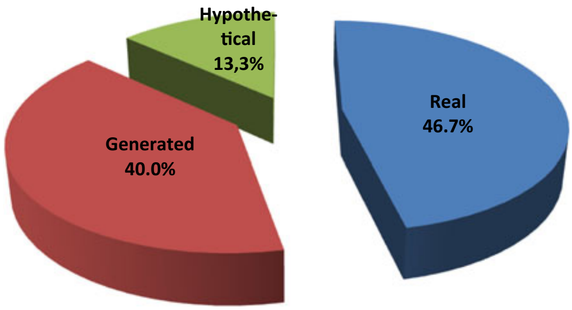

Fig. 2 Percentage of each type of data instances

In relation to the database considered, Fig. 2 shows the three types of instances found in the literature. The most frequent type in the sample is the real data, present in 46.7% of the papers. However, this amount does not represent even half of the papers, which is noteworthy, since the sample composed of cases studies. Of the other types of instances, 40.0% of papers have considered generated data and 13.3% have used hypotheticals.

Apart from the references cited in Table 1 (which considers just paper of journals), we can also refer to some publications of events: Zhao and Lv [36] studied an Apple industry cluster for optimizing the facility location, production capacity selection and choice of transportation mode for an ASC network design; Yandra et al. [35] addressed an integrated decision support system with multi-objective optimization for Transportation of coconut or palm oil and biodiesel; and Quadra et al. [24] considered a three-level (resource, production, and distribution) multi-period multilocation and multi-crop sustainable supply chain model.

5 Conclusion

The present work has updated the state-of-the-art of mathematical programming applications in the fresh agri-food supply chain. Despite the considerable amount of research that has used the MIP formulation for fresh ASC, this is clearly not the only modeling technique, nor is it the only exact (or optimal) solution approach.

As observed in the reviewed papers, mathematical formulations are used in cases where de input data are considered deterministic, as is also the case of dynamic programming and goal programming. Otherwise, stochastic modeling approaches or simulation can be used.

A sample of fifteen journal papers, published from 1991 to 2017, was analyzed. No article addressing fresh ASC and applying MIP models was found from 2013 to 2016. The publication sources are relatively spread: the International Journal of Production Economics was the one that the most had publications (4 papers); in the Journal of Food Engineering and the Computers and Electronics in Agriculture was found 2 papers each; and all others had just one article.

As can be seen, less than half of works applied their models to solve real-life problems using actual data (just 7 papers, i.e., 46.7% of the sample). This fact is interesting, since most of them presented a case study, even so with artificially generated instances. Therefore, identifying this gap in the literature, we suggest for future works the utilization of real data in the MIP models for fresh ASC problems.

It can be noticed in the literature review that there are many other papers not considering the perishability characteristic, simplifying the analysis and thereafter the results. However, the perishability is a real-life feature and important data for the models to provide solutions more accurate and effective. This reveals considerable research potential in the area of ASC problems with perishability.

Although it is not a new solution technique, this literature review highlights how little this approach has been explored in the ASC area. Also as can be noticed, mathematical formulations can be applied at several points in the supply chain under study: in production (planting and harvesting), localization, distribution and dimensioning, including the integrated way. For this reason, the use of mathematical formulations, combined with the advances in information technology and the high processing power of modern computers, is strongly recommended and highly encouraging in the fresh ASC problems.

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