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# A literature review of the perishable inventory routing problem☆

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ABSTRACT

The inventory routing problem arises when inventory management and vehicle routing decisions are integrated instead of treated as separate problems. The technique of combining such decisions could lead to solutions that are better than merging the optimal solutions of the smaller subproblems. Hence, the problem is prominent and has been the focus of extensive research in recent years. When the products considered in such a problem are perishable, the importance is intensified; the current paper presents a literature review of the inventory routing problem for perishable products. This review classifies papers according to five attributes, namely, the number of products, the type of product (including the types of product perishability and types of perishable products), the type of demand, the number of objective functions, and the solution approach. A comprehensive analysis is performed based on these five attributes. Finally, based on 89 relevant reviewed papers, directions for future research on the perishable inventory routing problem are presented.



## 1. Introduction

Nowadays, despite technological growth, managing perishable products remains a challenging problem in many industries, such as the food industry (Kumar, Mangla, Kumar, & Karamperidis, 2020), agri-food industry (Weerabahu, Samaranayake, Dasanayaka, & Wickramasinghe, 2022), pharmaceutical industry (Singh, Kumar, & Kumar, 2016) and blood transfusion centers (Beliën & Forcé, 2012). This management occurs in a supply chain where inventory and transportation are two of the key elements, known as logistical drivers of the supply chain by Chopra and Meindl (2015), which are considered in the current paper.

The combination of smaller subproblems into larger problems that better reflect real life (Bonyadi, Michalewicz, Przybyłek, & Wierzbicki, 2014) has attracted the attention of researchers. This integration is also important in the supply chain, where the aim is to coordinate processes within the supply chain (Jemai, Rekik, & Kalaï, 2013). One example is the simultaneous consideration of inventory management decisions and the classical vehicle routing problem (VRP), leading to the inventory routing problem (IRP), as mentioned in (Jemai et al., 2013). Furthermore, since perishable products are highly sensitive to transportation issues (Yakavenka, Mallidis, Vlachos, Iakovou, & Eleni, 2020), temperature conditions (Aung & Chang, 2014), storage conditions Liu, Zhao, and Goh (2021), time delays (Yakavenka et al., 2020), etc., the importance of a combined strategy becomes even greater. This integration leads to the perishable inventory routing problem (PIRP), which has not been addressed separately in previous reviews of the IRP literature.

There exist, however, some review papers in the separate fields of inventory management for perishable products and for the IRP. Review papers focusing on inventory management began with Nahmias (1982), who reviewed the literature for ordering policies of perishable products with fixed lifetimes and with continuous exponential decay. Goyal and Giri (2001) focused on deteriorating inventory and reviewed the literature from the early 1990s to 2001. This work was continued by Bakker, Riezebos, and Teunter (2012), who studied the literature on inventory control of perishable products from 2001 to 2012, and Janssen, Claus, and Sauer (2016), who reviewed the literature from 2012 to 2015. Two relevant review papers on the IRP are Andersson, Hoff, Christiansen, Hasle, and Løkketangen (2010), who presented a literature survey on joint inventory management and routing focusing on industrial aspects, and Coelho, Cordeau et al. (2014), who presented a comprehensive review of the IRP within the past 30 years.

The objective of this paper is to present a literature review of the IRP of perishable products. To the best of our knowledge, this paper

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**Table 1**
Review of perishability classification.

| References | Classification | | |
|---|---|---|---|
| | Class 1 | Class 2 | Class 3 |
| Nahmias (1982) | Fixed lifetime | Random lifetime | |
| Goyal and Giri (2001) | Fixed lifetime | Random lifetime | Decaying products |
| Bakker et al. (2012) | Fixed lifetime | Age-dependent deterioration rate | Time or inventory (but not age) dependent deterioration rate |
| Janssen et al. (2016) | Fixed lifetime | Random lifetime | |

provides the first classification of the PIRP literature, for which the lack of literature review was noted in a study of this field by Ghiami, Demir, Van Woensel, Christiansen, and Laporte (2019). This is an important research area that has attracted the attention of researchers in recent years, as it is relevant for real-world problems within different areas, such as food companies, supermarket chains, hospitals, and biodiesel production companies.

The rest of this paper is organized as follows. Section 2 describes the IRP and states different types of perishable products for which this problem is relevant. Section 3 describes the research method and the general classification of papers that will be used in the remainder of the paper. The reviewed papers are analyzed in Section 4; finally, conclusions and future research directions are given in Section 5.

## 2. Inventory routing problem and perishable products

The IRP is briefly explained in Section 2.1, along with a brief explanation of PIRP; then, types of product perishability are discussed in Section 2.2.

### 2.1. Inventory routing problem

As previously stated, the IRP is an extension of the VRP, where inventory management is considered in addition to the routing decisions. According to Coelho, Cordeau et al. (2014), transportation and inventory management decisions in the IRP are made in such a way that a supplier must make decisions for each period about when to deliver to each customer, how much to deliver to those customers, and which routes to choose for delivery. The basic version of the IRP is defined as distributing a product from a depot to some customers using a certain number of vehicles, where each vehicle (starting and ending at the depot) can be used on at most one route per time period and cannot exceed its own capacity. The objective of the problem is to minimize the total cost, including inventory and distribution costs, while satisfying the demand of the customers and ensuring the inventory levels neither exceed the maximum capacity nor become negative (Coelho, Cordeau et al., 2014).

This is the basic version of the IRP, which is a complex problem (Coelho, Cordeau et al., 2014). For perishable products, even more considerations must enter the problem. For example, the ability to control the quality of the product or the ability to reduce product waste (e.g., food waste) are two factors in considering perishability in supply chain management (Soysal, Bloemhof-Ruwaard, Haijema, & Van Der Vorst, 2015). Accordingly, the assumption that product shelf life in the IRP is unlimited restricts the use of the proposed IRP models in PIRPs (Soysal et al., 2015), and this is the main obstacle to the use of IRP models for PIRPs. Therefore, the PIRP is defined as an IRP where the product is subject to any type of perishability. In the next section, different types of product perishability are presented to narrow the problem.

### 2.2. Types of product perishability

Table 1 summarizes the key classifications used by the four review papers on inventory management for perishable products. All four papers have a similar concept for "fixed lifetime", which indicates the predetermined deterministic lifetime for the products. However, they have different ideas about the "random lifetime" of products. Nahmias (1982) considers random lifetime when the product lifetime is a random variable with a specified probability distribution, and he also includes exponentially decaying products in the same class. In contrast, Goyal and Giri (2001) introduce random lifetime models, where random lifetimes are examined as exponential decay products in continuous review inventory models. Bakker et al. (2012) instead define the "age-dependent deterioration rate", which implies random lifetime products for which a probabilistic distributed lifetime is considered, and Janssen et al. (2016) present a broad definition for random lifetime, which includes all models with a probabilistic distributed lifetime, constant, known, unknown deterioration rate, etc. Models with simultaneous deterioration rates and fixed lifetimes are considered in this class as well. Goyal and Giri (2001) introduced a third class of products that decays corresponding to the proportional inventory decrease regarding its utility or physical quantity and named this class "decaying products", while Bakker et al. (2012) introduced another class that is not age dependent but rather the "time- or inventory-dependent deterioration rate". This includes models with a constant deterioration rate per stored item.

Considering the classifications in the review papers above, this paper introduces the following four groups for classifying papers based on lifetime.

(1) **Strict fixed lifetime:** In this category, products have a definite maximum usable lifetime. Some examples of this group are newspapers, blood products, and pharmaceuticals.
(2) **Non-strict fixed lifetime:** In this category, products still have a definite maximum usable lifetime, but the exact length depends on different external factors, which makes it different from the previous category. Such factors could be season, humidity, conditions of storage, conditions of transportation, loading methods, and other factors. Some examples of this group are fruits, vegetables, cut flowers, fresh meat, and fresh seafood.
(3) **Random shelf life:** Products of this category have an indefinite shelf life, which means that it is generally difficult to determine their maximum usable lifetime. Some examples of this group are gasoline and radioactive substances.
(4) **Gradual deterioration by time:** Products whose shelf life will decrease gradually (with or without a certain probability distribution function), which leads to a lower quality or efficiency. Some examples of this group are alcohol and pesticides.

## 3. Method

For the two reasons given by Siddaway, Wood, and Hedges (2019), this paper uses a systematic literature review methodology. First, there is a need to synthesize current PIRP papers to reach comprehensive conclusions; second, there is a requirement to identify the direction of progress of existing PIRP research. The three research questions (RQs) formulated to guide the literature review are as follows:

**RQ1:.** Which components of PIRP are most researched, and which areas are still uncovered?

**RQ2:.** What new concepts are emerging in PIRP?

**RQ3:.** What are the less developed theories of PIRP that need further investigation?

The current paper adopts the proposed methodology of Vom Brocke et al. (2009) to conduct the systematic literature review. This review approach employs three steps.

- The first step consists of searching proper keywords in relevant databases. The keywords selected were "inventory routing problem", "perishable inventory routing problem", "routing problem + perishable", "inventory routing problem + deteriorate", and "vendor-managed inventory + perishable", and the following databases were used: Scopus, ScienceDirect, Taylor & Francis, SpringerLink, Wiley, and Informs. This study does not restrict the year of publication of the papers because the topic itself (PIRP) is sufficiently narrow. Naturally, the review is limited to papers published in English. International conference papers in the mentioned databases are included for having maximum coverage of the subject and to avoid losing any relevant research.
- In the second step, the papers gathered in the previous step were examined by checking their abstracts. If no relevance was found, the paper was excluded from the review. If some indication of relevance was found, then all the sections of the paper were checked to determine whether the paper should be included in the current research.
- In the third and final step, a backward and forward search was conducted to identify all relevant papers. The backward search involved checking the reference lists of the identified papers, and forward search involved checking the sources that cited the identified papers. The results of these steps are summarized in Table 2.

After careful examination of the databases in March 2022, 89 papers considered relevant remained. Table 3 shows the distribution of the PIRP papers in their actual sources consisting of 52 different journals and conference proceedings. The top journals in terms of the frequency of the published papers are "International Journal of Production Economics" and "Computers & Industrial Engineering", with 7 papers each. The quality of each source is measured with respect to two metrics: the impact factor by Journal Citation Reports (JCR) by Clarivate Analytics and the H-index by SCImago Journal Rank (SJR) from the latest published report.

These papers have been classified based on the five attributes shown in Table 4 accompanied by their possible options. As we are considering inventory and routing problems, we must determine how various products should be stored and delivered, and since we are interested in perishable products, it is necessary to be specific about the type of product. The demand is the vital attribute, and for a classification, the type of demand must be known. Each problem has at least one objective, which is generally minimization of cost for PIRP, but for several problems, it is useful to look at other objectives simultaneously, and some papers treat the problem as a multiple objective problem. The solution approach is the last of the considered attributes in the current study. The last column of Table 4 indicates the category code for each alternative attribute, and they are used in Table 5.

**Table 2**
Results of review steps.

| Steps | Description | Number of papers |
|---|---|---|
| Step 1 | Searching five keywords | 161 |
| Step 2 | Duplicates and irrelevant papers were removed | 81 |
| Step 3 | Forward and backward search | 9 |
| Sample size: | | 161–81 + 9 =**89** |

## 4. Analysis

This section presents the reviewed papers and several analyses based on them. First, Table 5 shows all 89 papers sorted in ascending order according to the year of publication and classifies them according to the five attributes described above. Then, an overview of these data is given and shown in the figures in Section 4.1. Next, Section 4.2 focuses on the demand attribute and presents a comparison of deterministic and non-deterministic demand among the 89 papers. Then, the multi-objective papers are examined in Section 4.3, and a detailed review of perishability is provided in Section 4.4. Section 4.5 investigates the different types of solution approaches that are employed in the reviewed papers. Section 4.6 analyses the PIRP papers using real-world data. Finally, the distribution of published papers per year is illustrated in Section 4.7.

### 4.1. Classification of reviewed papers

Figs. 1, 2, 3, and 4 show the distribution of the papers in Table 5 according to the attributes described in Table 4. As shown in Fig. 1, more than two-thirds of the papers consider a single product (67.4%), approximately one-fourth of the papers consider non-deterministic demand (29.2%), and multiple objectives are included in 15.7% of the PIRP papers.

Fig. 2 shows the types of product perishability considered in each paper. Some authors considered products with a fixed lifetime without distinguishing their type; therefore, they are considered a combined category (1 +2) of 1 and 2. Additionally, several papers considered a fixed lifetime product with a random shelf life, which is considered another combined category (1 +2 +3) here. Based on this figure, non-strict fixed lifetime products are studied more often than are other categories in the literature. A more detailed observation about the types of product leads to a Pareto chart of the papers with perishable products, which is shown in Fig. 3. The most popular category is the one with a general "fixed lifetime" and "food products", each covered by 23.60% of the reviewed papers, followed by "LNG" with 11.24%, then "blood products" and the general "gradual deterioration by time", each covered by approximately 8.99% of the papers.

Researchers use different solution approaches to solve their PIRPs, and Fig. 4, which is in accordance with the category code of Table 4, shows that approximate solution approaches, such as heuristic and metaheuristic methods, are used more often than are exact methods. This is because the IRP is NP-hard, as it involves the VRP (Coelho, Cordeau et al., 2014).

Fig. 4 shows a 32.6% usage of exact methods in the reviewed papers. However, this share can be split even further, as shown on the left-hand side of the figure. Here, the exact methods are divided into two parts. The first part, consisting of 22 papers (24.7%), uses the default capability of software, such as the CPLEX solver, to obtain solutions for the problem, while the second part, including 7 papers (7.9%), employs exact methods, such as the branch-and-cut algorithm, coded explicitly in the method described in their papers.

### 4.2. Comparison of types of demand

Clearly, real-world problems normally face non-deterministic demand, and to address such a demand, authors consider uncertain, stochastic or fuzzy behavior. Notably, different methods are employed by different authors, and the literature does not describe any specific method that is applicable in general for this research field. However, it should be noted that approximately 29% of the papers

**Table 3**
Distribution of the PIRP papers in different sources.

| Rank | Title | Number of papers | Percentage | Quality measures | |
|---|---|---|---|---|---|
| | | | | Impact factor 2020 | H-Index 2020 |
| 1 | International Journal of Production Economics | 7 | 7.86 | 7.885 | 185 |
| 1 | Computers & Industrial Engineering | 7 | 7.86 | 5.431 | 128 |
| 3 | European Journal of Operational Research | 5 | 5.62 | 5.334 | 260 |
| 3 | Computers & Operations Research | 5 | 5.62 | 4.008 | 152 |
| 5 | Transportation Research Part E | 4 | 4.49 | 6.875 | 110 |
| 5 | Annals of Operations Research | 4 | 4.49 | 4.854 | 105 |
| 5 | IFAC-PapersOnLine | 4 | 4.49 | – | 72 |
| 8 | Journal of Cleaner Production | 2 | 2.25 | 9.297 | 200 |
| 8 | International Journal of Production Research | 2 | 2.25 | 8.568 | 142 |
| 8 | Expert Systems with Applications | 2 | 2.25 | 6.954 | 207 |
| 8 | Transportation Science | 2 | 2.25 | 4.117 | 115 |
| 8 | Optimization Letters | 2 | 2.25 | 1.769 | 42 |
| 8 | OR Spectrum | 2 | 2.25 | 1.652 | 69 |
| 8 | Mathematical Problems in Engineering | 2 | 2.25 | 1.305 | 62 |
| 8 | Journal of Modelling in Management | 2 | 2.25 | – | 29 |
| 16 | Other (journals or conferences with only one paper) | 37 | 41.57 | – | – |
| Total: | | **89** | **100%** | | |

**Table 4**
The classification attributes used for the PIRP.

| Attributes | Alternatives | Category code |
|---|---|---|
| **Product** | • Single | S |
| | • Multiple | M |
| **Type of product** | • Strict fixed lifetime | 1 |
| | • Non-strict fixed lifetime | 2 |
| | • Random shelf life | 3 |
| | • Gradual deterioration by time | 4 |
| **Type of demand** | • Deterministic | D |
| | • Non-deterministic (Uncertain, Stochastic, Fuzzy) | N |
| **Objective function** | • Single | S |
| | • Multiple | M |
| **Solution approach** | • Exact | 1 |
| | • Metaheuristic | 2 |
| | • Heuristic | 3 |
| | • Hybrid methods | 4 |
| | • Matheuristic | 5 |
| | • Other | 6 |

consider non-deterministic demand; details about the different demand types are shown in Table 6.

### 4.3. Comparison of multi-objective papers

In today's world, we are facing complicated problems that may include several conflicting objectives. Hence, it is highly probable that the PIRP with more than one objective should be a conscious decision. The main two approaches for solving multi-objective problems according to Deb (2001) are classical methods with different weights, epsilon or target values on the single-objective problems or metaheuristics such as evolutionary algorithms.

Some of the difficulties and weaknesses of the classical methods, according to Deb (2001), are as follows:

- Classical multi-objective methods provide only a Pareto-optimal solution with the given parameter values.
- They require some prior knowledge of the problem, such as suitable weights, epsilon, target values.
- Classical methods may face difficulties and are not efficient when handling practical optimization problems since many real-world problems involve discrete values for some of their variables.
- Many of the classical methods are not efficient when using parallel systems because in each iteration, one solution is updated to a new solution, and a point-by-point approach is implemented.
- Most classical methods are drawn to a suboptimal solution and cannot escape local optimum.
- Most classical methods are designed for one specific type of problem.

Hence, the use of more advanced methods, such as evolutionary algorithms, for solving real-world problems with more than one objective is increasingly popular (Deb, 2001). Such methods can identify a Pareto set of several unique solutions of which all can be considered optimal under some conditions. Some of the methods used for solving multi-objective optimization problems are as follows:

A. Classical methods:

- Weighted sum method
- Weighted metric method
- $\varepsilon$-constraint method
- Goal programming method
- Interactive methods:
  - Reference point method
  - NIMBUS method (Nondifferentiable interactive multi-objective bundle-based optimization system)
  - Fuzzy approach

B. Evolutionary algorithms:

- NSGA-II (Non-dominated sorting genetic algorithm-II)
- MOPSO (Multi-objective particle swarm optimization)
- MOEA/D (Multi-objective evolutionary algorithm based on decomposition)
- SPEA2 (Strength Pareto evolutionary algorithm 2)
- PESA-II (Pareto envelope-based selection algorithm II)

Among the 89 reviewed papers, only 14 papers addressed the multi-objective PIRP. These papers are shown in Table 7, which provides both the applied technique and the different objectives. Amorim et al. (2012) aggregate two objectives with varying weights to obtain a variety of solutions and construct a Pareto front. The weighted sum method is used by Rahimi et al. (2014, 2015, 2016) for two different objectives in each of the papers.

Govindan et al. (2014) used a hybrid metaheuristic algorithm that combined MOPSO and the adapted multi-objective variable neighborhood search algorithm (AMOVNS). Niakan and Rahimi (2015) faced a lack of information for some parameters and therefore used

**Table 5**
Reviewed PIRP papers.

| No. | References | Products | Demand | Objective function | Type of product category | Type of product | Solution approach category | Solution approach |
|---|---|---|---|---|---|---|---|---|
| 1 | Brodheim and Prastacos (1979) | S | N | S | 1 | Blood | 3 | Programmed blood distribution system (PBDS) |
| 2 | Federgruen, Prastacos, and Zipkin (1986) | S | N | S | 1 + 2 | Products with a fixed lifetime | 6 | Lagrangean dualization approach and heuristic method |
| 3 | Hsu, Hung, and Li (2007) | S | D | S | 2 | Food products | 3 | Heuristic method (Time-oriented nearest-neighbor heuristic) |
| 4 | Zanoni and Zavanella (2007) | M | D | S | 1 + 2 | Products with a fixed lifetime | 3 | Heuristic algorithms |
| 5 | Hemmelmayr, Doerner, Hartl, and Savelsbergh (2009) | S | D | S | 1 | Blood | 2 | Variable neighborhood search (VNS) |
| 6 | Grønhaug, Christiansen, Desaulniers, and Desrosiers (2010) | S | D | S | 3 | LNG* | 1 | Branch-and-price |
| 7 | Bilgen and Günther (2010) | M | D | S | 2 | Perishable products (Fruit juices) | 1 | CPLEX |
| 8 | Ahumada and Villalobos (2011) | M | D | S | 2 | Fresh products | 1 | CPLEX |
| 9 | Amorim, Günther, and Almada-Lobo (2012) | M | D | M | 1 + 2 + 3 | Fixed shelf-life & loose shelf-life | 1 | CPLEX |
| 10 | Aksen, Kaya, Salman, and Akça (2012) | S | D | S | 3 | Waste vegetable oil | 1 | CPLEX |
| 11 | Stålhane et al. (2012) | M | D | S | 3 | LNG | 3 | Construction and improvement heuristic (CIH) |
| 12 | Popović, Vidović, and Radivojević (2012) | M | D | S | 3 | Fuel | 2 | Variable neighborhood search (VNS) |
| 13 | Goel, Furman, Song, and El-Bakry (2012) | S | D | S | 3 | LNG | 2 | Large neighborhood search (LNS) |
| 14 | Le, Diabat, Richard, and Yih (2013) | S | D | S | 1 + 2 | Products with a fixed lifetime | 1 | Column generation-based solution approach |
| 15 | Uggen, Fodstad, and Nørstebø (2013) | S | D | S | 3 | LNG | 3 | Fix-and-relax time decomposition heuristics |
| 16 | Archetti, Doerner, and Tricoire (2013) | S | D | S | 1 | Newspaper | 4 | Heuristic approaches + LNS |
| 17 | Bilgen and Çelebi (2013) | M | D | S | 2 | Dairy plants (yogurt) | 6 | Iterative hybrid optimization-simulation procedure |
| 18 | Seyedhosseini and Ghoreyshi (2014) | S | D | S | 1 + 2 | Fixed lifetime | 5 | LINGO and particle swarm optimization (PSO) |
| 19 | Vidović, Popović, and Ratković (2014) | M | D | S | 3 | Fuel | 5 | The MIP model and heuristic approaches |
| 20 | Jia, Li, Wang, and Li (2014) | S | D | S | 1 + 2 | Fixed lifetime | 4 | Tabu search & neighborhood search |
| 21 | Agra, Christiansen, Delgado, and Simonetti (2014) | M | D | S | 3 | Fuel oil | 4 | Hybrid heuristics (rolling horizon, local branching, and feasibility pump) |
| 22 | Rahimi, Baboli, and Rekik (2014) | S | D | M | 2 | Food products | 1 | CPLEX |
| 23 | Coelho and Laporte (2014) | S | D | S | 1 + 2 + 3 | Fixed lifetime & decaying | 1 | Branch-and-cut |
| 24 | Govindan, Jafarian, Khodaverdi, and Devika (2014) | S | D | M | 2 | Perishable foods | 4 | Novel hybrid metaheuristic algorithm (multi-objective particle swarm optimization (MOPSO) and adapted multi-objective variable neighborhood search (AMOVNS)) |
| 25 | Aksen, Kaya, Salman, and Tüncel (2014) | S | D | S | 3 | Waste vegetable oil | 2 | Adaptive large neighborhood search (ALNS) |
| 26 | Abdelhalim, Eltawil, and Fors (2015) | M | D | S | 2 | Food products | 1 | LINGO software |
| 27 | Andersson, Christiansen, and Desaulniers (2015) | S | D | S | 3 | LNG | 1 | Branch-and-cut |
| 28 | Shao, Furman, Goel, and Hoda (2015) | S | D | S | 3 | LNG | 4 | Hybrid heuristic (rolling time algorithm + greedy randomized adaptive search procedure (GRASP)) |
| 29 | Mirzaei and Seifi (2015) | S | D | S | 4 | Perishable goods considering an exponential lost sale | 4 | Hybridization of simulated annealing (SA) and Tabu search (TS) |
| 30 | Niakan and Rahimi (2015) | M | N | M | 1 | Healthcare (Drug) | 1 | CPLEX (A fuzzy possibilistic approach) |
| 31 | Soysal et al. (2015) | S | N | S | 2 | Food logistics | 6 | Optimization and simulation model |
| 32 | Ghiami, Van Woensel, Christiansen, and Laporte (2015) | S | D | S | 3 | LNG | 1 | CPLEX |
| 33 | Rahimi, Baboli, and Rekik (2015) | M | D | M | 2 | Food products | 1 | CPLEX |
| 34 | Diabat, Abdallah, and Le (2016) | S | D | S | 1 + 2 | Fixed lifetime | 2 | Tabu search based heuristic |
| 35 | Gunpinar and Centeno (2016) | S | D | S | 1 | Blood | 1 | Branch-and-price |
| 36 | Shaabani and Kamalabadi (2016) | M | D | S | 1 + 2 | Fixed lifetime | 2 | Population-based simulated annealing (PBSA) |
| 37 | Li, Chu, and Yang (2016) | S | D | S | 2 | Food products | 1 | CPLEX |
| 38 | Li, Chu, Chu et al. (2016) | S | D | S | 2 | Food products | 1 | CPLEX |
| 39 | Rahimi, Baboli, and Rekik (2016) | M | D | M | 2 | Food products | 1 | CPLEX |

(continued on next page)

**Table 5** (*continued*)

| No. | References | Products | Demand | Objective function | Type of product category | Type of product | Solution approach category | Solution approach |
|---|---|---|---|---|---|---|---|---|
| 40 | Azadeh, Elahi, Farahani, and Nasirian (2017) | S | D | S | 4 | Deteriorated at the exponential rate | 2 | Genetic algorithm and Taguchi approach |
| 41 | Kazemi, Rabbani, Tavakkoli-Moghaddam, and Shahreza (2017) | S | N | S | 1 | Blood | 1 | Branch-and-cut |
| 42 | Hiassat, Diabat, and Rahwan (2017) | S | D | S | 1 + 2 | Fixed lifetime | 2 | Genetic algorithm |
| 43 | Vahdani, Niaki, and Aslanzade (2017) | M | N | S | 4 | Products with decay rate | 6 | Heuristic and metaheuristic algorithms |
| 44 | Rahimi, Baboli, and Rekik (2017) | M | N | M | 1 + 2 | Fixed lifetime | 2 | NSGA-II** (A fuzzy possibilistic approach) |
| 45 | Li, Chu, and Chen (2017) | S | D | S | 2 | Food Products | 3 | Two-phase iterative heuristic |
| 46 | Zhang et al. (2017) | S | N | S | 3 | LNG | 5 | A hybrid computational method (ACO†-MILP‡) |
| 47 | Cho, Lim, Jin, and Biobaku (2018) | S | D | S | 3 | LNG | 6 | Two computational techniques to improve the optimization performance |
| 48 | Tavana et al, (2018) | M | D | M | 1 + 2 | Fixed lifetime | 2 | NSGA-II and reference point-based NSGA-II |
| 49 | Soysal, Bloemhof-Ruwaard, Haijema, and van der Vorst (2018) | M | N | S | 2 | Food logistics | 1 | CPLEX |
| 50 | Rafie-Majd, Pasandideh, and Naderi (2018) | M | N | S | 1 + 2 | Fixed lifetime | 6 | Lagrangian relaxation, heuristic, and SCIP solver |
| 51 | Jafarkhan and Yaghoubi (2018) | M | N | S | 1 | Red Blood Cells | 3 | Local Search |
| 52 | Crama, Rezaei, Savelsbergh, and Van Woensel (2018) | S | N | S | 1 + 2 | Fixed lifetime | 5 | Expected-value method, deliver up-to-level (UL) policy, decomposition method, and decomposition-integration method |
| 53 | Montagné, Gamache, and Gendreau (2018) | S | D | S | 3 | Waste vegetable oil | 3 | A constructive heuristic based on the shortest path and split procedures |
| 54 | Hu, Toriello, and Dessouky (2018) | M | D | S | 1 + 2 | Fixed lifetime | 3 | A decomposition procedure and a local search |
| 55 | Wang, Tao, and Shi (2018) | S | D | S | 3 | Fuel (Refined oil logistics) | 4 | An adaptive genetic algorithm combined with greedy algorithm |
| 56 | Sun, Chien, Hu, and Bing-shan (2018) | S | D | S | 1 + 2 | Fixed lifetime | 1 | LINGO software |
| 57 | Stellingwerf et al, (2018) | S | D | M | 2 | Fresh and frozen food | 1 | CPLEX |
| 58 | Chao, Zhihui, and Baozhen (2019) | S | D | S | 2 | Food products | 4 | Hybrid heuristic (Improved ant colony optimization (IACO) + distance-based clustering approach) |
| 59 | Qiu, Qiao, and Pardalos (2019) | S | D | S | 4 | Products with decay rate | 1 | Branch-and-cut |
| 60 | Timajchi, Mirzapour Al-e-Hashem, and Rekik (2019) | S | D | M | 1 | Pharmaceutical items | 4 | Hybrid genetic algorithm |
| 61 | Widyadana and Irohara (2019) | S | D | S | 4 | Products with constant deteriorating rate | 2 | Particle swarm optimization (PSO) |
| 62 | Fatemi Ghomi and Asgarian (2019) | S | D | S | 2 | Food products | 2 | Bio-geographical-based optimization (BBO) |
| 63 | Nikzad, Bashiri, and Oliveira (2019) | M | N | S | 1 | Drug | 5 | Two-phase matheuristic method |
| 64 | Cárdenas-Barrón, González-Velarde, Treviño-Garza, and Garza-Nuñez (2019) | S | D | S | 3 | Waste vegetable oil | 3 | Heuristic algorithm based on reduce and optimize approach |
| 65 | Rohmer, Claassen, and Laporte (2019) | S | D | S | 4 | Gradual decrease in product quality | 5 | Two-stage matheuristic combining an ALNS with an MILP formulation |
| 66 | Ghiami et al. (2019) | S | D | S | 3 | LNG | 5 | A matheuristic combining MILP formulation with an ALNS |
| 67 | Onggo, Panadero, Corlu, and Juan (2019) | S | N | S | 2 | Fresh food | 6 | Simheuristic method |
| 68 | Ghasemkhani et al, (2019) | M | N | S | 2 | Food products | 1 | CPLEX |
| 69 | Li, Chu, Feng, Chu, and Zhou (2019) | S | D | M | 2 | Food logistics | 3 | An $\varepsilon$-constraint-based two-phase iterative heuristic and a fuzzy logic method |
| 70 | Alkaabneh, Diabat, and Gao (2020) | S | D | S | 1 + 2 | Fixed lifetime | 6 | Benders decomposition and a two-stage metaheuristic |
| 71 | Violi, Laganá, and Paradiso (2020) | S | N | S | 2 | Agri-food | 1 | CPLEX |
| 72 | Dai, Gao, and Giri (2020) | S | D | S | 4 | Products with constant deteriorating rate | 4 | Hybrid heuristic (cuckoo algorithm + improved Clarke-Wright savings algorithm) |
| 73 | Ji et al. (2020) | S | N | S | 2 | Fresh products | 1 | Robust optimization + Gurobi |
| 74 | Esmaili and Mousavi (2020) | S | N | S | 2 | Fresh products | 1 | Julia software |
| 75 | Yavari, Enjavi, and Geraeli (2020) | S | D | S | 1 + 2 | Fixed lifetime | 2 | Genetic algorithm |
| 76 | Alvarez et al, (2020) | S | D | S | 1 + 2 | Fixed lifetime | 4 | Hybrid heuristic (construction heuristic + randomized variable neighborhood descent (RVND)) |

(*continued on next page*)

**Table 5** (*continued*)

| No. | References | Products | Demand | Objective function | Type of product category | Type of product | Solution approach category | Solution approach |
|---|---|---|---|---|---|---|---|---|
| 77 | Imran et al. (2020) | M | D | M | 1 + 2 | Fixed lifetime | 1 | Interactive multi-objective fuzzy programming |
| 78 | Liu, Ke, Chen, and Zhang (2020) | S | D | S | 1 | Blood | 6 | Decomposition method and ALNS |
| 79 | Liu, P., Hendalianpour, A., Razmi, J., & Sangari, M. S. (2021) | S | N | S | 1 | Blood | 3 | Heuristic algorithm |
| 80 | Shirzadi, Ghezavati, Tavakkoli-Moghaddam, and Ebrahimnejad (2021) | S | D | S | 2 | Agri-food | 1 | GAMS software |
| 81 | Ghasemkhani et al. (2021) | M | N | S | 2 | Food products | 4 | Hybrid imperialist competitive algorithm (HICA) and self-adaptive differential evolution (SADE) |
| 82 | Wang, Wei, and Pan (2021) | S | N | S | 1 + 2 | Fixed lifetime | 2 | Improved differential evolution (DE) algorithm |
| 83 | Hajibabaie and Lotfi (2021) | M | N | M | 1 | Blood (platelets + red blood cells) | 6 | NSGA-II and multi objective simulated annealing (MOSA) |
| 84 | Fattahi and Tanhatalab (2021) | S | N | S | 1 + 2 | Fixed lifetime | 6 | Lagrangian relaxation heuristic enhanced by local search heuristic |
| 85 | Daroudi, Kazemipoor, Najafi, and Fallah (2021) | M | N | M | 1 + 2 | Fixed lifetime | 6 | NSGA-II and Pareto envelope-based selection algorithm II (PESA-II) |
| 86 | Harahap and Rahim (2022) | S | D | S | 2 | Vegetables | 1 | CPLEX |
| 87 | Song and Wu (2022) | M | D | S | 4 | Gradual decrease in product quality | 3 | A two-stage heuristic algorithm based on SA |
| 88 | Pratap, Jauhar, Paul, and Zhou (2022) | M | N | S | 2 | Food products | 6 | Flower pollination algorithm (FPA) and cuckoo search algorithm (CSA) |
| 89 | Mousavi, Bashiri, and Nikzad (2022) | S | N | S | 2 | Food products | 5 | A five-phase matheuristic |

* Liquefied natural gas ** Non-dominated sorting genetic algorithm-II
† Ant colony optimization ‡ Mixed-integer linear programming

an interactive fuzzy method to address three different objectives. The NSGA-II method was used by Rahimi et al. (2017), who tuned the parameters using the statistical Taguchi method. Tavana et al. (2018) used the ε-constraint method to solve small-sized instances and used NSGA-II and reference point-based NSGA-II because of the high complexity of the problem. They sorted the members of each front by the diversity index for reference point-based NSGA-II rather than the crowding distance used for NSGA-II. Stellingwerf et al. (2018) employed the ε-constraint method to calculate the trade-offs between cost and emissions and additionally presented the trade-off between age and emissions. Timajchi et al. (2019) used a compromise programming method in which they first solved the problem in terms of each objective function separately and then formulated a single objective model ($l_p$-metrics) to minimize the normalized deviation from their optimal values for the weighted sum of each objective function. Their method can be classified as a weighted metric method. Li et al. (2019) proposed an approach that combined the ε-constraint method with a fuzzy logic method to find a preferred solution. Imran et al. (2020) utilized the same idea of the interactive fuzzy method as Niakan and Rahimi (2015), as they considered cost uncertainty in their problem.

The most recent study with a bi-objective mathematical model is that of Hajibabaie and Lotfi (2021), who used the ε-constraint method to solve the model but developed NSGA-II and MOSA for large problems. Daroudi et al. (2021) proposed a mathematical model with three objectives. Although they used the ε-constraint method for small instances, they implemented NSGA-II and PESA-II to find a solution for large problems involving real conditions.

### 4.4. Perishability

Perishability can be treated in several ways, and this section presents several approaches to perishability taken by different researchers. The type of product has been classified once according to the type of product perishability (see Fig. 2) and once according to the type of perishable products (see Fig. 3). Since this section describes the papers in detail, the types of perishable products shown in Fig. 3 are used for further explanation because they contain more detailed categories and cover the type of product perishability. Fig. 3 shows that more than 75% of the papers belong to five categories. Therefore, these five categories are explained separately, and the remaining papers on other perishable products are explained together.

As shown in Fig. 3, products with a fixed lifetime are the most common among PIRP researchers. These products typically consider a specific number of days as the maximum shelf life. Federgruen et al. (1986) was among the first studies to introduce the fixed lifetime concept for the PIRP. They treat perishability by considering an out-of-date cost paid for each item that reaches its maximum lifetime without being used, leading to the product being discarded. Le et al. (2013) followed a similar approach in which unused products were discarded after their shelf life. Rahimi et al. (2014) considered a maximum shelf life for products, and they assumed expired products were recycled, with an additional cost. This is a minor difference from the out-of-date cost in Federgruen et al. (1986), who considered an expected out-of-date cost for old shipments at each location, while Rahimi et al. (2014) used a recycling cost for the number of expired products at the end of each period for the inventory of each customer. The idea of recycling used in Rahimi et al. (2017) is similar to that in Rahimi et al. (2014) for multi-product problems, in which modeling of the reverse logistics for recycling perished products is operational. They employed a stepwise nonlinear unit holding cost due to nonfreshness for products transferred from one period to another. Shaabani and Kamalabadi (2016) employed constraints that ensured that perishable products would never be spoiled by considering the maximum shelf life,

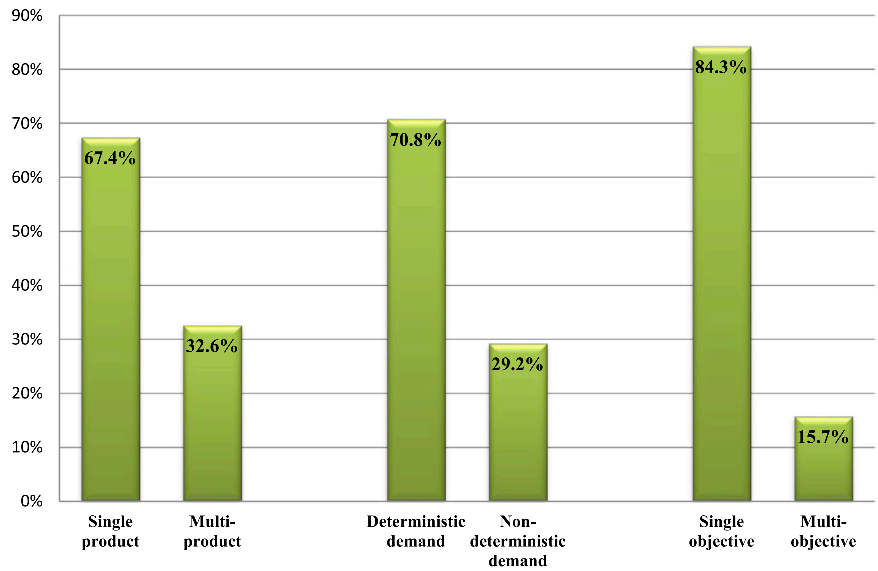


**Fig. 1.** The percentage of PIRP papers with single vs. multiple products, deterministic vs. non-deterministic demand and single vs. multiple objectives.

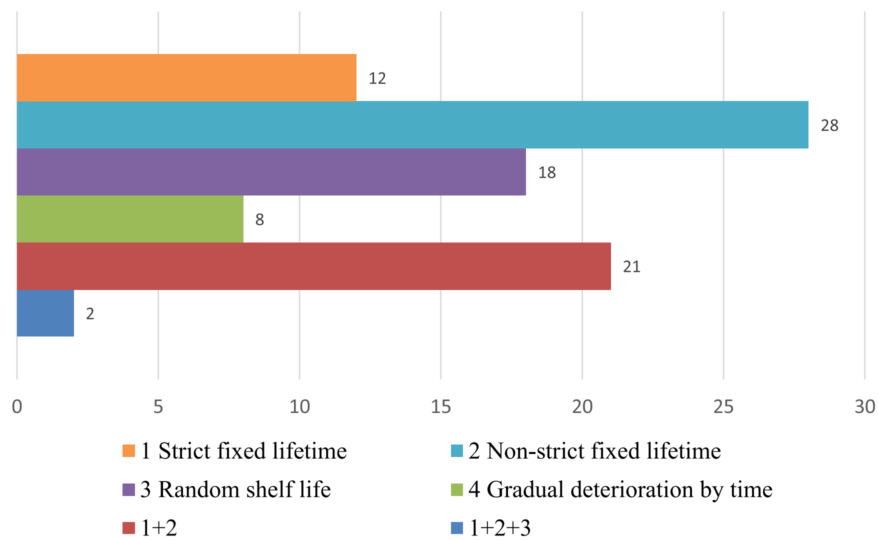


**Fig. 2.** Types of product perishability based on introduced category in Section 2.2.

demand and inventory level. Profit loss was considered as a perishability cost by Crama et al. (2018), while Rafie-Majd et al. (2018) considered expected waste cost in the objective function of their model as a factor for the PIRP. Alkaabneh et al. (2020) introduced a valid inequality for the PIRP that handled perishable products in such a way that the number of customer visits must be at least as large as the number of product life cycles during the planning horizon. Daroudi et al. (2021) used two constraints to model perishability. If no time remains from the corruption time of the product, then the products are perishable.

Food products with uncertain lifetimes are another type of product considered in the PIRP. Govindan et al. (2014) introduced a maximum consecutive storage time for perishable food. They used two related constraints in their model: the first guarantees that the inventory level at the distribution center will never exceed “a coefficient of the total amount of products sent by the distribution center in the previous consecutive time period”, and the second guarantees that the inventory level at the retailer never exceeds the total demand in the next consecutive time period. Soysal et al. (2015) considered waste costs for products that are kept longer than their shelf life. A similar idea was employed in their subsequent study, where they extended the previous research by considering multiple products and a many-to-many distribution structure (Soysal et al., 2018). Rahimi et al. (2015) presented an age discount function by the foodstuff supplier to sell aged products and accordingly reduce the amount of expired product. Li, Chu, Chu et al. (2016) developed three valid inequalities together with one food perishability constraint indicating that there will be at least one visit to each retailer within the specified time period. Stellingwerf et al. (2018) utilized the demand data and outputs from a model of the amount of delivered quantity and inventory in all time periods to calculate the average product age. They also quantified the environmental effects of implementing cooperation through vendor-managed inventory (VMI), and found that the use of VMI is helpful to establish a trade-off between product age and emissions. The cargo damage cost for perishable food was proposed by Chao et al. (2019), in which the main damage costs were assumed to be accumulated due to transit time and breakage during transportation. Fatemi Ghomi and Asgarian (2019) considered lost sale costs as a linear and exponential function of perishable products’ age. Shirzadi et al. (2021) proposed a model that addresses agri-food perishability only for customers; their formulation neglects the freshness reduction for plants.

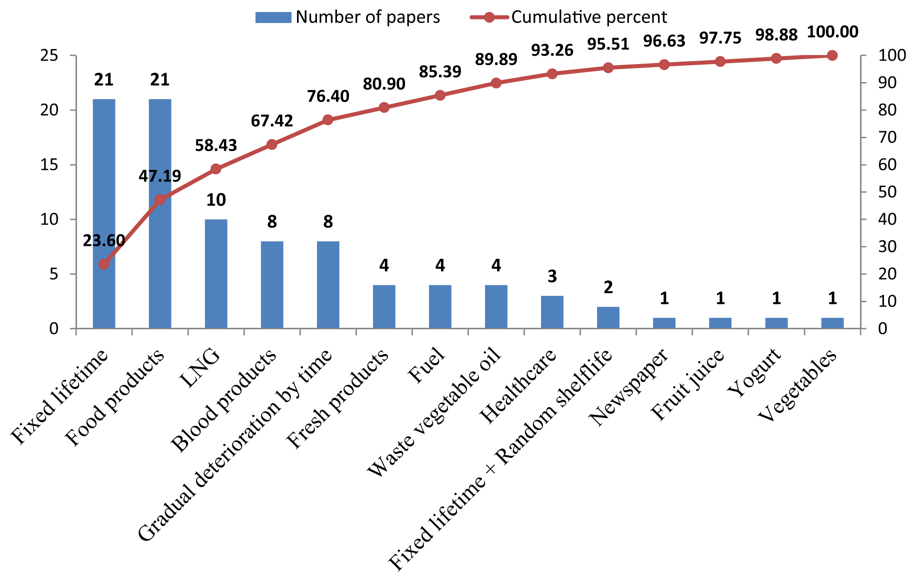


**Fig. 3.** Types of perishable products studied in the PIRP papers.

Mousavi et al. (2022) introduced penalty costs per unit of non-fresh product at a given age and used them in the objective function of the mathematical model to minimize the penalty costs of delivering non-fresh products.

Liquefied natural gas (LNG) is the liquid form of natural gas, where the temperature is decreased to approximately $-162°C$, which is the main form used for transporting natural gas to its markets. Some of the gas evaporates during transportation because it is kept in a boiling state (Ghiami et al., 2015); thus, LNG is considered a deteriorating product. The IRP for LNG was first considered by Grønhaug et al. (2010). Goel et al. (2012) and Stålhane et al. (2012) employed two different solution approaches for an LNG-IRP; more

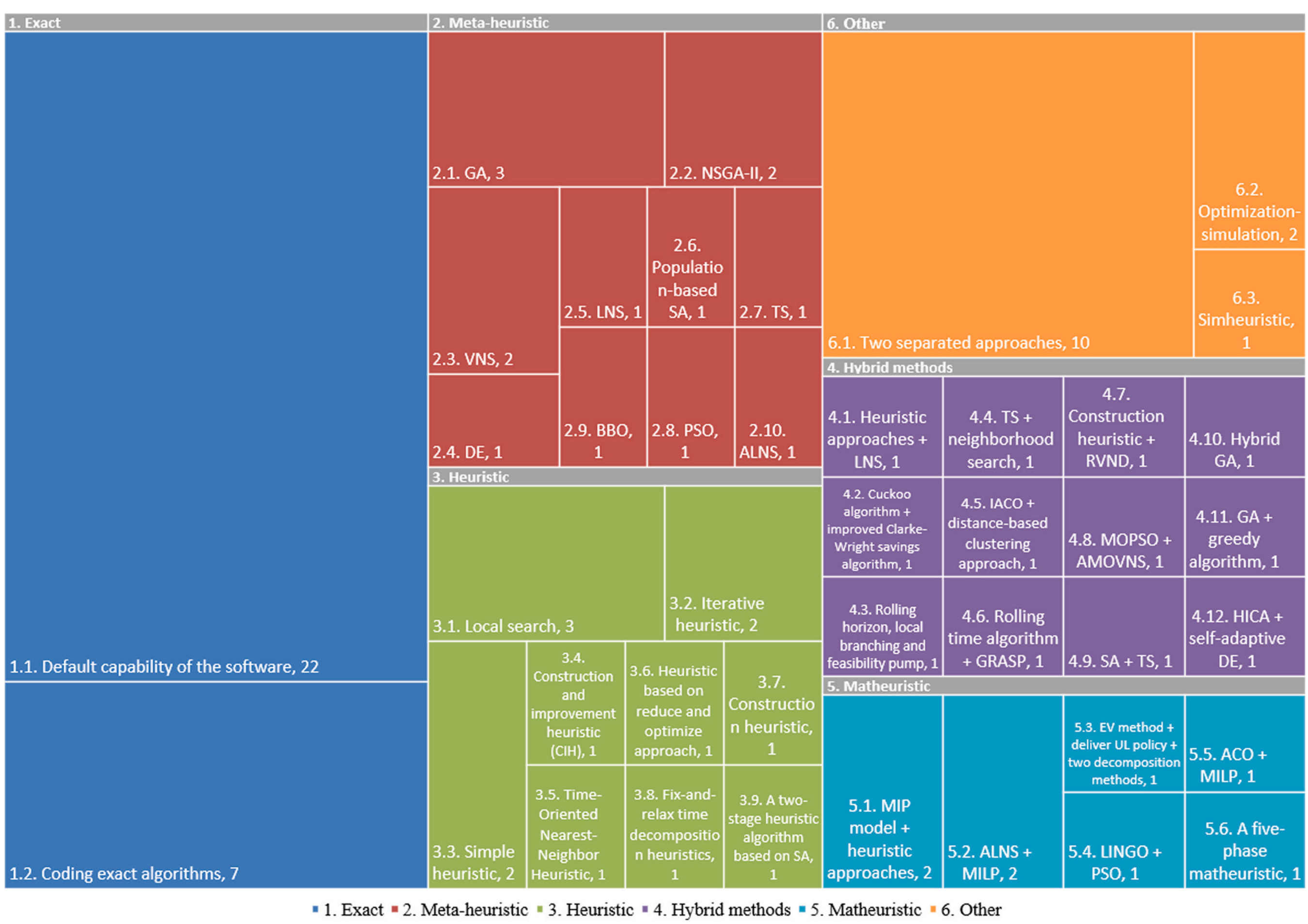


**Fig. 4.** Distribution of employed solution approaches for the PIRP papers.

**Table 6**
Comparison of different demand types.

| Type of demand | Type of treatment | Demand description | Number of papers | Percentage of usage among 89 papers |
|---|---|---|---|---|
| **Deterministic Modeling** | Deterministic demand | Deterministic demand | 63 | **70.80%** |
| **Non-deterministic Modeling** | Uncertain | Markov chain modeling | 1 | **7.86%** |
| | | Chance-constrained programming model | 2 | |
| | | Robust possibilistic programming approach | 1 | |
| | | A random variable from a certain interval | 1 | |
| | | Robust optimization approach | 2 | |
| | Stochastic | A random variable with a normal distribution with a coefficient of variation equal to one | 1 | **13.48%** |
| | | A random variable with a certain probability distribution function | 5 | |
| | | Following a normal distribution with certain mean and standard deviation | 5 | |
| | | Following a binominal distribution function | 1 | |
| | Fuzzy | A hybridized fuzzy possibilistic programming method | 2 | **7.86%** |
| | | A credibility-based chance-constrained programming | 1 | |
| | | Triangular fuzzy numbers | 2 | |
| | | Considering fuzzy distributions for certain problem inputs | 1 | |
| | | Triangular fuzzy with a specific corruption rate | 1 | |

details about their approaches are given in Section 4.5.2. Uggen et al. (2013) studied a maritime IRP where they tested their algorithms on four real LNG cases with five different characteristics. They considered different numbers of vessels and ports, which are of great importance due to binary variables in the model. The continuous part of their model is indicated by contracts and spot market characteristics; in addition, another characteristic, called contract limit tightness, indicates where and when to deliver the gas. An inland IRP for LNG was also studied by Ghiami et al. (2015), who focused on a distribution network in the Netherlands. Andersson et al. (2015) proposed a new formulation and solution approach for the LNG-IRP compared to Grønhaug et al. (2010). In their new formulation, the route and schedule can be broken down into smaller parts, named duties, that represent "a sequence of ports that starts in a loading port, visits one or two unloading ports and ends up in a loading port". In their new model, paths are composed of duties instead of

**Table 7**
PIRP papers with more than one objective function.

| No. | References | Applied technique | Type of objectives |
|---|---|---|---|
| 1 | Amorim et al. (2012) | Weighted sum method | 1) **min** total cost<br>2) **max** the mean fractional remaining shelf-life of products to be delivered |
| 2 | Rahimi et al. (2014) | Weighted sum method | 1) **min** total cost<br>2) **min** total delay which might occur when visiting the customers |
| 3 | Govindan et al. (2014) | Robust multi-objective metaheuristic | 1) **min** total cost<br>2) **min** total environmental impacts of $CO_2$ emissions |
| 4 | Niakan and Rahimi (2015) | Interactive fuzzy approach | 1) **min** total cost<br>2) **min** the amount of errors in demand and the quantity of expired drugs (maximizes customer satisfaction)<br>3) **min** GHG* emissions of the transportation vehicles |
| 5 | Rahimi et al. (2015) | Weighted sum method | 1) **max** profit<br>2) **min** driver injury rate |
| 6 | Rahimi et al. (2016) | Weighted sum method | 1) **max** profit<br>2) **min** accident rate in distribution of products and gathering the expired products |
| 7 | Rahimi et al. (2017) | NSGA-II | 1) **max** profit<br>2) **min** rate of delays, rate of the number and frequency of backordered products (maximizes the service level)<br>3) **min** GHG emissions resulting from transportation, loading/unloading and recycling of expired products |
| 8 | Tavana et al. (2018) | $\varepsilon$-constraint, NSGA-II, and reference point-based NSGA-II | 1) **min** total cost of procurement and preparation before a disaster occurs<br>2) **min** total relief operational cost in the action phase after a disaster has occurred<br>3) **min** total operational relief time in the action phase after a disaster has occurred |
| 9 | Stellingwerf et al. (2018) | $\varepsilon$-constraint method | 1) **min** $CO_2$ emissions<br>2) **min** transportation and inventory costs |
| 10 | Timajchi et al. (2019) | Compromise programming | 1) **min** total cost of logistics (ordering, transportation, delivery, pickup, shortage and inventory holding costs)<br>2) **min** the maximum accident loss during distribution among all periods |
| 11 | Li et al. (2019) | $\varepsilon$-constraint method | 1) **min** total cost<br>2) **max** the average food quality level |
| 12 | Imran et al. (2020) | Interactive multi-objective fuzzy programming | 1) **min** total cos<br>2) **min** GHG emission<br>3) **max** priority index |
| 13 | Hajibabaie and Lotfi (2021) | NSGA-II and MOSA | 1) **min** total holding, shortage, wastage, and transportation costs<br>2) **min** total delivery time |
| 14 | Daroudi et al. (2021) | NSGA-II and PESA-II | 1) **min** total supply chain cost<br>2) **min** networks time<br>3) **min** the amount of pollution caused by chain activities |

* Greenhouse Gas

whole schedules. Since the number of duties is limited, pre-generated paths exist, and a branch-and-bound algorithm is used to solve the model. Shao et al. (2015) used a model similar to that of Goel et al. (2012) and proposed a hybrid heuristic strategy to improve the previous solutions. Zhang et al. (2017) considered infrastructure development and IRP simultaneously for LNG, while Cho et al. (2018) studied LNG-IRP with respect to maritime transportation and proposed different models to address uncertain weather conditions. Ghiami et al. (2019) proposed a new model for LNG-IRP considering LNG evaporation for all facilities, and they analyzed several replenishment policies.

As blood products (platelets, red blood cells, etc.) have a short lifetime, they have been the focus of some researchers in the PIRP domain. The first study of a blood distribution system with inventory considerations was performed by Brodheim and Prastacos (1979), in which a programmed blood distribution system (PBDS) model was proposed. Hemmelmayr et al. (2009) studied the real PIRP associated with the blood bank of the Austrian Red Cross. The new feature of determining the optimum number of blood mobile units every day together with an appropriate strategy for collecting enough such units while minimizing the traveled distance was studied by Gunpinar and Centeno (2016). A mathematical model for the blood IRP under uncertainty was developed by Kazemi et al. (2017), who implemented their method and proposed solution approaches for a real blood supply chain in Iran. Jafarkhan and Yaghoubi (2018) proposed an IRP for red blood cells with the possibility of transshipment and substitution in a case study of the blood transfusion service of Tehran. Liu Hendalianpour Razmi and Sangari (2021) proposed a model for the blood IRP under demand uncertainty with a fresh-first policy, in which the seller always sells the freshest items first.

In some research, products are considered to experience gradual deterioration over time. Mirzaei and Seifi (2015) considered the demand of end customers to be a linearly or exponentially decreasing function of the perishable product age. They also considered similar functions of the inventory age for lost sales. Product deterioration at an exponential rate during storage was taken into account by Azadeh et al. (2017). Vahdani et al. (2017) employed different decay rates for different products in their research, and Qiu et al. (2019) assumed that remaining inventories from previous periods deteriorated through the current period at known rates. A constant deteriorating rate was applied to products after they departed from a depot by Widyadana and Irohara (2019). The PIRP studied by Rohmer et al. (2019) focused on perishable products whose quality decreases gradually.

Other perishable products that few researchers are concerned with account for approximately a quarter of the papers (based on Fig. 3), and some of these are discussed below:

- **Fresh products:** Ahumada and Villalobos (2011) managed perishability by limiting the maximum permitted storage time and incorporating criteria such as the color of the fruit, which can be used as a key element for determining its freshness. Onggo et al. (2019) assumed that all products are fresh, and they assigned a rate of degradation to product quality. Ji et al. (2020) controlled the maximum shelf life of products by introducing time window constraints. Esmaili and Mousavi (2020) introduced a set of constraints to ensure that each customer receives fresh products from distribution centers.
- **Fuel:** In the context of fuel delivery, Popović et al. (2012) and Vidović et al. (2014) proposed a similar model with different solution approaches. Agra et al. (2014) examined a fuel oil IRP, and a refined oil IRP with low-carbon and environmental protection was considered by Wang et al. (2018).
- **Waste vegetable oil:** Biodiesel is a biodegradable alternative fuel that is a substitute for petroleum and is produced from renewable sources such as vegetable oil. Aksen et al. (2012) considered the collection of waste vegetable oil by a biodiesel production company; they proposed an ALNS in their next study on the same problem, Aksen et al. (2014). Montagné et al. (2018) added new valid inequalities to the previous papers by Aksen and colleagues. Cárdenas-Barrón et al. (2019) used a model similar to that of Aksen et al. (2012) but proposed a new solution approach and achieved better results.
- **Healthcare:** Niakan and Rahimi (2015) noted the importance of medical products and proposed a PIRP in which the distribution of pharmaceuticals and their shortage risk were considered. Timajchi et al. (2019) presented a PIRP with deteriorating pharmaceutical products, while Nikzad et al. (2019) studied the PIRP with different types of pharmaceutical while considering demand uncertainty.
- **Fixed lifetime + random shelf life:** Amorim et al. (2012) considered two types of perishable products, namely, products with a fixed shelf life and products with a variable shelf life. A similar categorization of products with a fixed lifetime and decaying products was considered by Coelho and Laporte (2014).
- **Newspaper:** Newspapers are highly perishable as they aim to provide the latest news, and new issues replace older issues every day. This case was studied by Archetti et al. (2013).
- **Fruit juice:** Bilgen and Günther (2010) analyzed a case study of the integrated production planning and PIRP from a company producing fruit juices and soft drinks.
- **Yogurt:** Another integrated production planning and PIRP, conducted by Bilgen and Çelebi (2013), analyzed a dairy plant, with its yogurt production line as a case study.
- **Vegetables:** Harahap and Rahim (2022) considered a case study of the vegetable distribution process.

### 4.5. Comparison of solution approaches

In this section, the different solution approaches applied to PIRP problems are examined in detail based on the classification shown in Fig. 4. First, exact methods are reviewed in Section 4.5.1, followed by heuristics and metaheuristics in Sections 4.5.2 and 4.5.3. The use of matheuristics is explained in Section 4.5.4. Then, hybrid methods are explained in Section 4.5.5; finally, other methods are discussed in Section 4.5.6.

#### 4.5.1. Exact methods

In some of the previous research, no specific solution method was developed. These researchers prefer to use the default capability of various software, the CPLEX solver being a popular example. This is the most frequently used tool among researchers applying exact methods and can be found in Bilgen and Günther (2010), Ahumada and Villalobos (2011), Amorim et al. (2012), Aksen et al. (2012), Rahimi et al. (2014), Niakan and Rahimi (2015), Ghiami et al. (2015), Rahimi et al. (2015), Li, Chu, and Yang (2016), Li, Chu, Chu et al. (2016), Soysal et al. (2018), Stellingwerf et al. (2018), Violi et al. (2020), and Harahap and Rahim (2022). In addition, two of the research papers use LINGO software: Abdelhalim et al. (2015) and Sun et al. (2018).

The branch-and-cut algorithm is another tool for solving the PIRP by exact methods that is used by, among others, Coelho and Laporte (2014) in their study of the replenishment delivery and inventory management of perishable products. Their algorithm generated subtour elimination constraints at the time of their violation, found with the help of given valid inequalities. Andersson et al. (2015) proposed a new decomposition algorithm as well as a branch-and-cut algorithm. These authors introduced several valid inequalities, and different combinations of inequalities were tested to determine their usefulness. Kazemi et al. (2017) introduced an iterative branch-and-cut algorithm, which first dropped the subtour elimination constraints and then continued solving the problem until an optimal solution was found. Then, the identified violated constraints were added to the problem for reoptimization. Qiu et al. (2019) proposed a branch-and-cut algorithm based on strengthened lot-sizing and lifted MTZ-type (Miller-Tucker-Zemlin) valid inequalities.

Another algorithm used for solving the PIRP is branch and price. Grønhaug et al. (2010) implemented a tailor-made branch-and-price method to obtain integer solutions. They also employed a depth-first strategy with backtracking and presented several branching strategies. Le et al. (2013) presented a column generation-based heuristic algorithm that operates in two steps. First, a linear programming model with valid inequalities is solved to optimality by the column generation method; then, in the second step, an upper bound for the problem is found using CPLEX. These authors claim that a branch-and-cut and price algorithm is effective for small- and medium-sized PIRP instances. Gunpinar and Centeno (2016) found that the branch-and-price algorithm is most useful for small-sized problems of up to 30 locations, three vehicles and two days.

#### 4.5.2. Heuristics

As the VRP and its extensions are NP-hard problems, several algorithms and heuristics have been proposed to find near-optimal solutions. This section summarizes some of the most significant heuristics used on the PIRP; other solution approaches are given in the following sections.

Brodheim and Prastacos (1979) introduced a tool called the programmed blood distribution system (PBDS) using the structure of heuristic methods. It consists of three steps. First, a plan is created for regional distribution and forecasting performance measures. The second step is to implement this regional distribution plan, and the third step involves evaluating the actual performance with respect to the forecast and identifying required modifications for the distribution plan whenever appropriate. Zanoni and Zavanella (2007) introduced six heuristics in two categories, namely, “heuristics based on frequency-set limitation” and “heuristics not based on frequency set limitation”, and they concluded that the heuristics in the second category achieved the best performance. A construction and improvement heuristic (CIH) was presented by Stålhane et al. (2012), who used a multi-start approach to construct a set of initial solutions followed by an intensified search in the neighborhood of each solution to improve it. Uggen et al. (2013) used a type of heuristic approach based on fix-and-relax time decomposition, which was extended with two new features. Montagné et al. (2018) developed a constructive heuristic based on the shortest path and split procedures. Cárdenas-Barrón et al. (2019) presented a reduced cost heuristic algorithm based on a reduce-and-optimize approach consisting of four steps. In the first step, a feasible reduced set of variables is constructed. In the second step, the mathematical model is optimized with the help of the feasible reduced set of variables. Then, in the third step, new variables to be included in the reduced set are selected; finally, the reduced mathematical model is redefined and returned to step two.

Local search is a popular approach in this category. Jafarkhan and Yaghoubi (2018) introduced a ruin-and-recreate heuristic algorithm in which the first step is to create an initial solution and demolish it by removing the nodes responsible for the highest cost when analyzing the solution. Next, the solution space is changed using a shaking process, and two local search methods are used to improve the current solution in several iteration loops. The removed nodes are inserted by a local search in such a way that yields the lowest possible total cost. Then, another local search procedure removes the nodes making the greatest contribution to the total cost, and the procedure is repeated for a given number of iterations. An iterative solution approach was proposed by Hu et al. (2018), who decomposed the problem into multiple subproblems and employed an optimization-based local search with the ability to escape local optima. Another type of iterative solution approach was reported by Liu et al. (2021), where the algorithm starts with an initial solution and then two local search methods that insert the best solution and remove the worst solution are implemented to improve the solution.

#### 4.5.3. Metaheuristics

Metaheuristics, as well as heuristics, have been used by several researchers. The most studied metaheuristic for the PIRP is genetic algorithms (GAs). Azadeh et al. (2017) proposed a GA, in which the parameters were tuned based on the Taguchi method. Hiassat et al. (2017) developed a GA to efficiently solve medium- and large-sized instances; however, enumeration was used to optimize the parameters of their algorithm. Rahimi et al. (2017) designed an NSGA-II to obtain Pareto-optimal solutions, and Tavana et al. (2018) proposed the reference point-based NSGA-II (RPBNSGA-II). The structures of the two algorithms are similar, but in RPBNSGA-II, a diversity index is used instead of the crowding distance to sort the members of each front. Yavari et al. (2020) utilized a GA for a joint pricing and location IRP of perishable products under disruption.

Some other metaheuristics used for PIRP are mentioned here. Popović et al. (2012) employed a variable neighborhood search (VNS) that used a randomized variable neighborhood descent method for the local search procedure. Goel et al. (2012) proposed a large neighborhood search (LNS) algorithm that starts with a three-step heuristic method with a construction heuristic to build an initial feasible solution. Then, the solutions are improved by allowing the departure dates of each voyage to change within a small time window. In the last step, another improvement procedure allows a subset of ships to change schedules over the whole planning horizon. Aksen et al. (2014) developed an ALNS with a variety of moves and repair steps for their problem. Tabu search was used by Jia et al. (2014) and Diabat et al. (2016). A population-based SA (PBSA) was proposed by Shaabani and Kamalabadi (2016) by adding the population aspect to the SA algorithm for adequate diversification and intensification. Furthermore, a general PSO was used by Widyadana and Irohara (2019) for the PIRP with time windows, and Fatemi Ghomi and Asgarian (2019) applied a simple version of the biogeographical-based optimization (BBO) algorithm, with the parameters tuned via the Taguchi method.

#### 4.5.4. Matheuristic

Generally, the matheuristics for basic IRPs are classified as follows by Bertazzi and Speranza (2012):

1) Routing-based matheuristics: First, minimize the routing cost; then, optimize the inventory management decisions.
2) Inventory-first, routing-second matheuristics: First, the inventory part is solved; then, the best routes are found for the inventory decisions that have been made.
3) Cluster-first, IRP-second matheuristics: First, the customers are divided into different clusters; then, the IRP for each cluster is solved separately.
4) Customer-based matheuristics: The optimal solution of the subproblem for every single customer is obtained and iteratively inserted into the partial solution.
5) Policy-based matheuristics: The search space is restricted by focusing on the specific policies (for different reasons).
6) Intensified neighborhood search matheuristics: While Bertazzi and Speranza (2012) specifically addressed intensified TS matheuristic, this category involves the thorough explorations of neighborhoods through a mathematical model. However, finding the neighborhood with the highest quality solutions for intensification is the main challenge.

For the PIRP, the following researchers have used a type of matheuristic in their research. An inventory-first, routing-second matheuristic was proposed by Vidović et al. (2014). They used a relaxed MIP model to obtain an initial solution for the inventory segment, and then a variable neighborhood descent (VND) search on this solution was implemented to complete it with the routing segment. Another similar matheuristic was proposed by Seyedhosseini and Ghoreyshi (2014), who used a combination of exact solutions and a PSO algorithm, where the initial feasible solution for the PSO algorithm was obtained via LINGO software.

A combination of MILP and ACO was considered by Zhang et al. (2017). In the first stage, several groups of MILP models are generated under uncertain conditions by changing one uncertain parameter each time. Then, based on a sensitivity analysis for each of the uncertain parameters, the approximate decision variables are defined as the decision variables that differ from one another after a number of runs. Furthermore, the coordinate vectors for the location of artificial ants are used to create the vectors of decision variables, and the objective function is calculated based on the ACO food density. The decision variable and the approximate decision variable are separated based on the sensitivity analysis of the first stage. Then, the generation of artificial ants is performed, and each decision variable is incorporated into a submodel. Finally, there is an evaluation of the food density of each artificial ant's location, and as the last step, iterations are conducted based on the ACO rules to find the best solution.

Crama et al. (2018) employed an expected value method to reduce the complexity of the stochastic model. Then, they replaced the first step of the expected value algorithm with a replenishment rule using a deliver-up-to-level algorithm. Since such methods generally neglect the importance of revenue and the routing cost, a decomposition algorithm including stochastic dynamic programming and solving the vehicle routing problem was proposed. To improve the estimation of the expected profit in the previous algorithm, a decomposition-integration method was introduced as an optimization problem to obtain the optimal expected total profit. The authors proposed a matheuristic to solve the mentioned optimization problem. Nikzad et al. (2019) developed a two-phase matheuristic method based on a multi-phase heuristic introduced by Solyalı and Süral (2017).

Ghiami et al. (2019) and Rohmer et al. (2019) utilized matheuristics and employed a concept similar to the combination of ALNS with an MILP formulation. Rohmer et al. (2019) introduced three variants of a heuristic method. In the first variant, the optimal delivery patterns of customer, linehaul travel and the inventory of products at the depot were determined by solving an MILP. Then, routing decisions were made based on the results from the previous stage. In the second variant, daily delivery routes were constructed before solving the linehaul and inventory part of the problem, coming from integration of the selection of customer delivery patterns with the routing decisions. In the third variant, the initial solution was generated based on the first variant, and the general structure of the heuristic was similar to that in the second variant, making it a hybridization of the two previous variants. Ghiami et al. (2019) first solved an assignment problem by means of a mathematical model; then, the quantities obtained from the previous step were used to construct a feasible initial solution to be used in an ALNS.

In the most recent study, Mousavi et al. (2022) proposed a five-phase matheuristic. In Phase 1, they solved a traveling salesman problem (TSP) to determine an initial visit order of retailers and then solved a restricted model to obtain an initial solution in Phase 2. In Phase 3, routing decisions were determined by solving a capacitated VRP via a heuristic-based clustering algorithm. Infeasibility repair was then performed in Phase 4; finally, in Phase 5, the obtained solution was improved by optimizing the restricted model and solving a set of TSPs iteratively.

#### *4.5.5. Hybrid methods*

Several researchers have attempted to combine two or more heuristic and metaheuristic methods to take advantage of different algorithms simultaneously since each solution approach has its own capabilities. These types of hybrid methods employed in the context of the PIRP are explained below.

A construction heuristic for the newspaper delivery problem proposed by Archetti et al. (2013) made use of a subroutine. When starting from the first product release ($r$), the set $N_r$ is defined as the number of stations that have to be serviced by a trip starting before the next product ($r + 1$) is released. Trips that visit all the stations in $N_r$ are constructed through a heuristic inspired by Solomon (1987). Then, the procedure is repeated for the following product releases. They also proposed an LNS algorithm to improve the obtained solution by means of a constructive heuristic, and their hybrid approach was applied to these two algorithms.

Agra et al. (2014) considered a hybrid heuristic combining three single heuristics, namely, rolling horizon, local branching and feasibility pump. Another hybrid heuristic that operates in two phases was proposed by Shao et al. (2015). In the first phase, a rolling time algorithm and GRASP are employed, and the best solution found is used for improvement in the second phase, where a combination of neighborhood searches is employed. Hybridization of metaheuristics was performed by Mirzaei and Seifi (2015), who combined simulated annealing (SA) and tabu search (TS). A predefined delivery pattern is the starting point of their algorithm, and a neighborhood search is used to improve this pattern. Wang et al. (2018) developed a GA that utilized greedy algorithms to optimize the initial individuals. Chao et al. (2019) first introduced a distance-based clustering algorithm to split customers into several sets and then used an ACO method with mutation operations to find a good solution for location decisions. Finally, a relocate exchange method for distribution centers was performed to avoid local optimum solutions. Two studies that employed hybrid heuristics are Dai et al. (2020) and Alvarez et al. (2020). The first used a construction heuristic to generate an initial feasible solution and then used an RVND heuristic to improve it. The second proposed a combination of the improved Clarke-Wright savings algorithm with the cuckoo algorithm to solve inventory and routing segments simultaneously. A hybrid imperialist competitive algorithm (ICA) with a self-adaptive differential evolution (SADE) algorithm was proposed by Ghasemkhani et al. (2021) to handle the multi-perishable version of the PIRP under uncertainty.

Govindan et al. (2014) hybridized the multi-objective PSO and an adaptive multi-objective variable neighborhood search. In the context of multi-objective problems, a hybrid GA was developed by Timajchi et al. (2019), who implemented compromise programming, making their proposed hybrid GA capable of generating Pareto solutions.

#### *4.5.6. Other employed methods*

Different types of methods specialized for specific research purposes in the PIRP literature are summarized here.

Bilgen and Çelebi (2013) proposed a simulation-optimization approach to handle uncertainty for production scheduling and route planning in the dairy industry, while Soysal et al. (2015) presented optimization models that are deterministic approximations of the corresponding stochastic models. Their solutions are obtained by a commercial MILP solver; then, a simulation model is proposed to evaluate these solutions to determine whether they are feasible. In another study, Onggo et al. (2019) minimized the expected total cost of the stochastic PIRP with their proposed simheuristic method.

Two computational techniques were proposed by Cho et al. (2018) to improve the optimization performance. The first technique reduces the number of binary variables by eliminating infeasible and inferior solutions with respect to the time windows. The second technique eliminates the need for a tour sequencing process by a logical inequality. Rafie-Majd et al. (2018) first solved their problems using the SCIP solver and then applied Lagrangian relaxation and heuristic algorithms to produce lower and upper bounds, respectively, while Alkaabneh et al. (2020) used Benders decomposition for

**Table 8**
The PIRP papers with a case study.

| No. | References | Type of products | Place of study | Considered case | Type of the case* |
|---|---|---|---|---|---|
| 1 | Brodheim and Prastacos (1979) | Blood | USA (New York city) | New York blood center | CS |
| 2 | Hemmelmayr et al. (2009) | Blood | Austria (Eastern region) | Blood bank of the Austrian red cross of eastern Austria | SCS |
| 3 | Grønhaug et al. (2010) | LNG | International | Suez Energy International | SCS |
| 4 | Bilgen and Günther (2010) | Fruit juices | Germany | The Frutado Case for the beverage industry | SCS |
| 5 | Ahumada and Villalobos (2011) | Fresh products | Mexico (Northwest region) | Mexican growers of green bell peppers and vine ripe tomatoes | CS |
| 6 | Aksen et al. (2012) | Waste vegetable oil | Turkey (Istanbul city) | Biodiesel production company | CS |
| 7 | Stålhane et al. (2012) | LNG | Unknown | Unknown | SCS |
| 8 | Goel et al. (2012) | LNG | Unknown | Unknown | SCS |
| 9 | Uggen et al. (2013) | LNG | International | GDF Suez and Statoil | SCS |
| 10 | Archetti et al. (2013) | Newspaper | Austria (Vienna city) | A production plant in Vienna | SCS |
| 11 | Bilgen and Çelebi (2013) | Dairy plants (yogurt) | Turkey | Dairy manufacturing company | CS |
| 12 | Agra et al. (2014) | Fuel oil | Cape Verde | An oil company | CS |
| 13 | Aksen et al. (2014) | Waste vegetable oil | Turkey (Istanbul city) | Biodiesel production company | CS |
| 14 | Abdelhalim et al. (2015) | Food products | Unknown | Food processing company | SCS |
| 15 | Andersson et al. (2015) | LNG | International | Suez Energy International | SCS |
| 16 | Shao et al. (2015) | LNG | Unknown | Unknown | SCS |
| 17 | Niakan and Rahimi (2015) | Healthcare (Drug) | France (Rhône-Alpes region) | A pharmaceutical supplier | SCS |
| 18 | Soysal et al. (2015) | Food logistics | Turkey | Fresh tomato distribution operations of a supermarket chain | SCS |
| 19 | Azadeh et al. (2017) | Deteriorated at the exponential rate | Iran (Shiraz city) | Dairy company (milk production) | SCS |
| 20 | Kazemi et al. (2017) | Blood | Iran (Sari city) | Blood supply chain | SCS |
| 21 | Zhang et al. (2017) | LNG | China | LNG supply system along the Yangtze river | CS |
| 22 | Soysal et al. (2018) | Food logistics | Unknown | Supplier of figs and cherries | SCS |
| 23 | Jafarkhan and Yaghoubi (2018) | Red blood cells | Iran (Tehran city) | Social security hospitals | SCS |
| 24 | Hu et al. (2018) | Fixed lifetime | USA (California state) | Cut flower sales data | CS |
| 25 | Montagné et al. (2018) | Waste vegetable oil | Canada | Company in the agri-food industry | CS |
| 26 | Sun et al. (2018) | Fixed lifetime | Unknown | Unknown | SCS |
| 27 | Stellingwerf et al. (2018) | Fresh and frozen food | Netherlands | Supermarket chains | CS |
| 28 | Chao et al. (2019) | Food products | China (Dalian city) | Perishable food products delivery | SCS |
| 29 | Qiu et al. (2019) | Products with decay rate | China (Nanjing city) | Food company | SCS |
| 30 | Cárdenas-Barrón et al. (2019) | Waste vegetable oil | Turkey (Istanbul city) | Biodiesel production company | SCS |
| 31 | Ghiami et al. (2019) | LNG | Netherlands | Generation of instances based on real geographic data of the Netherlands | SCS |
| 32 | Li et al. (2019) | Food logistics | Unknown | Fresh-meat product logistics network | CS |
| 33 | Violi et al. (2020) | Agri-food | Italy (Calabria region) | Agri-food company which supplies tangerines | CS |
| 34 | Ji et al. (2020) | Fresh products | China (Shanghai city) | Fresh-hema stores | CS |
| 35 | Yavari et al. (2020) | Fixed lifetime | Unknown | Dairy company | CS |
| 36 | Imran et al. (2020) | Fixed lifetime | Unknown | Group of surgical instrument manufacturing industries | CS |
| 37 | Liu et al. (2021) | Blood | Iran (Tehran city) | Blood transfusion center | CS |
| 38 | Ghasemkhani et al. (2021) | Food products | Iran | A chemical factory | CS |
| 39 | Harahap and Rahim (2022) | Vegetables | Malaysia (Kedah state) | Federal agriculture marketing authority (FAMA) | CS |
| 40 | Song and Wu (2022) | Milk | China (Beijing city) | YH chain supermarket | CS |

* **CS**: Case study-based research **SCS**: Secondary case study-based research

small- and medium-sized instances and a two-stage metaheuristic for larger-sized instances.

Hajibabaie and Lotfi (2021) developed two metaheuristics, i.e., NSGA-II and MOSA. They found that NSGA-II outperforms MOSA in terms of solution quality, but MOSA requires less computational effort. Another study by Daroudi et al. (2021) used NSGA-II and PESA-II. They reported that NSGA-II performs better on small instances and PESA-II has higher efficiency on medium and large instances in terms of solution time and proximity to the Pareto boundary. A recent study by Pratap et al. (2022) used two nature-inspired algorithms, the flower pollination algorithm (FPA) and the cuckoo search algorithm (CSA), with CSA performing slightly better than FPA on all 10 instances considered by the authors.

### 4.6. Investigation of case studies for the PIRP

It is more applicable to have a case study when writing a research paper about perishable products. This is because each perishable

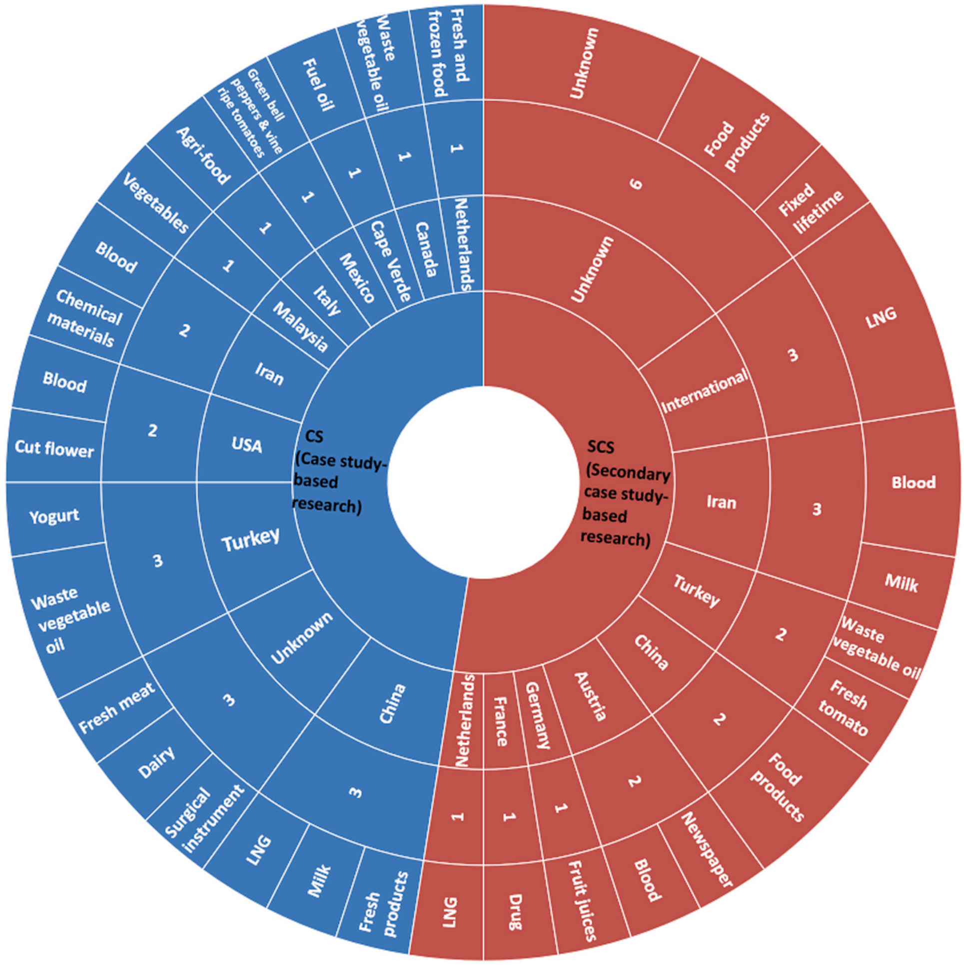


**Fig. 5.** Distribution of case studies for the PIRP papers.

product has its own characteristics, which make the PIRP papers specialized in their own field. Based on Yin (2018), a case study is defined as “a social science research method, generally used to investigate a contemporary phenomenon in depth and in its real-world context”. Apart from research papers considering random instances, the other papers can be classified into two categories. The first is case study-based research (CS), where the authors are faced with a new real case for which they propose and develop their method and solution approaches. The second approach is named secondary case study-based research (SCS), where the authors first work on a general framework and then aim to assess their findings based on real-world data. Hence, this is not pure case study-based research despite the use of real data. Of the reviewed papers, 40 used real-world data. Among these, 19 papers are classified as CS, while the remaining 21 papers use real-world data only to assess their results, leaving them in the SCS category. Details about these papers

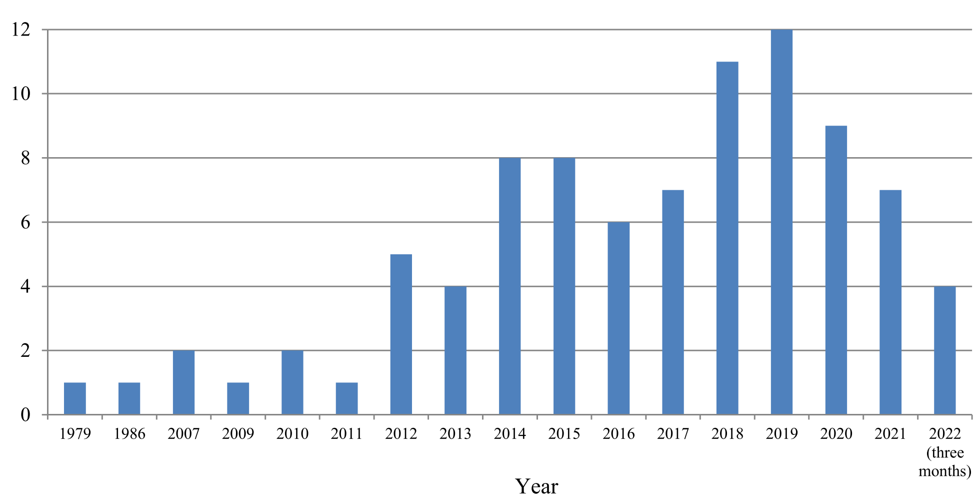


**Fig. 6.** Distribution of published papers by year for the PIRP.

are presented in Table 8, and a graphical summary of these two categories is shown in Fig. 5, indicating the countries in which the cases are employed and the products considered.

### 4.7. Comparison of publication year

Fig. 6 illustrates the distribution of published papers by year for the PIRP. At least one paper has been published each year since 2009. The number of publications has increased in the past eight years, and the growing trend is clear, showing increased interest in this field. The number of papers for 2022 includes only three months, as the current study was completed in late March 2022.

## 5. Conclusions and future research directions

This paper provides a specialized review of the perishable inventory routing problem (PIRP), reviewing 89 relevant papers and classifying them according to the number of products, type of product, type of demand, single objective vs. multiple objectives and solution approach. In addition, the journals publishing work within this field are listed.

The following aspects may be considered for future studies of the PIRP:

### 5.1. Key conclusion

Analysis reveals that in the IRP literature, only a few papers have studied problems with perishable products. Since the IRP is the coordination of the two components of the supply chain, inventory management and vehicle routing, the problem is important and complex by itself. Hence, whenever perishability is considered for the IRP, it makes the problem more sophisticated and more similar to real-world problems, and the need for considering the IRP with perishable products is evident.

### 5.2. Covered and uncovered areas

It is now possible to answer the first research question regarding the components of the PIRP that are most researched and areas that are still uncovered.

- Among the PIRP papers, more than two-thirds consider single products. This makes the problem easier to analyze but limits the practical interest, so consideration of multiple products for the PIRP is recommended to cover more real-world problems.
- It is also easier to consider deterministic demand for the PIRP problems, which is the focus for most researchers thus far. However, real-world problems usually do not have deterministic demand and will confront uncertainties. Hence, it is strongly recommended to consider uncertain demands in future studies of the PIRP.
- The definition of objectives for a problem is related to its conditions. Nevertheless, it is natural to consider the PIRP with respect to multiple objectives. This is not extensively studied in the existing research papers.

### 5.3. Emergence of new concepts

The second research question is answered as follows. Three papers from three different years address “social issues”, which is a new concept. The driver injury rate (Rahimi et al., 2015), rate of vehicle accidents (Rahimi et al., 2016) and accident loss (Timajchi et al., 2019) are concepts that all refer to social issues. Such social issues are new concepts in the field of the PIRP, and other important considerations can be added to the PIRP models, e.g., digital technology, sustainable consumption, and energy transition. The accident risk in the PIRP can be considered to reduce the risk of possible disastrous accidents.

### 5.4. Less developed theories

Based on the conducted review, the less developed theories of the PIRP are listed here in response to the third research question.

- Exact solution approaches are used less than approximate methods, and most researchers use the default capability of existing software to solve small- or medium-sized problems instead of coding new exact algorithms. Therefore, using exact solution approaches and, in particular, coding novel exact algorithms is highly recommended for future studies of the PIRP.
- Another notable point is related to the matheuristic solution approach, which was most recently employed for the PIRP; it is expected that more matheuristics will be developed for this field in the near future.
- In terms of the deterioration rate, a nonlinear rate as a function of time that closely resembles the real-world problem, is recommended.
- Analysis regarding the advantages and disadvantages of considering more than one depot (supplier) for the PIRP is needed. Although a multi-depot PIRP will be more challenging, it can lead to lower inventory levels and shorter routes for perishable products.
- Pricing is another element of the supply chain that can be considered together with inventory and transportation elements. Since perishability directly affects the price of such products, considering pricing together with the PIRP is a practical future research direction.
- Other real-life objectives should be defined for the PIRP to consider different objectives simultaneously. In addition, more evolutionary algorithms should be developed to address multiple objectives.
- Case study-based research provides a better understanding of the model and problem; therefore, it can greatly contribute to the PIRP literature. Hence, more relevant case studies are recommended for the PIRP.
- Supply chain disruptions can be caused by natural disasters (e.g., earthquakes, landslides, floods) and human-caused events (e.g., strikes, bankruptcies), but these disruptions are studied in only one paper by Yavari et al. (2020), who examined the location-inventory routing problem for perishable products when route disruptions occur in some periods. Therefore, the study of the PIRP in the presence of disruptions requires further research.

### 5.5. Current and future studies

Most of the PIRP papers are devoted to specific perishable products, such as food products, since these are common products used by people daily. Another large group considered is general products, which may have a fixed lifetime or a random shelf life. More attention should be paid to other crucial perishable products, such as drugs, pharmaceutical items, and blood, which are important real-world problems with a limited research focus.

Another recommendation for future research is related to research areas concerning perishable products that are close to the IRP, disregarding some assumptions of the IRP to better apply the problem to real cases. For example, in the IRP, each vehicle (starting and ending at the depot) can be used on at most one route per time period. However, in the home health care route-scheduling problem studied by Shahnejat-Bushehri, Tavakkoli-Moghaddam, Boronoos, and Ghasemkhani (2021), a model is proposed where a vehicle can be deployed more than once in a given time period to provide the ability to visit a customer multiple times within a time period. This feature may be critical for the distribution and inventory management of perishable products.

Basic versions of the IRP assume that there is sufficient inventory in the depot to meet all demand (Coelho, Cordeau et al., 2014). In addition to this assumption, most PIRPs assume that the freshest products are always available in the depot, for example, Rohmer et al. (2019) and Alkaabneh et al. (2020). Coelho and Laporte (2014) and Qiu et al. (2019) are the only two studies that have investigated joint replenishment, delivery, and inventory management policies for perishable products. Therefore, it is recommended that more studies consider inventory management policies when addressing the PIRP. According to Sazvar, Mirzapour Al-e-hashem, Govindan, and Bahli (2016), some specific inventory management policies for perishable products that are directly related to product quality are FEFO (first expires first out), LQFO (lowest quality first out), LEFO (latest expiry first out), and HQFO (highest quality first out).

## Conflicts of interest

The author has no conflicts of interest to declare.

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