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Review Article

Optimization models for perishable product scheduling: a literature review

Modelos de optimización para la producción de productos perecederos: una revisión de la literatura

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Spanish version

Abstract

Introduction: The production scheduling problem has been widely studied in the literature; however, the lifespan variable has only recently been considered for modeling processes. Thus, it is relevant to understand how product lifespan has been addressed by researchers and academic community.
Objetive: The aim is to identify how lifespan factors have been included in production scheduling decisions as well as the methods applied to their processing.
Materials and methods: A literature review process was conducted based on the SCOPUS and WEB OF SCIENCE databases. The search, with no date range, allowed to obtain 272 documents. After the selection stage, a group of 35 articles were filtered for analysis.
Results: Five cases of decision aggregation were identified during the review, among which the definition of batch size associated with scheduling decisions is highlighted, as well as three ways in which the perishability condition of products, or raw materials, can be incorporated into the models. Mixed integer linear programming was also found to be the most widely used methodology in the cases reviewed.
Conclusions: This study confirms the importance of incorporating perishability into production scheduling problems. In addition, due to the risk of losses that characterizes these environments, scheduling decisions are often associated with batch sizing, route design, and cost strategies, that seek to minimize losses or improve profits or consumer satisfaction.

Keywords: perishable products, sequencing, scheduling, mixed-integer linear modeling.

Resumen

Introducción: Los problemas de secuenciación han sido ampliamente abordados por la literatura, sin embargo, la variable vida útil solo se ha incorporado recientemente a su modelación, por lo que se considera relevante conocer el tratamiento que ha tenido por parte de los investigadores.
Objetivo: Se busca identificar la forma en que se ha incluido la consideración de vida útil en las decisiones de secuenciación de la producción y los métodos para su tratamiento.
Materiales y métodos: Se realizó una búsqueda de literatura en las bases de datos SCOPUS y WEB OF SCIENCE, sin límites de tiempo, de la cual se obtuvieron 272 documentos que, una vez seleccionados, dejaron un grupo de 35 artículos para el análisis.
Resultados: La revisión permitió identificar cinco casos de agregación de decisiones entre los que sobresale la definición de distribución y ruteo asociado a decisiones de programación, así como tres formas en las cuales se incorpora la condición de perecibilidad de los productos o materias primas en los modelos. También se encuentra que la programación lineal de enteros mixtos es la metodología más usada en los casos presentados.
Conclusiones: La revisión ratifica la importancia que ha ganado la incorporación de la característica de perecibilidad en los problemas de programación de la producción. Adicionalmente, por el riesgo de pérdidas propio de estos entornos, las decisiones de programación suelen ir asociadas a decisiones de tamaño de lote, diseño de rutas y estrategias de costo que buscan minimizar las pérdidas o mejorar la utilidad o la satisfacción del consumidor.

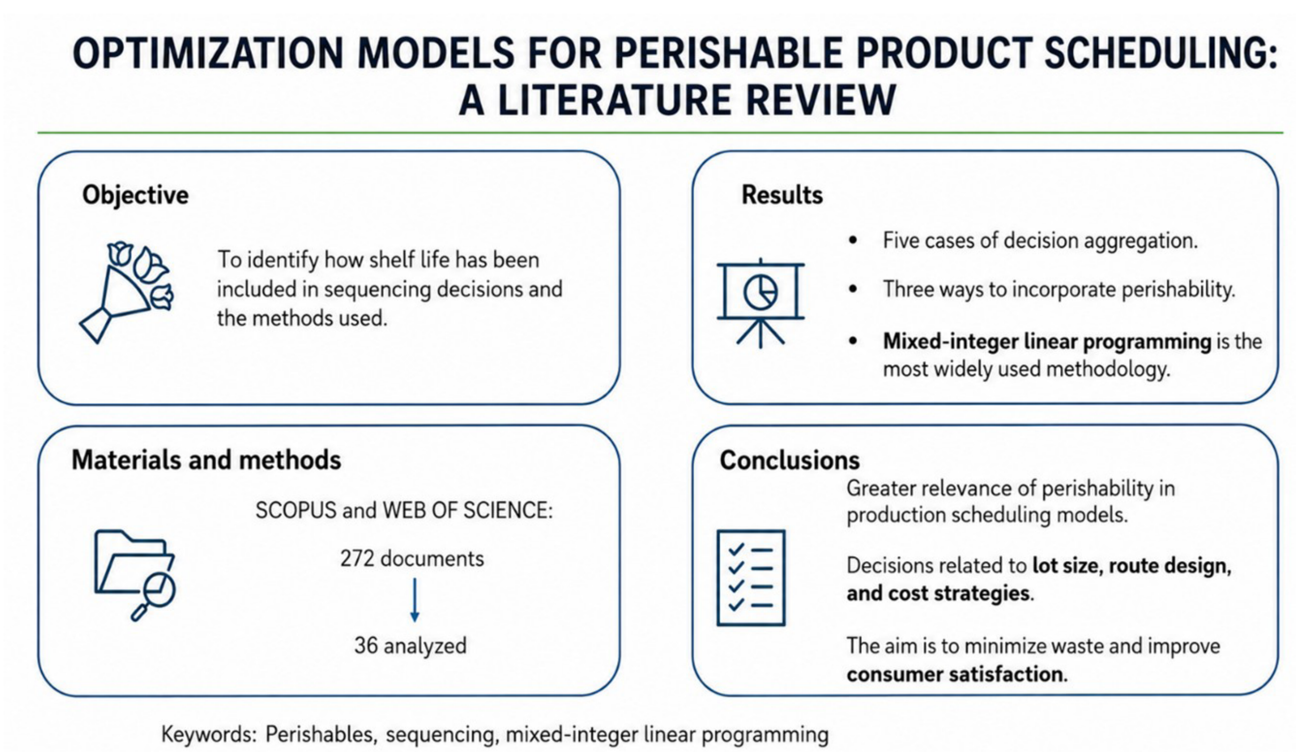
Palabras clave: productos perecederos, secuenciación, programación, modelación lineal de enteros mixtos.

Why was this study conducted?
This review is part of a broader research project aimed at designing a scheduling model for postharvest flower operations. The study seeks to define how perishability has affected production scheduling decisions, as well as the methods used for modeling and solving these problems.

What were the most significant findings?
The reviewed literature shows three approaches through which the perishability variable has been incorporated into production scheduling in industrial environments based on resources derived from the agricultural sector. Additionally, the findings reveal that mixed-integer linear programming is the most frequently used method to support scheduling decisions in these environments, which are commonly integrated with other decision types such as lot sizing and route design.

What do these results contribute?
From an academic perspective, the review findings enable the identification of methods and techniques for addressing order sequencing problems in perishable production environments. From a practical perspective, the results provide guidance for decision-makers regarding the complexity associated with these decisions and the factors that should be considered during the decision-making process.

Graphical Abstract



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Introduction

Scheduling problems have been extensively addressed in the production management literature; however, the consideration of product shelf life remains a relatively recent aspect. One of the earliest studies incorporating this variable was conducted by Monahan (1), although interest in this type of problem has increased considerably in recent years due to factors such as climate change, urban densification, and the post-COVID-19 context, which have increased pressure for more efficient utilization of production resources. A representative study within this trend is that of Hariga (2), who incorporated product expiration dates associated with deterioration rates into an inventory optimization model.

Despite the growing interest in incorporating perishability into production scheduling models, its treatment remains heterogeneous and fragmented throughout the literature. In many cases, traditional scheduling models do not explicitly consider product shelf life, which may lead to significant losses, quality deterioration, and reduced customer satisfaction. This situation is particularly critical in agro-industrial sectors, where products have limited shelf lives and high sensitivity to storage and processing conditions. Consequently, it becomes necessary to consolidate and analyze the cases reported in the literature in which perishability is integrated into sequencing decisions in order to identify trends, predominant methodologies, and research opportunities.

The importance of incorporating perishability into production sequencing, as well as its close relationship with strategic and tactical problems such as vehicle routing and inventory management, is reflected in the studies reviewed, in which these decisions are integrated to achieve more coordinated and comprehensive operations that contribute to improved product preservation (3).

This article presents a literature review on optimization models applied to the production scheduling and sequencing of perishable products (PPs), with the purpose of providing a reference framework for this type of problem. The article is organized into the following sections: review methodology, bibliometric review of results, results analysis, discussion of results, and conclusions.

Methodology

A search was conducted in the ScienceDirect, Scopus, and Web of Science databases within the title, abstract, and keywords fields. No time restrictions were established in order to identify seminal studies and examine the evolution of the incorporation of the perishability variable into production scheduling models. The search equations used were as follows:

“production scheduling” AND parameters AND “perishable products” (1)

“production sequencing” AND “perishable products” (2)

A total of 272 articles were retrieved from this search and subsequently filtered according to the following criteria: 1. Articles written in English. 2. Articles related to perishable products of agricultural origin (fruits, vegetables, meat products, dairy products, among others), excluding products such as concrete, pharmaceuticals, chemicals, and similar products. 3. The problems addressed had to correspond to postharvest stages; therefore, the selected studies focused on the transformation stage of PPs. 4. Articles concerning the development of optimization models. 5. The

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modeling approach had to incorporate product perishability through the consideration of either a maximum consumption period or an expiration date, as proposed by Vahdani et al. (4).

Review articles addressing the scheduling of PPs, as well as optimization models applied in agriculture, were also included to perform cross-search procedures aimed at identifying studies not retrieved through the initial search equations, as in the case of Shadkam and Irannezhad (5). Conference papers were also included, provided that no journal article addressing the same topic had been published by the same author(s).

Bibliometric review of results

Based on the procedure described above, 35 articles were selected for analysis. Figure 1 shows that 51% of the studies incorporating the perishability variable were published between 2018 and 2025 (the latest publication year among the selected articles). This trend may be explained by the development of information chnologies and the implementation of decision support systems within perishable supply chains (6).

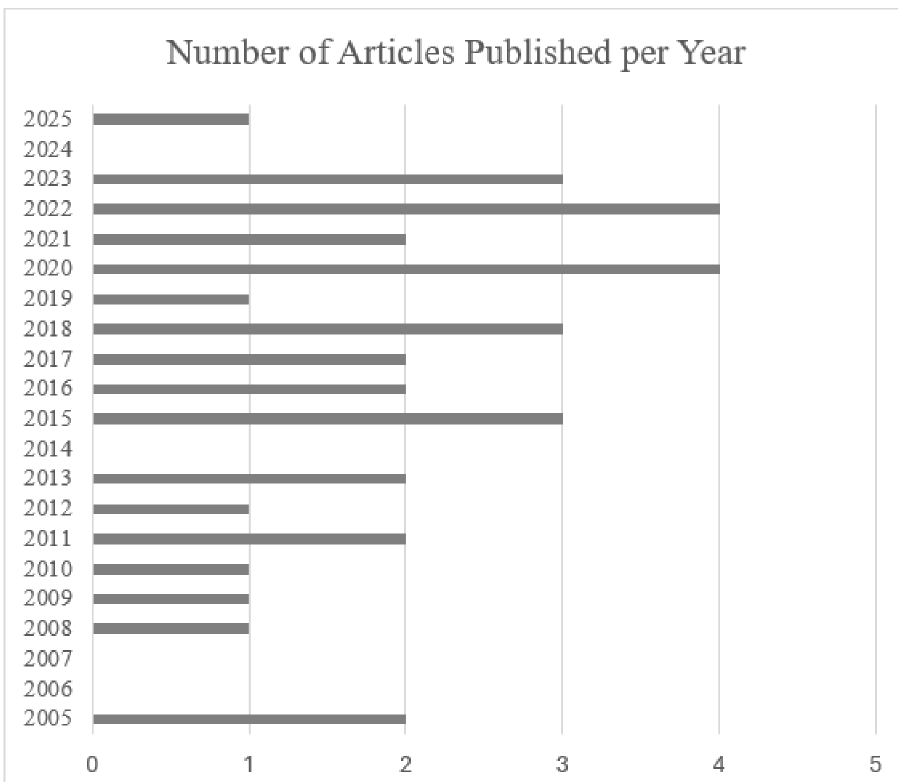

Figure 1. Number of Articles Published per Year

Based on the institutions with which the authors are affiliated, Table 1 was constructed. It shows that 44.9% of the studies originated from countries in Asia, 38.2% from European countries, and 16.9% from countries in the Americas. Among all countries, the highest levels of participation corresponded to Iran (22.5%), Germany (15.7%), China (13.5%), and the Netherlands (10.1%).

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Table 1. Distribution of Authors by Country of Institutional Affiliation

Country	**Number of Authors**	**Percentage**
Iran	20	22.5%
Germany	14	15.7%
China	12	13.5%
Netherlands	9	10.1%
United States	7	7.9%
Brazil	5	5.6%
France	4	4.5%
Portugal	4	4.5%
Taiwan	3	3.4%
Türkiye	3	3.4%
Argentina	2	2.2%
India	2	2.2%
Italy	2	2.2%
United Kingdom	1	1.1%
Chile	1	1.1%
TOTAL	92	100%

To identify the main thematic lines and research trends present in the selected articles, a keyword density analysis was conducted based on the terms reported by the authors in each publication. According to Figure 2, the results are concentrated around terms associated with production scheduling and the integration of logistics decisions in PPs. The most frequently occurring keywords were *production scheduling*, *vehicle routing*, *perishability*, and *lot sizing*, indicating a predominant interest in developing integrated models aimed at coordinating production, storage, and distribution activities.

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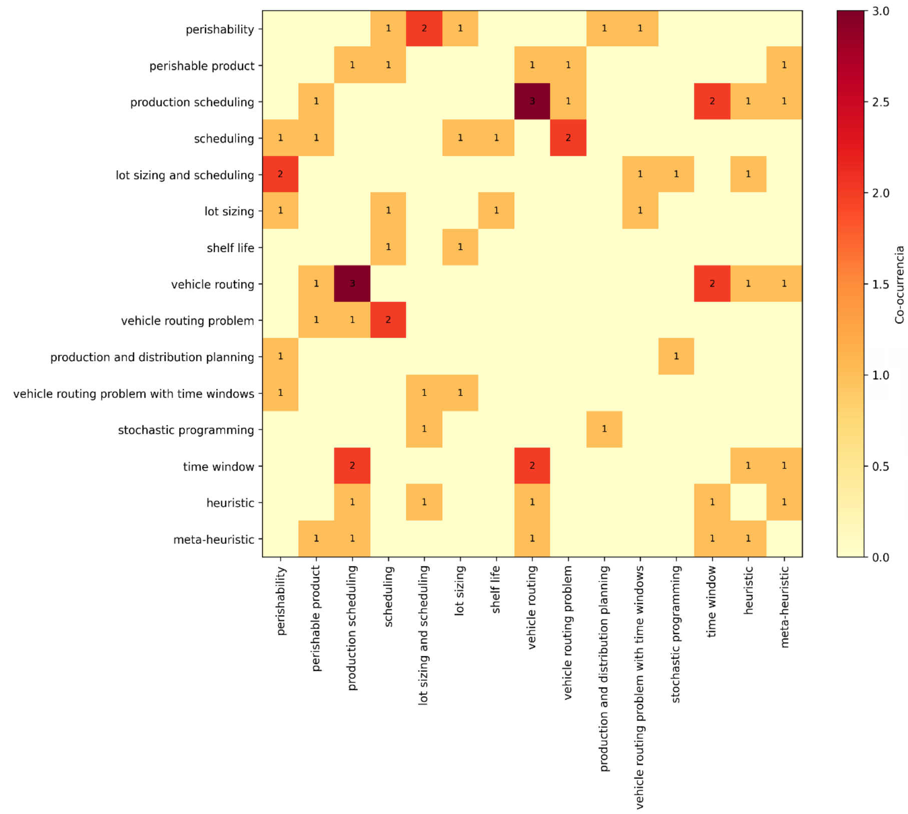

Figure 2. Keyword Heat Map

Based on these results, the articles were classified according to the integration of production scheduling with other decisions within the operations management process. Accordingly, it was found that distribution and routing (DR) problems constitute the most extensively studied category, as shown in Table 2.

Table 2. Percentage of Articles by Problem Addressed

Problem Addressed in Conjunction with Production Scheduling	Number of Articles	%
Distribution and Vehicle Routing	16	45.7%
Lot Sizing	11	31.4%
Production Planning	6	17.1%
Inventory Management	1	2.9%
Production Scheduling	1	2.9%

The categories mentioned above are reviewed in the following section.

Results

Classification

This article proposes a classification of the reviewed studies based on how they address the integration of production scheduling decisions with other operational and strategic activities, with

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the objective of highlighting the importance of functional coordination to improve the overall efficiency of production systems. This classification was based on identifying the activity or process stage that, together with production scheduling, presented the greatest level of detail both in model development and in the presentation and discussion of results.

Although previous literature reviews (7)(8)(9) have proposed classifications based on the integration of scheduling decisions with areas such as inventory management and resource optimization, the classification proposed in this article differs because the search strategy was not designed to identify these combinations; rather, they emerged as a result of the review itself. The resulting categories were: lot sizing (LS), distribution and vehicle routing (DR), production planning, inventory management, and production scheduling.

Production Scheduling and Lot Sizing (LS) Problems

Problems integrating production scheduling and LS decisions have been extensively addressed in the literature. These problems may be analyzed from an inventory management perspective because one of their primary objectives is associated with reducing holding costs generated by lot sizes exceeding production consumption rates (10). The two main questions addressed by these models are how much and when to produce (11). According to Chen (8), these problems may involve tactical and/or operational decision-making levels.

An important characteristic is that LS is not treated as a static decision but is adjusted according to factors such as product demand (12) and production capacity (13).

Regarding the methodologies applied, Table 3 shows that mixed-integer programming (linear or nonlinear) is the most frequently employed approach for problem modeling, although both solution methods and objective functions differ among studies. Only the work by Yao and Huang (14) employed stochastic programming and a genetic algorithm to minimize production and inventory holding costs.

Regarding the solution methods employed, three (3) studies used CPLEX software; however, genetic algorithms and different heuristic approaches were also implemented to solve the proposed models.

Pahl and Voß (15) addressed the discrete LS problem jointly with production scheduling and incorporated product perishability as a fixed deterioration rate. To represent time, the authors divided macro-periods into micro-periods.

Pahl et al. (16) revisited the discrete LS problem integrated with production scheduling and additionally incorporated sequence-dependent setups. This characteristic is relevant because, as explained by the authors, LS affects setup costs, inventory costs, and product freshness; therefore, the trade-off generated among these factors becomes determinant for decision effectiveness. In their model, product shelf life was incorporated through a deterioration factor, where a value of zero indicates that the product cannot be stored, whereas a value of one indicates that the product may be stored during the period immediately following production.

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The incorporation of sequence-dependent setup costs was also addressed in (17), (18), and (13). In the first study, the authors developed a stochastic integer programming model in which product shelf life was treated as a constant. The solution approach consisted of combining a path relinking algorithm with a mixed-integer linear programming solver. In the second publication, parallel machines were incorporated into system configuration because these problems cannot be addressed by decomposing the system into a set of simple machines, particularly when only one resource is available for setup activities. The third study incorporated multiple production lines and resource scarcity; the proposed solution consisted of a heuristic combining a branching rule with a relax-and-fix procedure.

Amorim et al. (19) proposed multi-objective mixed-integer programming models for sequencing and lot sizing under two production scenarios: pure make-to-order and a hybrid configuration between make-to-order and make-to-stock. One of the main contributions to the scheduling problem of PPs was the inclusion of two objective functions: minimizing costs and maximizing product freshness at dispatch time.

Study (20) compared two mathematical models with different decision levels. In the first model, the problem focused on defining the continuous scheduling of similar jobs. The second model was proposed as an extension of the first because it aimed to determine how product batches should be produced in terms of timing and quantity, as shown in Table 3.

Table 3. Publications Addressing the Integrated Problem of Production Scheduling and Lot Sizing

Article	Model Type	Solution method	Objective Function	Related Perishable Product
(14)	Stochastic Programming	Hybrid Genetic Algorithm	Minimize production and inventory holding costs	Vegetables, fruits, and fresh food pro
(15)	Mixed-Integer Linear Programming	CPLEX	Minimize production and inventory holding cost	Fruits and vegetable

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(16)	Mixed-Integer Programming	Author-developed heuristic	Minimize setup costs, inventory holding costs, and disposal costs associated with capacity constraints	Food products
(19)	Mixed-Integer Programming	Genetic Algorithm	Minimize production costs; maximize the freshness of dispatched products	Yogurt
(20)	Mixed-Integer Programming	CPLEX	Minimize production costs	Prepared food products
(17)	Stochastic Integer Programming	Author-developed heuristic	Maximize profit	Food products
(21)	Mixed-Integer Linear Programming	Adaptive Large Neighborhood Search (ALNS)	Minimize total production and distribution costs	Food products
(18)	Mixed-Integer Programming	Hybrid Relax-and-Fix and Fix-and-Optimize Heuristic	Minimize production and inventory holding costs	Fruit preparations
(12)	Mixed-Integer Linear Programming	CPLEX	Minimize makespan	Dairy products
(13)	Mixed-Integer Programming	Relax-and-Fix Heuristic with Branch-and-Bound	Minimize production and inventory holding costs	Meat-processing industry

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(22)	Mixed-Integer Programming	Hybrid Relax-and-Fix and Fix-and-Optimize Heuristic	Minimize costs related to production, inventory holding, production sequence setup, and shelf life	Food products

The integration of LS, production scheduling, and vehicle routing problems was further addressed by Belo-Filho et al. (21). To solve this problem, the authors proposed a mixed-integer linear programming model in which product shelf life was represented as a fixed time interval. In this study, an adaptive large neighborhood search algorithm was implemented with the objective of minimizing production and distribution costs.

The studies described above use deterioration rates that vary according to different factors to model product perishability characteristics or limit product or raw material shelf life to a fixed number of days. In contrast, Sel et al. (12) developed a mixed-integer linear programming model aimed at minimizing makespan and proposed a deterministic approximation to the probability of product perishability. This approach was complemented with a simulation model to evaluate different shelf-life durations and thereby estimate scheduling losses.

Alipour et al. (22) addressed LS and scheduling problems within a system composed of multiple parallel production lines, multiple periods, and sequence-dependent setups. In addition to minimizing production, inventory holding, and waste costs, the objective function incorporated costs associated with product shelf life. One of the most interesting aspects of this study is the use of two heuristics for model solution. The first heuristic, *relax-and-fix*, allows the identification of a feasible solution to the problem, which is subsequently improved using the second heuristic, *fix-and-optimize*.

Production Scheduling, Distribution, and Vehicle Routing (DR) Problems

DR problems have received considerable attention due to the importance of this stage for preserving PPs, since their objectives are associated with reducing transit times and ensuring product quality and safety conditions. Studies such as (23), (24), and (25) exemplify the treatment of this topic; however, these works do not incorporate production scheduling problems.

The integration of routing problems with production sequencing for PPs is justified by the relationship between both stages of the logistics process. Production scheduling aims to maximize product freshness and shelf life, whereas routing and distribution activities must ensure sufficient operational efficiency to transfer these benefits to final consumers.

As shown in Table 4, the treatment of problems integrating routing and production scheduling results in a greater diversity of models and solution methods compared with LS problems. In the

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earliest publications, the objective function focused on profit or profitability maximization, as illustrated in (26). To achieve this objective, the authors developed a nonlinear programming model considering stochastic demand and a single production line.

The formulation considered customers with different time windows; however, delivery delays were allowed, although associated with penalty costs. Product shelf life was incorporated into the model through a deterioration rate.

Table 4. Publications Addressing the Integrated Problem of Production Scheduling, Distribution, and Vehicle Routing

Article	Model Type	**Solution Method**	**Objective Function**	**Related Perishable Product**
(26)	Nonlinear Programming	Constrained Nelder–Mead Method and Author-developed Heuristic	Maximize profit	Food products
(27)	Multiobjective Mixed-Integer Programming	CPLEX	Minimize production, inventory holding, and transportation costs; maximize the average remaining shelf-life fraction of delivered products	Food products
(28)	Mixed-Integer Linear Programming	CPLEX	Maximize profit	Dairy products
(4)	Stochastic Programming	Author-developed Heuristic; Water Cycle Algorithm	Maximize profit	Food products
(29)	Mixed-Integer Linear Programming	Greedy Randomized Adaptive Search Procedure (GRASP) with Evolutionary Search Algorithm	Minimize makespan	Food products

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(30)	Stochastic Programming	Scenario Reduction Algorithm	Maximize profit	Dairy products
(31)	Multiobjective Mixed-Integer Linear Programming	Monte Carlo Criterion-Based Hyper-Heuristic	Minimize costs and maximize customer purchase probability	Food products
(32)	Mixed-Integer Nonlinear Programming	Neighborhood Search Algorithm Combined with Simulated Annealing	Minimize setup, inventory holding, and vehicle routing costs	Meat-processing industry (chicken)
(33)	Robust Multiobjective Programming	Not specified	Maximize profitability and minimize environmental impact	Lettuce
(34)	Mixed-Integer Linear Programming	CPLEX	Minimize total cost	Vegetables
(35)	Mixed-Integer Linear Programming and Fuzzy Programming	Hybrid Imperialist Competitive Algorithm and Self-Adaptive Differential Evolution	Maximize profit	Food products
(36)	Stochastic Programming	Five-Phase Metaheuristic	Minimize production, inventory, and distribution costs	Food products
(37)	Mixed-Integer Programming	CPLEX	Minimize production costs	Food products
(38)	Multiobjective Mixed-Integer Linear Programming	Goal Programming	Minimize total cost and maximize the reliability of selected suppliers	Meat-processing industry (chicken)
(39)	Mixed-Integer Linear Programming	Particle Swarm Optimization (PSO)	Minimize carbon emissions from production, inventory, and routing activities; minimize total costs	Food products
(40)	Mixed-Integer Linear Programming	Ant Colony Optimization and Fuzzy Genetic Algorithm	Minimize production and distribution costs	Food products

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The problem of stochastic demand was revisited by Mousavi et al. (36), who developed a stochastic programming model aimed at minimizing production, routing, and inventory costs. To solve the problem, the authors proposed a five-phase metaheuristic approach. Product shelf life was incorporated through a parameter intended to penalize lack of freshness according to a predefined time threshold.

Unlike the previous study, (28) did not consider stochastic demand but incorporated times and costs associated with production system reconfiguration into the model. The authors combined a simulation model with the optimization model to obtain dynamic operation times and increase model realism. Within the objective function, a component associated with product price allowed the impact of freshness on operational profitability to be quantified.

Setup costs were revisited in (34), where the authors additionally considered the energy impacts associated with production and distribution activities.

In (4), besides addressing vehicle routing and production scheduling problems, a multi-stage production system was considered, in which work-in-process inventory and the corresponding holding costs were incorporated at each stage. Similar to (26), the authors modeled stochastic demand using a known probability distribution. To solve the problem, they developed a proprietary solution approach and compared it with the Water Cycle algorithm (41), finding that the latter produced better solutions.

Distribution problems integrated with production scheduling and inventory management were also addressed by Ghasemkhani et al. (35), who proposed a mixed-integer linear programming model that was subsequently transformed into a fuzzy model to incorporate demand uncertainty and maximize system profitability. In this model, shelf life was represented through a parameter that determines product quality according to the time required to reach the final retailer.

Study (29) proposed a mixed-integer linear programming model to represent a production system composed of one machine and multiple distribution vehicles. The objective function was associated with makespan minimization rather than cost minimization, which is the most common approach. For solution purposes, the authors proposed a hybrid algorithm combining the greedy randomized adaptive search procedure with an evolutionary search algorithm (42). Product shelf life was defined as a constant incorporated into a constraint limiting both the maximum delivery time to the last customer within a sub-route and production completion time.

Publications such as Vahdani et al. (4) highlight the importance of uncertainty modeling in perishable production scheduling to improve efficiency, business integration, and responsiveness (43). However, demand is not the only source of variability; in these systems, the supply of raw materials, which is generally perishable, also presents uncertainty. Regarding this source of variability, Guarnaschelli et al. (30) incorporated a probability distribution for raw material supply and represented it through a set of scenarios and associated probabilities.

Studies such as (19) and (38) leveraged the potential of multi-objective models to identify the best possible solutions for two opposing or complementary objectives. Among the studies integrating distribution and production scheduling, works (31), (27), and (33) were identified. The first

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aimed to minimize production and distribution costs while simultaneously maximizing purchase probability. These objectives may be considered conflicting because increasing purchase probability is associated with expanding production and distribution capacities capable of guaranteeing customers fully fresh products within extremely short delivery times, thereby increasing costs.

In the second study, the authors incorporated lot sizing into a problem integrating production scheduling and distribution using both fixed shelf-life and flexible shelf-life approaches. The objective was to minimize total supply chain costs while maximizing the freshness of products delivered to customers.

The third article presented a robust optimization model aimed at maximizing profit while reducing environmental impacts. To achieve this objective, parameters associated with uncertainty in production and transportation costs were incorporated.

Although integrating multiple objectives into a single model is common practice, studies such as Sun et al. (39) addressed independent models to optimize the two objectives considered, which in their specific case were minimizing carbon emissions and minimizing total costs.

According to Schouten et al. (44) and Li (40), product quality is a customer priority and must be guaranteed throughout all stages of the logistics cycle. This is reflected in studies such as Manouchehri et al. (32), who incorporated warehouse and transportation vehicle temperatures into their model as both cost parameters and constraints. Additionally, they evaluated product degradation through microorganism counts measured at different stages of the process and restricted these counts according to predefined thresholds.

Lejarza et al. (37) integrated two models: the first related to quality dynamics, considering different environmental factors, and the second focused on the supply chain beginning from the production stage.

Production Planning and Production Order Scheduling

One of the most important differences between production planning and production scheduling lies in the time horizon to which they refer. Production planning generally considers long-term process capacity, whereas scheduling decisions belong to the operational level and are developed within subdivisions of the planning horizon, as shown in Figure 3.

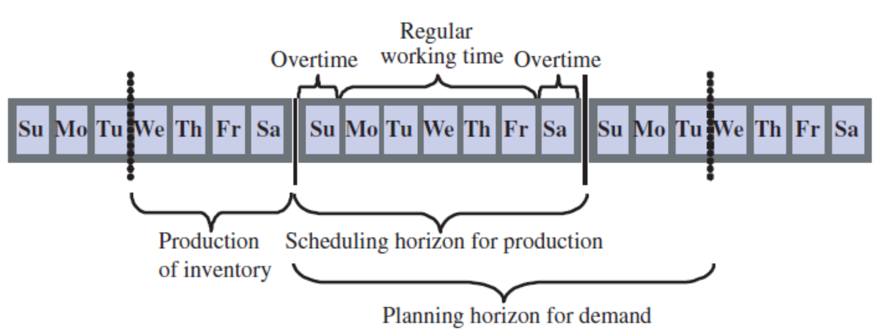

Figure 3. Planning Horizon. Reproduced from (45)

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Table 5 presents the articles that consider the relationship between planning and production scheduling for PPs. The first of these studies was conducted by Entrup et al. (45), who developed a mixed-integer linear programming model through which they addressed the scheduling of product flavoring and packaging stages using a continuous-time representation. The researchers employed a time grid in which each period corresponded to one day, and product shelf life was expressed in days. The objective function aimed to maximize contribution margins while considering variable costs and revenues throughout the planning horizon, for which product price was affected by shelf life.

Similarly, Singh et al. (46) addressed packaging operations by determining processing sequences while simultaneously defining inventory levels and facility capacity. Their approach consisted of two stages: the first focused on sequencing and assignment decisions, whereas the second modeled stochastic demand. The authors considered both maximum and minimum remaining shelf life as model parameters.

Likewise, Steinbacher et al. (47) addressed the production planning problem in a salad manufacturing company jointly with production order sequencing, using a mixed-integer linear programming model combined with a simulation model.

Table 5. Publications Addressing Sequencing Problems Integrated with Planning Problems

Article	Model Type	Solution Method	Objective Function	Related Perishable Product
(45)	Mixed-Integer Linear Programming	CPLEX	Maximize contribution margin while accounting for the shelf-life component	Yogurt
(48)	Mixed-Integer Linear Programming	Decomposition Heuristic	Minimize costs	Dairy products
(49)	Mixed-Integer Linear Programming	Relax-and-Fix heuristic	Minimize setup and inventory holding costs	Food products
(50)	Mixed-Integer Linear Programming	CPLEX	Minimize setup, production, and inventory holding costs	Food products
(46)	Stochastic Programming	Generalized Benders Decomposition-Based Heuristic	Maximize profit	Yogurt

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(47)	Mixed-Integer Linear Programming	Not specified (Gurobi)	Combination of makespan minimization and ingredient deterioration minimization	Delicatessen salads

As observed in Figure 2, the length of the time interval is a key factor in delimiting the scope of production planning and scheduling decisions. Sel et al. (48) proposed a heuristic that improves the computational efficiency of hybrid planning and scheduling problems. Their objective was to minimize costs associated with product deterioration, production, inventory management, overtime operations, packaging, transportation, and unmet demand.
The heuristic consists of dividing the problem into two submodels: the first considers a longer planning period, whereas the second addresses shorter scheduling intervals. According to the authors, the first submodel acts as a master process responsible for calling the second model to support scheduling decisions.

The model proposed by Claassen et al. (49) simultaneously addressed LS and production scheduling decisions while considering production system configuration and focusing on inventory levels and product changeovers. Perishability was incorporated through a deterioration rate parameter included in the objective function. Similarly, Wei et al. (50) incorporated LS decisions; however, unlike the models presented in subsection 3.2, these authors emphasized the division between macro-periods and micro-periods, which, as previously discussed, constitutes one of the foundations for differentiating long- and short-term decisions.

Inventory Management

Production scheduling and inventory decisions including raw materials, work-in-process inventory, and finished goods inventory are closely related, as observed in (12), since they determine both system costs and inventory levels required to achieve service objectives.

In Buisman et al. (51), the authors developed a mixed-integer linear programming model integrating food donation management with menu planning in a charitable organization. The model aimed to determine which donations should be accepted according to inventory availability and how these donations should be efficiently used in menu planning. Under this approach, maximum product shelf life was specified as a parameter, whereas the decision variable corresponded to the remaining shelf life of products at the time of consumption.

Production Scheduling

In Cai et al. (52), product shelf life was associated with a deadline after which products could no longer be delivered to customers but could still be used in another process or sold; therefore, a salvage value was assigned. This approach ensures that products delivered to customers maintain high freshness levels.

The authors proposed a nonlinear model and a proprietary solution algorithm composed of three phases: selection of the optimal sequence according to product type, selection of the optimal

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sequence within each product category, and finally, allocation of processing times to each product on the machines.

Discussion of results

Throughout the previous section, three main approaches for modeling and representing product perishability in production sequencing problems can be identified: fixed time periods, deterioration factors represented through fixed rates, and probabilities associated with product perishability. According to the information presented in Table 6, fixed time periods constitute the most frequently used approach in the literature available to date.

Table 6. Shelf-Life Classification

Shelf-Life Representation	Number of Articles	References
Fixed Shelf-Life Duration (Perishability represented through a predefined lifetime or expiration date)	23 (65.7%)	(13), (15), (16), (17), (18), (19), (20), (21), (22), (27), (28), (29), (30), (31), (33), (34), (36), (45), (46), (48), (50), (51), (52)
Deterioration Factor Based on a Fixed Deterioration Rate (Continuous deterioration or exponential/linear decay)	11 (31.4%)	(4), (14), (26), (32), (35), (37), (38), (39), (40), (47), (49)
Probability of Product Spoilage (Stochastic models or probability distributions such as Weibull)	1 (2.9%)	(12)

It is important to note that these approaches for modeling shelf life respond more to the characteristics of the available data and to the conditions of the proposed model or modeled system than to the product itself. Nevertheless, each approach implies a different conceptualization of perishability. When a deterioration factor is established based on product characteristics and maturation and decomposition processes, the effects of preservation agents and product freshness on final customers are considered. In contrast, when shelf life is modeled as a fixed period of time, these considerations are omitted.

On the other hand, modeling the probability of product perishability implies considering the effects of external factors on products or raw materials; therefore, product duration becomes a random parameter. These conceptualizations have a substantial impact on sequencing results because they determine the nature and comprehensiveness of the criteria used by the model for prioritizing production orders.

These differences in the representation of perishability are also reflected in the mathematical models

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employed throughout the literature. In particular, it was observed that perishability modeling in 28 of the reviewed articles was performed using mixed-integer programming models (linear and nonlinear), demonstrating a preference for deterministic structures that incorporate operational and capacity constraints inherent to production systems. Within these models, deterioration rates and fixed shelf life constitute the most frequent approaches for representing perishability, whereas probabilistic approaches generally require stochastic extensions or additional scenarios that increase model complexity.

Regardless of the method used to represent product duration, it is common among the reviewed studies to associate costs with shelf life, whether related to customer perception—where freshness is valued—inventory holding of products or raw materials, or salvage value associated with selling waste to other industries.

Product preservation conditions indicate that the shelf life of PPs does not depend solely on intrinsic product characteristics but also on operational conditions to which products are exposed, which may or may not be controllable by decision-makers. One such factor, identified in the reviewed articles as having an impact on both product quality and sequencing decisions, is setup and system reconfiguration time when required. Due to contamination risks associated with residual materials, setup times play a critical role in determining product sequencing within production systems.

Conclusions

The literature review conducted shows that, in 80% of the cases analyzed, the problem was modeled using mixed-integer programming approaches, whether linear or nonlinear. This finding suggests that this modeling approach is the most widely used for addressing scheduling problems involving PPs, demonstrating its capacity to support decision-makers facing these types of problems. Conversely, the dominance of deterministic models reveals the limited application of stochastic approaches, thereby highlighting an important research gap.

Regarding the conditions or cases favoring deterministic or stochastic approaches, the literature review remains inconclusive. Tables 3, 4, and 5 do not reveal a clear pattern relating modeling approaches to objective functions or product type. Identifying such relationships may constitute an opportunity for future research.

Regarding the methods and techniques used to solve the formulated models, the literature review reveals substantial diversity, including author-developed methods, classical techniques applied to novel cases, and combinations of different approaches. This diversity makes selecting an ideal method difficult; therefore, evaluating multiple solution approaches for each model is recommended.

Although seven of the identified articles addressed make-to-order systems, a dominance of make-to-stock systems was observed. This may be explained by the fact that agricultural raw materials generally exhibit harvest-dependent behavior, requiring periodic replenishment for subsequent processing and utilization. This finding suggests that relatively few studies have considered pull-

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based production strategies, which, although uncommon in this field, may be relevant in sectors such as floriculture.

As shown in Tables 3, 4, and 5, nineteen of the thirty-five analyzed articles referred broadly to “food products” without specifying particular product categories. This may be counterproductive for understanding perishability phenomena because understanding product-specific characteristics, value chains, and processing conditions is necessary for more precise modeling of factors associated with preservation and utilization.

It is important to emphasize that only two of the reviewed articles considered uncertainty in raw material availability, despite the fact that, in most cases, raw materials originated from agricultural systems and are therefore subject to factors such as climate, soil quality, planting conditions, harvest conditions, among others. This finding creates opportunities for future research aimed at incorporating this source of uncertainty into scheduling complexity, since it frequently represents one of the main concerns of decision-makers.

When formulating scheduling models, it is necessary to consider not only the type of production system but also the desired level of integration, since this factor plays a decisive role in problem delimitation. This article provides a reference framework for future researchers seeking to address integration levels similar to those presented here, with routing problems being the most frequently identified category, followed by lot sizing problems, represented by sixteen and eleven studies, respectively.

CrediT authorship contribution statement

Conceptualization - Ideas: David Ricardo Maldonado Porras, Diana María Cárdenas Aguirre. Data curation: David Ricardo Maldonado Porras. Formal analysis: David Ricardo Maldonado Porras. Investigation: David Ricardo Maldonado Porras. Methodology: David Ricardo Maldonado Porras. Project Management: David Ricardo Maldonado Porras, Diana María Cárdenas Aguirre. Resources: Anny Astrid Espitia Cubillos. Software: David Ricardo Maldonado Porras. Supervision: Diana María Cárdenas Aguirre. Validation: David Ricardo Maldonado Porras, Diana María Cárdenas Aguirre. Writing - original draft - Preparation: David Ricardo Maldonado Porraso. Writing - revision and editing -Preparation: David Ricardo Maldonado Porras, Diana María Cárdenas Aguirre.

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