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Invited Review

Order batching problems: Taxonomy and literature review☆

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ABSTRACT

Order Batching is a family of optimization problems related to the process of picking items in a warehouse as part of supply chain management. Problems classified into this category are those whose picking policy consists of grouping the orders received in a warehouse into batches, prior to starting the picking process. Once the batches have been formed, all items within the same batch are picked together on a single picking route. In this survey we review the optimization problems known in this family, focusing on manual picking systems and rectangular-shaped warehouses with only parallel and cross aisles, which is the most common warehouse configuration in the literature. First, we identify the decisions within the strategic, tactical, and operational levels that influence the picking task. Then, we characterize the optimization problems belonging to this family, whose objective function might differ. The identified problems are classified into a taxonomy proposed in this paper, which is designed to host future problems within this family. We also review the most outstanding papers by category and the strategies and algorithms proposed for the most relevant activities: batching, routing, sequencing, waiting, and assigning. To conclude, we outline the open issues and future paths of the topic under study.

1. Introduction

The supply chain is the sequence of events that cover the entire life cycle of a product or service, from conception to consumption (Blanchard, 2010). Among others, it involves entities (manufacturers, suppliers, wholesalers, retailers, etc.), resources (information, materials, human, financial, etc.), and activities (acquisition, transformation, storage, distribution, etc.). Management of the supply chain includes a variety of decisions and transactions between the different entities involved in the process, which are typically classified into strategic, tactical, and operational (Misni & Lee, 2017).

A key part of the supply chain usually occurs within a warehouse, where different materials or products are received, processed, and stored for later use (i.e., they are usually picked up and shipped). Within a warehouse, strategic decisions are usually long-term decisions related to aspects such as: determining the place to set the warehouse, choosing the right network of suppliers and transporters, selecting and customizing the software systems, determining the layout or mechanization of the warehouse, etc. The tactical point of view usually includes mid-term decisions such as: defining guidelines to meet quality and safety, determining the location where the products are going to be stored, setting the number and position of the depots (also known as Input/Output points), or performing inventory logistics, among others. Finally, the operational decisions are commonly short-term decisions such as: forecasting the daily and weekly demand, scheduling of production operations, managing incoming and outgoing products/materials, managing the orders received in the warehouse, etc. See further details in De Koster, Le-Duc, & Roodbergen (2007); Il-Choe & Sharp (1991); Misni & Lee (2017).

The profit obtained in the warehouse is strongly dependent on how the management systems determine the operational actions. In this literature review, we focus our attention on the operational activities related to the picking of orders in a warehouse. However, these activities are also influenced by some tactical and strategic decisions. In Fig. 1, we have compiled and classified the most rel-

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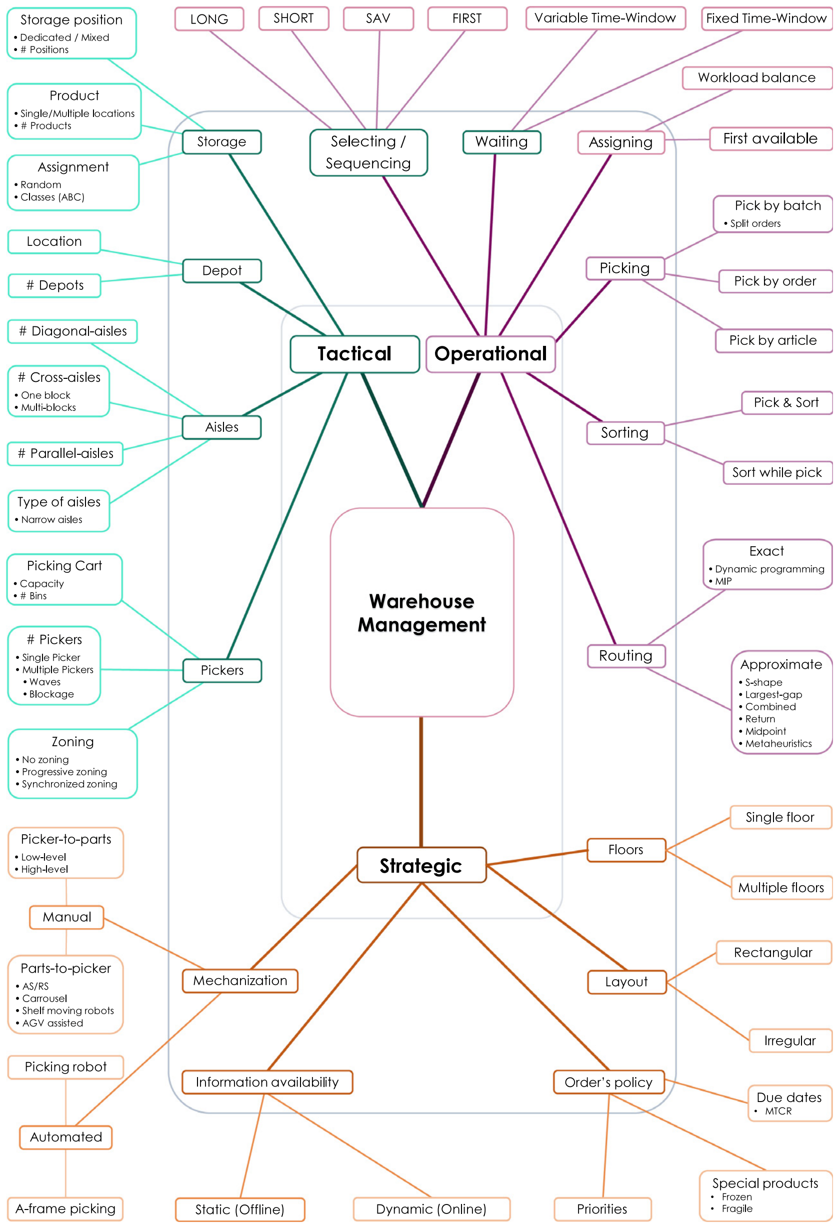

Fig. 1. Warehouse management decisions related with the picking of orders.

evant decisions, highlighted in the literature, that occur in warehouse management in relation to picking activities. Particularly, the decisions are classified into strategic, tactical, and operational. Additionally, we have split those categories into several subcategories, and then we have compiled the related decisions. These subcategories have been partially inspired by those introduced in previous research (De Koster et al., 2007; Gu, Goetschalckx, & Mc. Ginnis, 2007; Misni & Lee, 2017). Notice that there are many other decisions related to the supply chain within a warehouse, but we have focused only on those that have a deep influence on the picking process and have been previously reported in the literature.

On a daily basis, warehouses receive orders from customers, consisting of a list of products that need to be retrieved from its current location, moved to a common area, packaged together, and shipped to the customer. The operational management of the warehouse must determine the sequence in which those orders/products are picked, the picker assigned to collect them, the route that the picker must follow, or the moment in time when starting the picking, among others. The picking process in a warehouse was one of the first optimization targets to be considered (Gudehus, 1973). The picking is highly influenced by the storage policy (Ruben & Jacobs, 1999), the layout of the warehouse, and the routing strategy, among others (Petersen, 1997). Some authors stated that this process can consume up to 60% of the total time of all labor activities in a warehouse (Coyle, Bardi, & Langley, 1996; Drury, 1988), which can suppose more than half of the total operational costs (Tompkins, White, Bozer, & Tanchoco, 2010). In this context, an important operational decision consists of determining whether orders are collected in isolation (strict order picking) or grouped prior to being picked (order batching). The strict order picking is usually considered a naive strategy, consisting of assigning each order to a picker, who collects all the items within that order. Once all the items have been retrieved, they are placed in a depot, and then the system assigns a new order to the picker, and so on. On the contrary, order batching is considered a more advanced strategy. It consists of grouping several orders into a batch that does not exceed a predefined capacity. Then, once the batch is conformed, it is assigned to a picker who retrieves all items in the orders of the batch on a single route (Elsayed, 1981). The order batching policy has been shown to be very effective compared to the strict order picking policy. Additionally, it is possible to reduce travel time by up to 35% if the routes are designed considering batching at the same time (De Koster, Roodbergen, & Van Voorden, 1999a). However, it is important to remark that order batching policy is specially handful in Business-to-Customer contexts, where several small items/packages can be picked together instead of picking a whole pallet, which is typical from Business-to-Business (B2B) contexts. Therefore, in B2B scenarios, sometimes strict order picking is necessary. Other picking strategies also include zone picking and wave picking. In zone picking, a picker is assigned to a particular area in the warehouse, where the picker is responsible of picking only the items within that zone, while in wave picking, multiple picking routes are synchronized. Petersen (2000) performed a comparison of the main picking strategies: strict order picking, order batching, zone picking, and picking with waves.

In this survey, we focus our attention on a family of optimization problems that appears in a warehouse when the order-picking strategy is determined by the order batching policy. In particular, according to Fig. 1, we review all operational decisions that occur in manual order picking systems (strategic / mechanization), single-floor warehouses (strategic / floors), rectangular-shaped design (strategic / layout) that present only parallel and crossing aisles (tactical / aisles), which is probably the most common warehouse configuration in the literature. This family of problems has received growing interest from practitioners in operational research over the last few decades.

The rest of the paper is organized as follows: in Section 2 we define the family of problems denoted as "order batching problems", its main characteristics and common activities related to the problems within this family. In Section 3 we introduce a new taxonomy for the problems belonging to this family, based on four criteria: online / offline, single / multiple pickers, the optimized objective function, and the tasks handled. Then, in Section 4, we review in detail the literature of all journal articles found related to order batching. Closely related to this section, in Appendix A, we classify the papers related to order batching reviewed in this survey, following the proposed taxonomy. Finally, in Section 5, we present our conclusions and future perspectives on the field reviewed.

2. Order batching problems

The order batching family of problems groups all optimization problems whose main goal is to determine the best way to perform an efficient picking operation through the use of the batching strategy. The order batching strategy belongs to the operational decisions in a warehouse and consists of grouping several orders into the same batch before starting the picking. This indicates that items belonging to orders in the same batch must be retrieved together (i.e., on the same picking route). Each batch is restricted to contain a maximum capacity that might be measured in: weight, volume, number of items, or number of orders.

The batching strategy has led practitioners in the field of operations research to a wide range of related optimization problems. However, this strategy itself is not enough to define an applied optimization problem. Therefore, every problem that belongs to this family, in addition to following the pick-by-batch strategy, must face additional and separate optimization problems within it, which are closely related to any of the operational decisions presented in Fig. 1. Nevertheless, the batching strategy deeply influences the rest of operational decisions: new constraints must be taken into consideration; each picking route is more lengthy and complicated, since it needs to consider more products; orders collected together must be sorted while picking or in a later process, since more than one order is collected at the same time; waiting strategies for the arrival of new orders might be considered; the assignment of batches to pickers directly influences how workload is balanced; determining the batch to select next also has additional challenges, since orders within the same batch might have different due dates or priorities; etc.

Additionally, it is important to note that many tactical and strategic decisions related to order batching problems are usually stated in the instances within the data sets, either in the information about the characteristics of the warehouse or in the information about the orders.

It is important to notice that in this paper we are focusing on picker-to-part problems that occur in rectangular-shaped warehouses, where the picking is usually performed manually. These warehouses are usually formed by a set of parallel aisles, which contain several picking positions at each side of the aisle and one or more (typically two) cross aisles, which allow the pickers to move from one parallel aisle to another. In Fig. 2, we depict an example of a typical layout of the warehouse studied. Particularly, the warehouse represented in the figure has two cross aisles (one at the front and another one at the back) and five parallel aisles with twelve picking positions each (six at each side of the aisle). Picking routes start and end at a particular point of the warehouse denoted as the depot. In this example there is only one depot, placed in the leftmost corner of the front cross aisle. However, the depot can also be placed in the center or in the right corner of a cross aisle. Furthermore, sometimes more than one depot might exist. In the example of the figure, we have also highlighted in gray some picking positions, as an example of the positions that a picker must visit on a single picking route.

2.1. Operational decisions involved in the picking

In this section, we describe each of the operational decisions that might be addressed when handling any of the optimization problems belonging to the order batching family. Notice that some papers avoid studying some of the following tasks by handling a simplified variant of the problem or fixing a particular strategy for any of them. Specifically, the most common processes / tasks involved in the picking, together with the order batching task, are: waiting, selecting, sequencing, assigning, routing, and sorting.

The waiting task consists of determining the time that an available picker must wait to start a new route. This time is generally known in the literature as the "time window". The rationale behind this idea is that the longer the picker waits, the more orders are available in the system, which helps to construct more compact batches.

The selecting / sequencing task consists of determining the order in which the available batches are collected. When only one batch is selected as the next one to be collected, the task is generally known as "selecting". Otherwise, if all available batches are prioritized / sorted, the task is usually known as "sequencing".

The assigning task consists of determining which picker, among the available ones, is assigned to the next batch to be collected. This task only makes sense in scenarios with multiple pickers and is closely related to the balance of workload of the pickers.

The routing task consists of determining the route (i.e., the sequence of steps) that a picker must follow through the warehouse to collect all items in the orders contained in the assigned batch. The starting and finishing point for the routes is named the depot and it is the place where items are dropped once the picker has collected them. As mentioned above, the routing strategy has a profound impact on the results obtained for order batching problems. Determining the route is necessary to calculate the distance traveled by the pickers or the time required to collect the items.

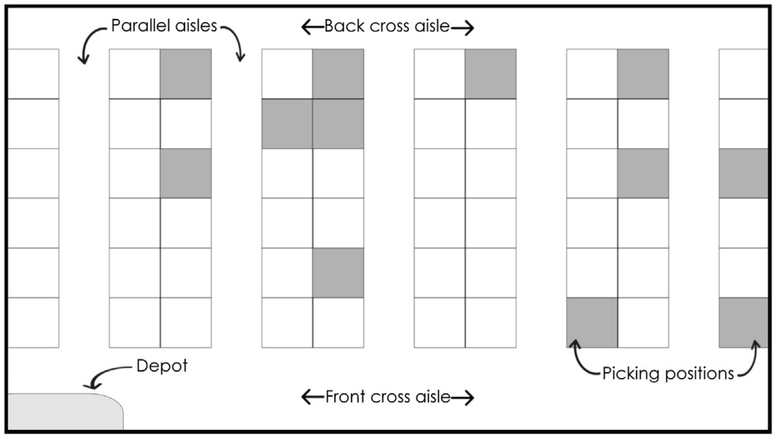

Fig. 2. Example of the layout of the logistic warehouse studied in this paper.

The sorting task consists of defining the strategy followed to sort the items picked in orders. Notice that when following a batching strategy, items from different orders are collected on the same picking route by the same picker, and they have to be classified later into orders (pick and sort), unless the picking cart has separate bins for each order (sort while pick).

It is worth mentioning that in the vast literature related to order batching problems, it is also possible to find variants of the problem that consider other activities, not explored in detail in this review, that can be the subject of optimization.

2.2. Objectives pursued

The target of any of the optimization problems belonging to the order batching family can be formalized through the use of different objective functions, not necessarily in conflict. Depending on the number of objectives pursued, optimization problems are traditionally classified in: single-objective optimization (only one objective function is optimized) or multi-objective optimization (two or more, in conflict, objective functions are optimized). However, in the context of order batching problems, further than the number of objectives that are optimized, we can classify the problems depending on the number of tasks that they are needed to solve in order to find a solution to the problem. If only the batching task is addressed, we denote the problem as “simple”. In contrast, when more than one task is optimized, we denote the problem as “joint” (Chen, Cheng, Chen, & Chan, 2015; Feng & Hu, 2021; Shavaki & Jolai, 2021). This means that the variables that represent a solution contain the information necessary to complete the tasks being pursued. In these contexts, the algorithms proposed assign values to all variables that represent the solution simultaneously. The most common task optimized together with batching is the routing task (Hong & Kim, 2017; Valle, Beasley, & Da Cunha, 2017). However, we can also find simultaneous optimizations of batching with selecting / sequencing (Jiang, Zhou, Zhang, Sun, & Hu, 2018; Menéndez, Bustillo, Pardo, & Duarte, 2017a) or assigning (Ardjmand et al., 2020; Matusiak, De Koster, & Saarinen, 2017), among others.

Objective functions are usually related to the maximization or minimization of a particular dimension. The most common ones are: time, distance, workload balance, or cost. However, some other minority objectives can also be found in the literature. The time dimension is probably the most studied one and it includes aspects such as: the time required to collect an order, a batch or a group of orders (Chen, Wei, & Wang, 2018; Gil-Borrás, Pardo, Alonso-Ayuso, & Duarte, 2020b; Henn, 2012; Rubrico, Higashi, Tamura, & Ota, 2011; Zhang, Wang, Chan, & Ruan, 2017); the time that orders or pickers wait before starting their picking (Gil-Borrás, Pardo, Alonso-Ayuso, & Duarte, 2020a; Henn, 2012; Zhang et al., 2017); the total time that an order remains in the system (Chew & Tang, 1999; Gil-Borrás et al., 2020b; Tang & Chew, 1997), also known in the literature as throughput time (Le-Duc & De Koster, 2007; Van Nieuwenhuyse, De Koster, & Colpaert, 2007; Yu & De Koster, 2009); the delay with respect to a due date, known in the literature as tardiness (Chen et al., 2015; Henn, 2015; Henn & Schmid, 2013; Menéndez et al., 2017a; Scholz, Schubert, & Wäscher, 2017; Zhao, Jiang, Bao, Wang, & Jia, 2019); the handing time before the expected due date, known in the literature as earliness (Elsayed, Lee, Kim, & Scherer (1993)); or the blocking time of pickers (Chen, Wang, Qi, & Xie, 2013; Chen, Wang, Xie, & Qi, 2016; Hahn & Scholz, 2017). Closely related, the distance dimension measures the distance traversed by pickers when collecting orders (Öncan, 2015; Pérez-Rodríguez & Hernández-Aguirre, 2015). However, this dimension can be easily transformed into time (Henn & Wäscher, 2012; Jarvis & Mc. Dowell, 1991). In the case where multiple pickers are considered, a common dimension is related to the workload of the pickers measured in either: number of orders processed, distance traversed, number of items retrieved, total time retrieving items, etc. (Chen et al., 2016; Gil-Borrás, Pardo, Alonso-Ayuso, & Duarte, 2021; Huang, Guo, Liu, & Huang, 2018; Mohring, Baumann, & Furmans, 2020; Zhang et al., 2017). Other minority dimensions identified in the literature include the amount of work in progress (Hong, 2019), or the orders picked per unit of time (Hong, 2019). Finally, some authors have studied the economic aspects associated with picking operations, and in this case, the dimension to minimize is the cost (Bukchin, Khmelnitsky, & Yakuel, 2012; Miguel, Frutos, Tohmé, & Rossit, 2019; Pinto & Nagano, 2019; Tian, Zhou, & Yang, 2019; Zhang, Wang, & Huang, 2018).

3. Taxonomy and classification of order batching problems

Once the order batching family of problems has been described, many different specific problems can be found in the literature, depending on the objective pursued, the tasks optimized, the warehouse characteristics, the types of products handled, the availability of information, the number of pickers, etc. In this paper, we propose a taxonomy to classify all variants of order batching problems present in the literature based on the constraints considered, the objective function tackled, and the tasks (decision variables) optimized. For each criterion, several subcategories have been outlined. Each subcategory is represented by the text in parentheses, and the particular classification in the taxonomy of a specific problem is composed as the assignment of several subcategories simultaneously.

1. **Constraints**: among the different constraints that can be identified in the order batching literature, we have selected the two most significant. However, many others can be found, depending on the variant studied.
    - **Availability of information**: it indicates when the information related to the orders is available for the optimization process.
        - **Offline** (OFF): a problem is considered offline when all information about the orders to process is already available when the batching process starts.
        - **Online** (ON): a problem is considered online when the information about all orders to process is not fully available when the batching process starts (i.e., orders arrive to the system dynamically).
    - **Number of pickers**: it indicates the number of people who are simultaneously working on the picking task.
        - **Single picker** (SP): a problem is considered "single picker" when the picking task in the warehouse is performed by only one operator.
        - **Multiple pickers** (MP): a problem is considered "multi-picker" when the picking task in the warehouse is carried out by two or more operators.
2. **Objective functions**: the objective function represents the subject of optimization. Particularly, we have collected the dimensions measured by all the objective functions identified in the literature of order batching. It is important to note that some objectives are closely related one to each other, and sometimes, minimizing one of them might also minimize another. Specifically, there exists an equivalence between the two most studied objective functions in the literature (distance and time) when the travel velocity is constant. This fact has been pointed out by several authors (Henn & Wäscher, 2012; Jarvis & Mc. Dowell, 1991).
    - **Distance** (DI): units of length that operators need to traverse to collect all items in the processed orders.
    - **Picking time** (PT): units of time needed to perform the picking task, when collecting items in the orders processed in the warehouse.
    - **Cost** (CO): unit of value that measures an economic indicator related to the picking operation in the warehouse.
    - **Tardiness** (TA): units of time corresponding to the delay in handling an order with respect to a predefined due date. In this category, we also include the earliness, which indicates the anticipation of serving an order with respect to its due date.
    - **Completion time** (CT): units of time needed to collect all orders arrived at the warehouse, including picking time and time waiting for the arrival of new orders (waiting time).
    - **Turnover time** (TT): units of time that an order remains in the system (i.e., difference between the instant in the time when the order is served and the instant in the time when the order arrives).
    - **Workload balance** (WB): units of effort that indicate the differences among the amount of work performed by different operators. It is usually measured in time; however, other dimensions could be used, such as: distance traversed, number of orders, batches retrieved, etc.
    - **Blocking time** (BT): units of time that a picker waits for before achieving a particular task, blocked by the operation of another picker or machine (i.e., extracting items from a particular picking position; using the depot; etc.). This objective is also known in the literature as congestion.
3. **Decision variables**: the solution to an optimization problem is expressed through the values assigned to a set of variables. In the context of order batching problems, depending on the number of processes/tasks studied, it is possible to solve a single optimization problem (i.e., batching) or more than one at the same time (i.e., batching together with Sequencing/Assigning/Routing/Waiting). Therefore, the variables that represent a solution to an order batching problem might be different depending on the number of tasks studied. We have defined a processes/tasks which could be studied:
    - **Batching** (B): set of variables that represent the group of orders in batches.
    - **Sequencing** (S): set of variables that represent the sequence in which batches are collected.
    - **Assigning** (A): set of variables that represent the assignment of each batch to a picker.
    - **Routing** (R): set of variables that represent the route to follow by the picker to collect a batch.
    - **Waiting** (W): set of variables that represent the waiting time of each picker before starting a new route.

Notice that we have avoided the inclusion of several tasks such as: sorting, packaging, or scheduling, to ease the taxonomy. However, the taxonomy can be easily extended in the future by including such or other tasks.

In Fig. 3, we graphically represent the proposed taxonomy, where the considered constraints, objective functions, and variables are represented. As far as constraints are concerned, we can observe that the offline version is a special case of the online one. Furthermore, for any particular instant in time, we can transform an online variant into an offline one, supposing that no further orders will arrive to the system. Similarly, in the case of the number of pickers, the single-picker variant is a particular case of the multiple-pickers one. Since the single-picker variant considers that there is only one picker in the warehouse, batches must be sequenced and collected one by one. In this sense, approaches for multiple pickers can be used to solve single picker problems. Therefore, in single-picker variants there are not blocking situations in the aisles, in the picking positions or in the depot. On the other hand, multiple picker variants consider two or more pickers to work simultaneously in the picking-order process. This context reveals not only possible blocking situations, but also other necessities, such as deciding the assignment of batches to pickers or balancing the workload among the pickers.

Among the objective functions compiled, note that we have indicated only the dimension used to measure the objective function, not indicating whether the optimization target is an average value, a total value, or a maximum / minimum value. The objectives included in Fig. 3 are divided into three different groups, the first group (i.e., tardiness, picking time, distance, and cost) contains those objectives present in any online / offline and single-picker / multiple-pickers variant. The second group (i.e., completion time and turnover time) contains those objectives that only make sense when considering an online variant. Finally, the third group (i.e., blocking time and workload balance) contains those objectives which only make sense when considering a multiple-pickers variant.

The taxonomy presented in Fig. 3, represents a general framework that can be used to classify all optimization problems currently present in the state of the art of order batching problems. Additionally, it can be extended further in the future by including new constraints, objectives, or tasks with its associated variables

Taxonomy of Order Batching Problems

Constrains		Objective functions								Variables					Problem name	
Availability of information	Number of pickers	Tardiness (TA)	Picking Time (PT)	Distance (DI)	Cost (CO)	Completion Time (CT)	Turnover Time (TT)	Blocking Time (BT)	Workload Balance (WB)	Batching (B)	Sequencing (S)	Assigning (A)	Routing (R)	Waiting (W)	Simple / Joint	(# Papers) & Acronym
Offline (OFF)	Single Picker (SP)		✓	✓	✓					✓					Simple	**(31) OBP**
		✓	✓	✓	✓					✓	✓				Joint	**(5) OBSP**
			✓	✓	✓					✓			✓			**(16) OBRP**
		✓	✓	✓	✓					✓	✓		✓			**(7) OBSRP**
	Multiple Pickers (MP)		✓	✓	✓					✓					Simple	**(10) OBPMP**
		✓	✓	✓	✓					✓	✓				Joint	**(6) OBSPMP**
			✓	✓	✓			✓	✓	✓		✓				**(3) OBAPMP**
			✓	✓	✓					✓			✓			**(3) OBRPMP**
		✓	✓	✓	✓			✓	✓	✓	✓	✓				**(4) OBSAPMP**
		✓	✓	✓	✓					✓	✓		✓			**(2) OBSRPMP**
			✓	✓	✓			✓	✓	✓		✓	✓			**(6) OBARPMP**
		✓	✓	✓	✓			✓	✓	✓	✓	✓	✓			(0) OBSARPMP
Online (ON)	Single Picker (SP)		✓	✓	✓	✓	✓			✓					Simple	**(10) OOBP**
		✓	✓	✓	✓	✓	✓			✓	✓				Joint	(0) OOBSP
			✓	✓	✓	✓	✓			✓			✓			**(2) OOBRP**
			✓	✓	✓	✓	✓			✓				✓		**(3) OOBWP**
		✓	✓	✓	✓	✓	✓			✓	✓		✓			**(1) OOBSRP**
		✓	✓	✓	✓	✓	✓			✓	✓			✓		(0) OOBSWP
			✓	✓	✓	✓	✓			✓			✓	✓		(0) OOBRWP
		✓	✓	✓	✓	✓	✓			✓	✓		✓	✓		(0) OOBSRWP
	Multiple Pickers (MP)		✓	✓	✓	✓	✓			✓					Simple	**(11) OOBPMP**
		✓	✓	✓	✓	✓	✓			✓	✓				Joint	(0) OOBSPMP
			✓	✓	✓	✓	✓	✓	✓	✓		✓				**(1) OOBRPMP**
			✓	✓	✓	✓	✓			✓			✓			(0) OOBAPMP
			✓	✓	✓	✓	✓			✓				✓		(0) OOBWPMP
		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				(0) OOBSAPMP
		✓	✓	✓	✓	✓	✓			✓	✓		✓			(0) OOBSRPMP
		✓	✓	✓	✓	✓	✓			✓	✓			✓		(0) OOBSWPMP
			✓	✓	✓	✓	✓	✓	✓	✓		✓	✓			(0) OOBARPMP
			✓	✓	✓	✓	✓			✓			✓	✓		(0) OOBRWPMP
			✓	✓	✓	✓	✓	✓	✓	✓		✓		✓		(0) OOBAWPMP
		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			**(4) OOBSARPMP**
		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		(0) OOBSAWPMP
		✓	✓	✓	✓	✓	✓			✓	✓		✓	✓		(0) OOBSRWPMP
			✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓		(0) OOBARWPMP
		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		(0) OOBSARWPMP

Fig. 3. Taxonomy for classifying the order batching optimization problems in the literature.

to represent them. It is also important to note that, depending on the objective pursued, this taxonomy could also be used to classify single-objective or multi-objective optimization problems.

The taxonomy let us label order batching problems through the notation in parentheses introduced for each subcategory. Therefore, we propose to identify each optimization problem with a tag composed of four subtags (one per subcategory) separating them with hyphens. For instance, OFF-SP-TA-B would stand for an offline variant of the problem, which considers a single picker and looks to optimize the tardiness through the optimization of the variables related to the batching task.

Finally, given the taxonomy, we have related the categories in the taxonomy with the acronym of the problem and the number of papers which handle each particular variant. Note that some of the variants identified in Fig. 3 have never been studied in the literature. Additionally, we have separated those problems that only look for the optimization of the batching task (denoted as "Simple") from those that look for the optimization of two or more tasks (denoted as "Joint").

4. State of the art

In this section, we review the most relevant approaches proposed in the literature of order batching. Particularly, we have organized this review, dividing the analysis of contributions into the main categories introduced in the taxonomy presented in Section 3, obtaining four groups: Offline / Single Picker (Section 4.1), Offline / Multiple Pickers (Section 4.2), Online / Single Picker (Section 4.3), and Online / Multiple Pickers (Section 4.4). Within each category, we identify different problems, depending on the tasks studied: batching, routing, sequencing, assigning, or waiting. When several tasks are optimized simultaneously, the problem could be considered as a special case of the joint order batching problem.

For each problem identified, we compile in a different table all the contributions found in a journal indexed in the Journal Citation Reports (JCR) or in the Scimago Journal & Country Rank (SJR), sorted in chronological order. In each row of the tables, we report the reference to the paper, the objective function studied, and the routing, batching, waiting, or assigning algorithm proposed. Furthermore, for each of the proposals, we denote if the proposed strategies in the paper include heuristic algorithms, exact algorithms, or a combination of both. Notice that sometimes more than one algorithm is used for the same task and more than one objective function is studied. Finally, to complement this information, we describe any notable aspect of the warehouse considered. To end this section, we perform a synthesis of the review performed (see Section 4.5).

4.1. Offline / single picker

In this section, we review the state of the art of offline order batching variants with a single picker. In these variants, all orders to collect are known before the process starts and there is only one picker in the warehouse.

4.1.1. Order batching problem (OBP)

We have classified under this category those papers that only consider the optimization of the batching task (see Table 1). As we can observe, most of the contributions study the minimization of the distance or the picking time as objective function. The first approach for the OBP was proposed in Elsayed (1981). In this case and other similar ones (Elsayed & Unal, 1989; Pan & Liu, 1995) the routing task was handled by an Automated Storage / Retrieval System (AS / RS), while the batching task was performed with basic heuristics. Several authors studied the influence of the routing strategy on the problem, comparing different routing algorithms (Albareda-Sambola, Alonso-Ayuso, Molina, & De Blas, 2009; Dukic & Oluic, 2007; Hwang & Kim, 2005) in combination with the same batching proposal. Most of the algorithms for the routing task are traditional heuristics such as S-shape, Largest Gap, or Combined. It is worth mentioning that Menéndez, Pardo, Alonso-Ayuso, Molina, & Duarte (2017b) proposed an extension of the Combined method. Similarly, most of the approaches for the batching task are also heuristic algorithms, and there are only a few exceptions of exact algorithms applied to solve the batching task (Lenoble, Frein, & Hammami, 2018; Muter & Öncan, 2015; Öncan, 2015). The first metaheuristic approach for batching was a Genetic Algorithm introduced in Hsu, Chen, & Chen (2005). Finally, with respect to the structure of the warehouse, most of the papers deal with a single-block warehouse, however some of them also considered a two or more blocks warehouse (Scholz & Wäscher, 2017; Yang, Zhao, & Guo, 2020).

4.1.2. Order batching and sequencing problem (OBSP)

We have classified under this category those papers which consider the optimization of the batching and sequencing tasks (see Table 2). As we can observe, for this problem, minimizing the tardiness (a penalty associated with the orders handled after an expected date / time) is one of the most studied objective functions. Elsayed et al. (1993) also considered the minimization of earliness together with tardiness. Most proposals under this category achieve the batching and the sequencing tasks simultaneously with the same algorithm. The well-known Earliest Due Date (EDD) strategy has been used by several authors (Bustillo, Menéndez, Pardo, & Duarte, 2015; Henn & Schmid, 2013; Menéndez et al., 2017a) as a naive but effective technique for constructing an initial solution to the problem, usually improved later with a metaheuristic. Elsayed et al. (1993) introduced an Optimal Release Times strategy (Fry, Armstrong, & Blackstone, 1987) to introduce time windows (i.e., delays between batches) with the aim of balancing the earliness / tardiness for each batch. Jiang et al. (2018) studied the minimization of the makespan of the last batch (which is equivalent to the completion time). In this case, the authors did not consider due dates, but sequencing was necessary due to the existence of a limited buffer space in the sorting-packing area. Miguel, Frutos, Méndez, & Tohmé (2022) studied the minimization of the total operational cost as an evolution of a previous work devoted to OBP (Miguel et al., 2019). They considered that the products could be stored at different heights, and the earliness and tardiness are considered factors that influence the cost.

4.1.3. Order batching and routing problem (OBRP)

We have classified under this category those papers that consider the optimization of batching and routing tasks (see Table 3). As we can observe, the minimization of the distance is the most studied objective function. Gademann & Velde (2005) studied for the first time the minimization of the total travel time for this problem. Several exact approaches have been introduced for the routing task (Ardjmand, Bajgiran, & Youssef, 2019; Gademann & Velde, 2005; Hong, Johnson, & Peters, 2012b; Hong & Kim, 2017; Matusiak, De Koster, Kroon, & Saarinen, 2014; Oxenstierna, Malec, & Krueger, 2021; Zuniga, Olivares-Benitez, Tenahua, & Mujica, 2015). Among them, the approach introduced by Matusiak et al. (2014) optimally solved the routing task with an A* algorithm (Hart, Nilsson, & Raphael, 1968). In addition, Ho & Tseng (2006) used a metaheuristic algorithm, for the first time, for the routing task. Zuniga et al. (2015) handled the routing task by modeling the problem as a traveling salesman problem, using a previous formulation (Gutin & Punnen, 2006). On the other hand, many seed methods have been studied for the batching task. Particularly, Ho & Tseng (2006) and Ho, Su, & Shi (2008), conducted a deep analysis of 90 and 154 seed variants, respectively, for the batching task. Zuniga et al. (2015) studied the minimization of the total travel time by combining an optimization algorithm and a simulation model. They used the EDD rule to conform and sequence the batches. However, in this case, the objective function studied is not affected by the sequencing task. Therefore, this paper can also be classified as a single-picker offline OBP. Despite the fact that most papers study a standard warehouse with a single block and a single depot, Matusiak et al. (2014) and Lin, Kang, Hou, & Cheng (2016) considered the existence of two blocks. Matusiak et al. (2014) also studied the presence of narrow aisles. Kübler, Glock, & Bauernhansl (2020) considered too the existence of multiple blocks in the warehouse, and solved an additional problem that consists of the relocation of products in the warehouse. Briant et al. (2020) and Schiffer, Boysen, Klein, Laporte, & Pavone (2022) studied several real warehouse instances with multiple blocks. Furthermore, Oxenstierna et al. (2021) studied the minimization of the traveled distance in six different irregular warehouse layouts. Finally, Schiffer et al. (2022) considered the existence of multiple depots and a variable multiblock layout.

4.1.4. Order batching, sequencing, and routing problem (OBSRP)

We have classified under this category those papers that consider the optimization of the batching, sequencing, and routing tasks (see Table 4). As we can observe, the minimization of tardiness (Azadnia, Taheri, Ghadimi, Mat Saman, & Wong, 2013; Chen et al., 2015; Elsayed & Lee, 1996) and cost (Miguel et al., 2019; Pinto & Nagano, 2019; Tsai, Liou, & Huang, 2008) are the most studied objective functions for this problem. Tsai et al. (2008) studied the minimization of the retrieval operation cost, calculated as the sum of the travel cost and the penalties associated to the earliness and tardiness. The most recent approach was introduced in Jiang, Sun, Zhang, & Hu (2022) by studying, for the first time, the total completion time. There are exact approaches for both, the routing and the batching tasks. Notice that the batching is usually performed together with the sequencing. The first approach for the problem was proposed in Elsayed & Lee (1996), where the authors introduced a Mixed-Integer Linear Programming model to formulate the problem as a whole. Additionally, they also achieved

Table 1
Publications related to Order Batching Problem (OBP) in a JCR / SJR indexed journal.

Publication	Objective Function				Routing		Batching	
	Distance	Picking Time	Cost	Completion Time	Type of Algorithm	Algorithm	Type of Algorithm	Algorithm
Elsayed (1981)	✓				-	AS/RS	H	SEED
Elsayed & Unal (1989)		✓			-	AS/RS	H H	EQ SL
Gibson & Sharp (1992)	✓				H	SS-OW	H H H	FCFS 4D-SFC SMD
Pan & Liu (1995)		✓			-	AS/RS	H	SEED
Rosenwein (1996)		✓			H	SS	H	SEED
De Koster, Van Der Poort, & Wolters (1999b)		✓			H H	SS LG	H H H H	FCFS C&W EQ SL+C&W+EQ
Hsu et al. (2005)	✓				H	SS	H	GA
Hwang & Kim (2005)		✓			H H H	SS RE MP	H	SLCA
Chen & Wu (2005)	✓				H	SS	M	ARM+MM
Dukic & Oluic (2007)	✓				H H H H H E	SS RE MP LG CP DP	H H	FCFS C&W
Bozer & Kile (2008)	✓				H	SS	H H	FFEBBA NTS
Albareda-Sambola et al. (2009)		✓			H H H	SS LG CO	H	VND
Henn, Koch, Doerner, Strauss, & Wäscher (2010)	✓				H H	SS LG	H H	ILS RBAS
Hsieh & Huang (2011)	✓				H H E	SS MLI DP	H H H H H	KMS SOMBA ARA PSO SOP
Henn & Wäscher (2012)		✓			H H	SS LG	H H	TS ABHC
Menéndez, Pardo, Duarte, Alonso-Ayuso, & Molina (2015)		✓			H	CO	H	GVNS
Muter & Öncan (2015)			✓		H H E	SS RE MP	E	TCGA
Öncan (2015)	✓				H H E	SS RE MP	E H	MM ILS+TT
Pérez-Rodríguez & Hernández-Aguirre (2015)		✓			H	SS	H H H	EDA GA MA
Koch & Wäscher (2016)	✓				H	SS	H	GGA
Menéndez et al. (2017b)		✓			H H H	SS LG CO	H	MS+VNS
Lenoble, Frein, & Hammami (2017)				✓	-	VC	E	MM

(*continued on next page*)

Table 1 (*continued*)

Publication	Objective Function				Routing		Batching	
	Distance	Picking Time	Cost	Completion Time	Type of Algorithm	Algorithm	Type of Algorithm	Algorithm
Scholz & Wäscher (2017)	✓				H H H H E	SS LG CO AA DP	H	ILS
Cano, Correa-Espinal, & Gómez-Montoya (2018)	✓				H	SS	H	GA
Lenoble et al. (2018)				✓	-	VLM	H	SA
Žulj, Kramer, & Schneider (2018)	✓				H H	SS LG	H	ALNS+TS
Van Gils, Ramaekers, Braekers, Depaire, & Caris (2018)	✓				H H H E	SS LG RE DP	H H H	FCFS SEED SV
Nicolas, Yannick, & Ramzi (2018)				✓	-	VLM	E H H H H	MM SV SA TS GA
Cano (2019)	✓				H	SS	H	GA
Yang et al. (2020)	✓				H H	SS CO	H E	TS MM
Yang, Zhou, & Liu (2021)		✓			-	MRS	H	HGA

Acronym key (alphabetically ordered) · **Type of algorithm:** Exact (E); Heuristic (H); Mixed (M); Not Defined (-). **Algorithm:**4-Dimensional Space Filling Curve (4D-SFC); Adaptive Large Neighborhood Search (ALNS); Aisle by Aisle (AA); Association Rule Algorithm (ARA); Association Rule Mining (ARM); Attribute-Based Hill Climber (ABHC); Automatic Storage and Retrieval System (AS/RS); Clarke & Wright (C&W); Combined (CO); Composite (CP); Dynamic Programming (DP); EQUAL (EQ); Estimation of Distribution Algorithm (EDA); First Come First Served (FCFS); First Fit-Envelope Based Batching Algorithm (FFEBBA); General Variable Neighborhood Search (GVNS); Genetic Algorithm (GA); Grouping Genetic Algorithm (GGA); Hybrid Genetic Algorithm (HGA); Iterated Local Search (ILS); K-Means Strategy (KMS); Largest Gap (LG); Mathematical Model (MM); Maximum Loop Insertion (MLI); Memetic Algorithm (MA); Mid-Point (MP); Mobile Rack System (MRS); Multi-Start (MS); Normalized Time Saving (NTS); Particle Swarm Optimization (PSO); Rank-Based Ant System (RBAS); Return (RE); Saving (SV); Seed (SEED); Self-Organization Map Batching Algorithm (SOMBA); Sequential Minimum Distance (SMD); Simulated Annealing (SA); Single-Link Clustering Algorithm (SLCA); Small and Large (SL); S-Shape (SS); S-Shape One Way (SS-OW); Strict-Order Picking (SOP); Tabu Search (TS); Tabu Thresholding (TT); Tailored Column Generation Algorithm (TCGA); Variable Neighborhood Descent (VND); Variable Neighborhood Search (VNS); Vertical Carousel (VC); Vertical Lift Module (VLM).

Table 2
Publications related to Order Batching and Sequencing Problem (OBSP) in a JCR/SJR indexed journal.

Publication	Objective Function			Routing		Batching & Sequencing	
	Tardiness	Cost	Completion Time	Type of algorithm	Algorithm	Type of algorithm	Algorithm
Elsayed et al. (1993)	✓			-	AS/RS	H	PL
Henn & Schmid (2013)	✓			H H E	SS LG MM	H H E	EDD+ILS EDD+ABHC MM
Menéndez et al. (2017a)	✓			H H H	SS LG CO	H	EDD+GVNS
Jiang et al. (2018)			✓	H	SS	H	CSA
Miguel et al. (2022)		✓		H	SS	H	HEA

Acronym key (alphabetically ordered) · **Type of algorithm:** Exact (E); Heuristic (H); Not Defined (-). **Algorithm:** Attribute-Based Hill Climber (ABHC); Automatic Storage and Retrieval System (AS/RS); Combined (CO); Cumulative-Seed Algorithm (CSA); Earliest Due Date (EDD); General Variable Neighborhood Search (GVNS); Hybrid Evolutionary Algorithm (HEA); Iterated Local Search (ILS); Largest Gap (LG); Priority List (PL); S-Shape (SS).

an additional task, the storage of products on the shelves in the same picking tour. Tsai et al. (2008) proposed a Genetic Algorithm (GA) to simultaneously handle batching and sequencing tasks and a second GA to optimize the routing. Jiang et al. (2022) proposed a mathematical model, based on a previous one introduced in Manjeshwar, Damodaran, & Srihari (2009), to jointly solve the batching, routing, and sequencing tasks. In this paper, the authors also considered the sorting task after the picking. All the approaches considered the existence of one block, except Chen et al. (2015) that studied the problem for two blocks in the warehouse.

4.2. Offline / multiple pickers

In this section, we review the state of the art of offline order batching variants with multiple pickers. In these variants, all orders

Table 3
Publications related to Order Batching and Routing Problem (OBRP) in a JCR/SJR indexed journal.

Publication	Objective Function			Routing		Batching	
	Picking Time	Distance	Cost	Type of algorithm	Algorithm	Type of algorithm	Algorithm
Gademann & Velde (2005)	✓			E	B&P	E	B&P
Ho & Tseng (2006)		✓		H H	LG LG+SA	H	SEED
Ho et al. (2008)		✓		H H	LG LG+SA	H	SEED
Kulak, Sahin, & Taner (2012)		✓		H H	SV+2-opt NN+Or-opt	H	TS+CA
Hong et al. (2012b)		✓		H E	SS MM	H H H H H E	FCFS SEED C&W RSBBA LPR MM
Matusiak et al. (2014)			✓	E	A*	H	SA
Zuniga et al. (2015)	✓			E	MM	H	EDD
Cheng, Chen, Chen, & Jung-Woon Yoo (2015)		✓		H	PSO+ACO	H	PSO+ACO
Lin et al. (2016)		✓		H	PSO	H	PSO
Hong & Kim (2017)		✓		H E	SS MM	H H H H H E	FCFS SEED C&W RSBBA LPR MM
Pferschy & Schauer (2018)		✓		H H H E	FIH+3-Opt CIH+3-Opt RIH+3-Opt MM	H E	SEED MM
Ardjmand et al. (2019)		✓		E H H H	MM GA SA GA+SA	E H H H	MM GA SA GA+SA
Kübler et al. (2020)		✓		H	NN+2-opt	H	DE-PSO
Briant et al. (2020)		✓		E	CG	E	CG
Oxenstierna et al. (2021)		✓		E	MM	H	SEED
Schiffer et al. (2022)		✓		E	B&PR	E	B&PR

Acronym key (alphabetically ordered) · **Type of algorithm:** Exact (E); Heuristic (H). **Algorithm:** Ant Colony Optimization (ACO); Branch and Price (B&P); Branch and Prune (B&PR); Cheapest Insertion Heuristic (CIH); Clarke & Wright (C&W); Clustering Algorithm (CA); Column Generation (CG); Discrete Evolutionary Particle Swarm Optimization (DE-PSO); Earliest Due Date (EDD); Farthest Insertion Heuristic (FIH); First Come First Served (FCFS); Genetic Algorithm (GA); Largest Gap (LG); Linear Programming Relaxation (LPR); Mathematical Model (MM); Nearest Neighbor (NN); Particle Swarm Optimization (PSO); Random Insertion Heuristic (RIH); Route Selection-Based Batching Algorithm (RSBBA); Saving (SV); Seed (SEED); Simulated Annealing (SA); S-Shape (SS); Tabu Search (TS).

to collect are known before the process starts, and there are two or more pickers in the warehouse.

4.2.1. Order batching problem with multiple pickers (OBPMP)

This category compiles all works which only consider the optimization of the batching task but there exist multiple pickers in the warehouse (see Table 5). In this case, the minimization of the picking time is the most studied objective function. Most of the algorithmic proposals are based on heuristic algorithms, however, it is possible to find some exact algorithms for the routing (De Koster et al., 1999a; Gademann, Van Den Berg, & Van Der Hoff, 2001; Menéndez, Pardo, Sánchez-Oro, & Duarte, 2017c) but also for the batching (Gademann et al., 2001; Yang, 2022). Ruben & Jacobs (1999) studied the influence of the several storage strategies in combination with the batching ones. The impact of storage assignment policies was also reviewed in Yang (2022). Additionally, Petersen (2000) and Gademann et al. (2001) considered a picking strategy with waves, where a couple of batches are picked simultaneously (i.e., in the same wave) by a group of pickers. Petersen (2000) also explored other picking policies such as: strict order picking, sequential zoning, or batch zoning. The zoning policy was also studied in Zhang, Zhang, & Zhang (2023). De Koster et al. (1999a) considered a real warehouse with two blocks and narrow aisles. Similarly, other approaches, such as Van Gils, Braekers, Ramaekers, Depaire, & Caris (2016), or Cergibozan & Tasan (2020) also considered the existence of two blocks.

4.2.2. Order batching and sequencing problem with multiple pickers (OBSPMP)

This category compiles all works where the batching and sequencing tasks are optimized in a warehouse with multiple pickers (see Table 6). In this case, the minimization of the completion time was the most studied objective function. Also, it is possible to find a multiobjective approach (Huang et al., 2018), which studies the completion time and the workload of pickers, by trying to balance the total number of items per batch and the total

Table 4
Publications related to Order Batching, Sequencing, and Routing Problem (OBRSP) in a JCR/SJR indexed journal.

Publication	Objective Function			Routing		Batching & Sequencing	
	Tardiness	Cost	Completion Time	Type of algorithm	Algorithm	Type of algorithm	Algorithm
Elsayed & Lee (1996)	✓			E	AS/RS+B&B	H H H	EDD+NSR EDD+SPTR EDD+MCR
Tsai et al. (2008)		✓		H	GA	H	GA
Azadnia et al. (2013)	✓			H	GA	H	GA+MINWAL
Chen et al. (2015)	✓			H	ACO	H	GA
Miguel et al. (2019)		✓		E H	MM MA	E H	MM MA
Pinto & Nagano (2019)		✓		H	GA	H	EDD+GA
Jiang et al. (2022)			✓	H E	SS MM	H E	SEED MM

Acronym key (alphabetically ordered) · **Type of algorithm:** Exact (E); Heuristic (H). **Algorithm:** Ant Colony Optimization (ACO); Automatic Storage and Retrieval System (AS/RS); Branch and Bound (B&B); Earliest Due Date (EDD); Genetic Algorithm (GA); Mathematical Model (MM); Memetic Algorithm (MA); Mining Association Rules with Weighted Items (MINWAL); Most Common Location Rule (MCR); Nearest Schedule Rule (NSR); Seed (SEED); Shortest Processing Time Rule (SPTR); S-Shape (SS).

Table 5
Publications related to Order Batching Problem with Multiple Pickerse (OBPMP) in a JCR / SJR indexed journal.

Publication	Objective Function			Routing		Batching	
	Distance	Picking Time	Cost	Type of algorithm	Algorithm	Type of algorithm	Algorithm
De Koster et al. (1999a)		✓		H H H E	SS LG CO DP	H H H	FCFS SEED C&W
Ruben & Jacobs (1999)		✓		H	SS-OW	H H H H H	RB FFDA SMD FFEBBA FFCBBA
Petersen (2000)			✓	H	CP	H	FCFS
Gademann et al. (2001)		✓		E	DP	M	B&B+2-Opt
Pan, Shih, & Wu (2015)		✓		-	RCS	H	GGA
Van Gils et al. (2016)	✓			H H H H H	SS LG RN AA LKH	H H	FCFS SEED
Menéndez et al. (2017c)		✓		H E	CO DP	H	PVNS
Cergibozan & Tasan (2020)	✓			H H H	SS MP RE	H H	GA GA+PSO
Yang (2022)			✓	-	RMFS	E	MM
Zhang et al. (2023)		✓		H	B&H	H	FCFS
						H	GA

Acronym key (alphabetically ordered) · **Type of algorithm:** Exact (E); Heuristic (H); Mixed(M); Not Defined (-). **Algorithm:** Aisle by Aisle (AA); Bartholdi and Hackman (B&H); Branch and Bound (B&B); Clarke & Wright (C&W); Combined (CO); Composite (CP); Dynamic programming (DP); First Come First Served (FCFS); First Fit-Class Based Batching Algorithm (FFCBBA); First Fit-Envelope Based Batching Algorithm (FFEBBA); First-Fit-Decreasing Algorithm (FFDA); Genetic Algorithm (GA); Group Genetic Algorithm (GGA); Largest Gap (LG); Lin-Kernighan-Helsgaun (LKH); Mathematical Model (MM); Mid-Point (MP); Parallel Variable Neighborhood Search (PVNS); Particle Swarm Optimization (PSO); Random Batching (RB); Return (RE); Robotic Mobile Fulfillment System (RMFS); Roller Conveyor System(RCS); Seed (SEED); Sequential Minimum Distance (SMD); S-Shape (SS); S-Shape one Way (SS-OW).

picking time per zone. Among the proposals, it is possible to find heuristic (Cano, Cortés Achedad, Campo, & Correa-Espinal, 2021; Hong, Johnson, & Peters, 2012a) and exact (Hong et al., 2012a; Žulj, Salewski, Goeke, & Schneider, 2021) algorithms for the routing and for the batching / sequencing tasks. Also, in Huang et al. (2018), the authors proposed a mixed model that combines a Genetic Algorithm with a Mathematical Model. There are two previous papers (Feng & Hu, 2021; Hofmann & Visagie, 2021) where the routing was calculated using a Roller Conveyor System (RCS). For this problem, several special cases of warehouses were considered. Hong et al. (2012a) studied the existence of narrow aisles. Žulj et al. (2021) considered the use of different picking zones with

Table 6
Publications related to Order Batching and Sequencing Problem with Multiple Pickers (OBSPMP) in a JCR / SJR indexed journal.

Publication	Objective Function				Routing		Batching & Sequencing	
	Picking Time	Completion Time	Tardiness	Workload Balance	Type of algorithm	Algorithm	Type of algorithm	Algorithm
Hong et al. (2012a)	✓				E H	MM SS-OW	E H	MM SA
Huang et al. (2018)		✓		✓	-	-	M	GA+MM
Cano et al. (2021)		✓			H	SS	H	GGA
Žulj et al. (2021)			✓		E H	MM OH	E H	MM ALNS+NEH
Feng & Hu (2021)		✓			-	RCS	H H	SEED+GA SEED+SA
Hofmann & Visagie (2021)		✓			-	RCS	H	GH

Acronym key (alphabetically ordered) · **Type of algorithm:** Exact (E); Heuristic (H); Mixed (M); Not Defined (-). **Algorithm:** Adaptive Large Neighborhood Search (ALNS); Genetic Algorithm (GA); Greedy Heuristics (GH); Group Genetic Algorithm (GGA); Mathematical Model (MM); Nawaz, Enscore, and Ham Algorithm (NEH); Optimal Heuristic (OH); Roller Conveyor System (RCS); Seed (SEED); Simulated Annealing (SA); S-Shape (SS); S-Shape one Way (SS-OW).

Table 7
Order Batching and Assigning Problem with Multiple Pickers (OBAPMP) in a JCR / SJR indexed journal.

Publication	Objective Function			Routing		Batching & Assigning	
	Distance	Picking Time	Completion Time	Type of algorithm	Algorithm	Type of algorithm	Algorithm
Matusiak et al. (2017)			✓	H	AA	H	ALNS
Ardjmand et al. (2018)		✓		E E	MM DP	E H H	MM LD+PSO PSA+ACO
Wagner & Mönch (2022)	✓			H H E	SS LG MM	E H	MM VNS+FFD

Acronym key (alphabetically ordered) · **Type of algorithm:** Exact (E); Heuristic (H). **Algorithm:** Adaptive Large Neighborhood Search (ALNS); Aisle-by-Aisle (AA); Ant Colony Optimization (ACO); Dynamic Programming (DP); First Fit Decreasing (FFD); Lagrangian Decomposition (LD); Largest Gap (LG); Mathematical Model (MM); Parallel Simulated Annealing (PSA); Particle Swarm Optimization (PSO); S-Shape (SS); Variable Neighborhood Search (VNS).

a robot assigned to each zone, and Hofmann & Visagie (2021) studied the existence of a single aisle which contains a conveyor belt. Also, Feng & Hu (2021) studied a fresh food processing warehouse, which handled the activity of cleaning and packing the food before storing it on shelves.

4.2.3. Order batching and assigning problem with multiple pickers (OBAPMP)

We have classified under this category those works in which batching and assigning tasks are optimized in a scenario with multiple pickers (see Table 7). In this case, three different objective functions have been studied: minimization of the distance, minimization of the picking time, and minimization of the completion time. In the three approaches identified for this variant, the batching and assigning tasks were simultaneously handled. Matusiak et al. (2017) proposed an Adaptive Large Neighborhood Search algorithm for jointly solving both tasks in a multiple-block scenario. While, Ardjmand, Shakeri, Singh, & Bajgiran (2018) proposed three different methods depending on the size of the instance, including an exact model solved with a solver. Similarly, Wagner & Mönch (2022) proposed an Integer Linear Programming model for the batching and assigning tasks as an extension of the previous model introduced in Gademann & Velde (2005).

4.2.4. Order batching and routing problem with multiple pickers (OBRPMP)

We have classified under this category those works where the batching and routing tasks are optimized in a scenario with multiple pickers (see Table 8). In this case, the minimization of the distance, cost, and completion time have been studied. Armstrong, Cook, & Saipe (1979) studied the minimization of the completion time in a semi-automated warehouse with a conveyorized order-picking system, with one picker per aisle who is in charge of placing the collected products on a conveyor. Additionally, they allowed the possibility of splitting orders in different batches and the existence of the same product in multiple aisles. Yousefi Nejad, Ebadi Torkayesh, Malmir, & Neyshabouri Jami (2021) studied the minimization of the total cost associated with the picking of orders. They proposed an improvement of the mathematical model introduced in Cortés Achedad, Gómez-Montoya, Muñuzuri, & Correa-Espinal (2017) to jointly solve batching and routing tasks. They also proposed three heuristic approaches for larger instances, and a scenario with multiple pickers (2 to 10) and variable capacity of the picking devices. Finally, Atchade-Adelomou, Alonso-Linaje, Albo-Canals, & Casado-Fauli (2021) studied the minimization of the total distance traveled by 2 to 4 robots, by simultaneously considering the batching and routing tasks. To that aim, they used a completely novel approach based on a classical hybrid quantum algorithm (Variational Quantum Eigensolver) which was compared in different quantum simulators.

4.2.5. Order batching, sequencing and assigning problem with multiple pickers (OBSAPMP)

We have classified under this category those works where the batching, sequencing, assigning, and routing tasks are optimized in a scenario with multiple pickers (see Table 9). In this case, only the minimization of tardiness has been studied as an objective function. Henn (2015) introduced a mathematical model for the problem, but the execution of the model on a solver resulted impossible. Therefore, two variants of the Variable Neighborhood

Table 8
Publications related to Order Batching and Routing Problem with Multiple Pickers (OBRPMP) in a JCR / SJR indexed journal.

Publication	Objective Function			Routing & Batching	
	Distance	Cost	Completion Time	Type of algorithm	Algorithm
Armstrong et al. (1979)			✓	E	BD+MM
Yousefi Nejad et al. (2021)		✓		E H H H	MM GA PSO ABC
Atchade-Adelomou et al. (2021)	✓			H	VQE

Acronym key (alphabetically ordered) · **Type of algorithm:** Exact (E); Heuristic (H). **Algorithm:** Artificial Bee Colony (ABC); Bender's Decomposition (BD); Genetic Algorithm (GA); Mathematical Model (MM); Particle Swarm Optimization (PSO); Variational Quantum Eigensolver (VQE).

Table 9
Order Batching, Sequencing and Assigning Problem with Multiple Pickers (OBSAPMP) in a JCR / SJR indexed journal.

Publication	Objective Function	Routing		Batching & Sequencing & Assigning	
	Tardiness	Type of algorithm	Algorithm	Type of algorithm	Algorithm
Henn (2015)	✓	H H	SS LG	H	VNS
Scholz et al. (2017)	✓	H	LKH	H H	ESD+VND SEED+VND
Kuhn et al. (2021)	✓	H E	SS MM	H E	C&W+ALNS+LPTR MM
Srinivas & Yu (2022)	✓	-	AMRs	H E	RSA-ANS MM

Acronym key (alphabetically ordered) · **Type of algorithm:** Exact (E); Heuristic (H); Not Defined (-). **Algorithm:** Adaptive Large Neighborhood Search (ALNS); Autonomous Mobile Robots (AMRs); Clarke & Wright (C&W); Earliest Start Date (ESD); Largest Gap (LG); Largest Processing Time Rule (LPTR); Lin-Kernighan-Helsgaun (LKH); Mathematical Model (MM); Restarted Simulated Annealing algorithm with an Adaptive Neighborhood Search (RSA-ANS); Seed (SEED); S-Shape (SS); Variable Neighborhood Descent (VND); Variable Neighborhood Search (VNS).

Search methodology were proposed for the batching task. Sequencing and assigning tasks are considered within the neighborhoods of the VNS, either in the local search procedures or in the shake. Scholz et al. (2017) adapted a previous mathematical model (Henn, 2015) for the problem. Also, they proposed a Variable Neighborhood Descent algorithm for jointly solving the batching, sequencing, and assigning tasks. Kuhn, Schubert, & Holzapfel (2021) studied the minimization of the total tardiness of all orders in a warehouse with multiple blocks. This time, the authors considered not only batching and sequencing activities, but also delivery operations from the warehouse to the shops. In fact, the tardiness is calculated after the delivery of the orders to the shops, not when the orders are handled to the depot of the warehouse. They proposed several heuristics and a mathematical model for the integrated Order Batching and Vehicle Routing Problem. Finally, Srinivas & Yu (2022) combined multiple pickers with robots, and studied the impact of the existence of multiple blocks. In this case, they also considered that orders could be split in different batches.

4.2.6. Order batching, sequencing, and routing problem with multiple pickers (OBSRPMP)

We have classified under this category those works where the batching, sequencing, and routing tasks are optimized in a scenario with multiple pickers (see Table 10). In this case, the minimization of tardiness and the minimization of distance have been studied. Particularly, Cano, Correa-Espinal, & Gómez-Montoya (2020) studied the minimization of several objectives such as: travel distance, total tardiness / earliness, and a combination of travel time and tardiness / earliness in an aggregated function. To that end, the authors proposed four different mathematical models inspired in previous works (Scholz, Henn, Stuhlmann, & Wäscher, 2016; Scholz et al., 2017; Scholz & Wäscher, 2017; Valle et al., 2017). The authors studied a warehouse with multiple blocks and more than one height level. On the other hand, Cals, Zhang, Dijkman, & Van Dorst (2021) studied the minimization of the number of orders with tardiness, proposing a method based on Deep Reinforcement Learning (i.e., Reinforcement Learning and Deep Neural Networks) inspired by the ideas proposed in Zhang et al. (2012) to optimize the batching, routing, and sequencing tasks.

Table 10
Publications related to Order Batching, Sequencing and Routing Problem with Multiple Pickers (OBSRPMP) in a JCR / SJR indexed journal.

Publication	Objective Function		Routing & Batching & Sequencing	
	Distance	Tardiness	Type of algorithm	Algorithm
Cano et al. (2020)	✓	✓	E	MM
Cals et al. (2021)		✓	H	DRL

Acronym key (alphabetically ordered) · **Type of algorithm:** Exact (E); Heuristic (H). **Algorithm:** Deep Reinforcement Learning (DRL); Mathematical Model (MM).

4.2.7. Order batching, assigning, and routing problem with multiple pickers (OBARPMP)

We have classified under this category those works in which batching, assigning, and routing tasks are optimized in a scenario with multiple pickers (see Table 11). In this case, the minimization of the distance and the picking time are the most studied objective functions. Additionally, a biobjective function to minimize the makespan together with the number of pickers is introduced. Valle, Beasley, & Da Cunha (2016) formulated three mathematical models to jointly solve batching and routing problems. The models considered the existence of multiple blocks. Later, Valle et al. (2017) proposed an evolution based on two Branch-and-Cut approaches to jointly solve the batching and routing tasks. Van Gils, Caris, Ramaekers, & Braekers (2019) also introduced a

Table 11
Order Batching, Assigning and Routing Problem with Multiple Pickers (OBARPMP).

Publication	Objective Function			Routing		Batching & Assigning	
	Distance	Picking Time	Others	Type of algorithm	Algorithm	Type of algorithm	Algorithm
Valle et al. (2016)	✓			E	MM	E	MM
Valle et al. (2017)	✓			E	B&C	E	B&C
Van Gils et al. (2019)		✓		E E H	MM DP LKH	E H	MM ILS
Valle & Beasley (2020)	✓			E	MM	E	MM
Ardjmand et al. (2020)		✓		M	CG+GA+ANN	M	CG+GA+ANN
Rasmi et al. (2022)		✓	✓	E E	MM DP	E M	MM KMS+MM

Acronym key (alphabetically ordered) · **Type of algorithm:** Exact (E); Heuristic (H); Mixed(M). **Algorithm:** Artificial Neural Networks (ANN); Branch and Cut (B&C); Column Generation (CG); Dynamic Programming (DP); Genetic Algorithm (GA); Iterated Local Search (ILS); K-Means Strategy (KMS); Lin-Kernighan-Helsgaun (LKH); Mathematical Model (MM).

mathematical model for the problem, adapted from Valle et al. (2017), to solve the batching, routing, and assigning tasks. They considered the existence of two blocks in the warehouse. Another mathematical model run with a solver was proposed in Valle & Beasley (2020) to find optimal solutions to the joint order batching and routing problem, which also took into consideration the assignation of batches to pickers. Their approach studied two variants of the routing, depending on the reversal constraint (i.e., pickers can perform a U-turn in the parallel aisles or not). They also considered single and multiple blocks warehouse scenarios. Ardjmand et al. (2020) jointly solved the batching, assigning, and routing tasks using a hybrid method which combines Column Generation, Genetic Algorithm, and Artificial Neural Networks. Their approach was compared with the previous proposal introduced in Ardjmand et al. (2018). Finally, Rasmi, Wang, & Charkhgard (2022) studied the minimization of the makespan together with the minimization of the number of active pickers in a biobjective approach. They proposed an Integer Linear Programming model to simultaneously solve the batching, assigning, and routing tasks. Also, they introduced a heuristic approach in which the batching task was solved with a k-means clustering algorithm (Lloyd, 1982), the routing task was tackled with the approach proposed in Ratliff & Rosenthal (1983), and the assigning task was solved with a mathematical model run in a commercial solver. The authors also compared several storage location assignment policies.

4.3. Online / single picker

In this section, we review the state of the art of online order batching variants with a single picker. In these variants, orders arrive to the system dynamically, i.e., once the picking process has already started. In this case, we have compiled in a single table (see Table 12) all previous works in this category.

4.3.1. Online order batching problem (OOBP)

We have classified under this category the works in which the batching task is optimized in a scenario with dynamic arrival of orders (see Table 12). In this case, the turnover time and the picking time were the most studied objective functions. However, we can also find approaches studying the minimization of the completion time or the cost. Almost all the reviewed papers tackled the routing and the batching tasks with heuristic algorithms. Tang & Chew (1997) studied the minimization of the average turnover time through the reduction of the waiting time of orders once they are in the system. The arrival of orders follows a Poisson process, so the problem was modeled as an $E_n/G/c$ queueing system, where n denotes the batch size. Chew & Tang (1999) studied the minimization of the average turnover time through the reduction of service time and travel time. Again, the arrival of orders follows a Poisson process, and the problem was modeled as an $E_n/G/c$ queueing system, where n denotes the batch size. Le-Duc & De Koster (2007) studied the minimization of the average throughput time (i.e., the time that the order remains in the system before being served) in a two-block warehouse. The arrival of orders follows a Poisson process and the problem was modeled as a $M/G^k/1$ queueing system, where k denotes the batch size. Schleyer & Gue (2012) studied the minimization of the average throughput time and the optimal batch size for efficient picking. In this work, the authors considered that the arrival of orders is not restricted to be a Poisson process, but any stationary arrival stream of orders. The problem was modeled as a $G/G/1$ queueing system. Other approaches considering the arrival of orders following a Poisson process were Henn (2012); Xu, Liu, Li, & Dong (2014) and Pérez-Rodríguez, Hernández-Aguirre, & Jöns (2015). Finally, Gil-Borrás et al. (2020b) studied the minimization of the total completion time of all orders, but also reported the maximum turnover time obtained. In fact, it can be considered as an extension of Gil-Borrás, Pardo, Alonso-Ayuso, & Duarte (2018).

4.3.2. Online order batching and waiting problem (OOBWP)

We have classified under this category those works in which batching and waiting tasks are optimized in a scenario with dynamic arrival of orders (see Table 12). In this case, the minimization of the picking time, completion time, and cost have been studied. Bukchin et al. (2012) studied the minimization of the average costs associated with the tardiness and overtime of the pickers. For the first time, they introduced a new waiting method that accurately calculates the departure time of each picker based on previous information. Then, they developed an approximate model to determine the waiting strategy for future arrivals of orders. Giannikas, Lu, Robertson, & Mc. Farlane (2017) studied the minimization of the average completion time. However, they considered a variant of the problem which allows the addition of new orders to a batch being collected. They considered a Variable Time-Window strategy based on the number of orders (1, 5, 10, 15, and 20) arriving at the system. Finally, Gil-Borrás et al. (2020a) studied the minimization of the picking time, but they also reported the completion time of collecting all orders. The authors evaluated and compared several time-window strategies: a No-Waiting strategy, a

Table 12
Publications related to Online Order Batching Problem with a Single Picker in a JCR/SJR indexed journal.

Online Order Batching Problem (OOBP)

Publication	Objective Function						Routing		Batching	
	Distance	Picking Time	Cost	Turnover Time	Completion Time	Others	Type of algorithm	Algorithm	Type of algorithm	Algorithm
Tang & Chew (1997)				✓			H	SS-OW	H	FCFS
Chew & Tang (1999)				✓			H	SS	H	FCFS
Le-Duc & De Koster (2007)		✓					H	SS	H	FCFS
Schleyer & Gue (2012)		✓				✓	H	SS	E	DTM
Henn (2012)					✓		H	SS	H	ILS
							H	LG		
Xu et al. (2014)		✓					H	SS	H	FCFS+ VTWB
Pérez-Rodríguez et al. (2015)				✓			H	SS	H	CEDA
Zhang et al. (2018)			✓				H	SS	H H	C&W ILS
Gil-Borrás et al. (2018)				✓			H	SS	H	BVNS
Gil-Borrás et al. (2020b)					✓		H	SS	H	GRASP+ VND

Online Order Batching and Waiting Problem (OOBWP)

Publication	Objective Function						Routing		Batching		Waiting	
	Distance	Picking Time	Cost	Turnover Time	Completion Time	Others	Type of algorithm	Algorithm	Type of algorithm	Algorithm	Type of algorithm	Algorithm
Bukchin et al. (2012)			✓				-	-	M	FCFS+ MDP	M	FCFS+ MDP
Giannikas et al. (2017)					✓		E	DP	H	GA	H	VTW
Gil-Borrás et al. (2020a)		✓			✓		H	SS	H H	FCFS GH	H H H	NW FTW VTW

Online Order Batching, and Routing Problem (OOBRP)

Publication	Objective Function						Routing & Batching	
	Distance	Picking Time	Cost	Turnover Time	Completion Time	Others	Type of algorithm	Algorithm
Ene & Öztürk (2012)			✓				E H	MM GA
Li et al. (2016)	✓						H	ACO

Online Order Batching, Sequencing, and Routing Problem (OOBSRP)

Publication	Objective Function						Routing & Batching & Sequencing	
	Distance	Picking Time	Cost	Turnover Time	Completion Time	Others	Type of algorithm	Algorithm
Won & Olafsson (2005)		✓		✓			E	MM

Acronym key (alphabetically ordered) · **Type of algorithm:** Exact (E); Heuristic (H); Mixed (M); Not Defined (-). **Algorithm:** Ant Colony Optimization (ACO); Basic Variable Neighborhood Search (BVNS); Clarke & Wright (C&W); Continuous Estimation of Distribution Algorithm (CEDA); Discrete-Time Models (DTM); Dynamic Programming (DP); First Come First Served (FCFS); Fixed Time Window (VTW); Genetic Algorithm (GA); Greedy Heuristic (GH); Greedy Randomized Adaptive Search Procedure (GRASP); Iterated Local Search (ILS); Largest Gap (LG); Markov decision process (MDP); Mathematical Model (MM); No Waiting (NW); S-Shape (SS); S-Shape One Way (SS-OW); Variable Neighborhood Descent (VND); Variable Time Window (VTW); Variable Time Window Batching (VTWB).

Fixed Time Window strategy based on time (3, 6, and 12 minutes), and a Variable Time Window strategy based on the number of orders arrived to the system (4, 8, 16 orders).

4.3.3. *Online order batching, and routing problem (OOBRP)*

We have classified into this category the works in which batching and routing tasks are optimized in a scenario with dynamic arrival of orders (see Table 12). In this case, the minimization of the distance and cost, have been tackled. Ene & Öztürk (2012) studied the minimization of the travel cost expressed as a function of the travel time. They proposed two approaches to jointly solve batching and routing tasks. Additionally, in this paper, the authors also studied the storage problem by minimizing the warehouse transmissions with another Integer Programming model using GAMS (Boisvert, Howe, & Kahaner, 1985). They considered a two-block warehouse. On the other hand, Li, Huang, & Dai (2016) studied the minimization of the total travel distance. They proposed an algorithm based on Ant Colony Optimization for jointly solving the batching and routing task. They considered warehouses with multiple blocks and up to 10,000 orders.

4.3.4. Online order batching, sequencing, and routing problem (OOBSRP)

We have classified into this category those works in which batching, sequencing, and routing tasks are optimized in a scenario with dynamic arrival of orders (see Table 12). In this case, the only paper found, studied the minimization of the picking time and the turnover time. Specifically, Won & Olafsson (2005) studied the minimization of a combined objective function that considers the minimization of the picking time together with the minimization of the time that orders remain in the warehouse. They proposed a formulation for the joint order batching, sequencing and routing problem. Notice that the warehouse studied in this paper includes a depot at the end of each aisle and the travel distance is assumed to be calculated using the Tchebychev metric (Bozer, Schorn, & Sharp, 1990) instead of the usual rectilinear metric.

4.4. Online / multiple pickers

In this section, we review the state of the art of online order batching variants with multiple pickers. In these variants, orders arrive to the system dynamically (once the picking process has already started) to a warehouse with two or more pickers. Again, we have compiled in a single table (see Table 13) all previous works in this category.

4.4.1. Online order batching problem with multiple pickers (OOBPMP)

We have classified into this category those works in which the batching task is optimized in a scenario with dynamic order arrival and multiple pickers (see Table 13). In this case, the completion time was the most studied objective function. However, other objectives were also considered in the literature such as picking time, cost, workload balance, or turnover time. Yu & De Koster (2009) considered picking zones within the warehouse (each of them assigned to a different picker) and the arrival of orders was determined by a Poisson distribution. The warehouse had a random storage policy. The authors tackled the batching task with an approximation model based on the queueing network theory, and they used the S-Shape routing strategy. Van Nieuwenhuyse & De Koster (2009) studied a two-block warehouse where the arrival of orders followed a Poisson process and the problem was modeled as a $G/G/1$ and a $G/G/m$ queueing system. They proposed the use of different batching strategies based on waiting for the arrival of orders. Particularly, they proposed a Fixed Time Window Batching, consisting of waiting for a fixed amount of time, and a Variable Time Window Batching, consisting of waiting while there is available space in the batch. Also, they compared the pick-and-sort and sort-while-pick picking policies. Rubrico et al. (2011) studied a variant of the problem, named Online Rescheduling Problem with multiple pickers, by considering the existence of static and dynamic arrival of orders. Additionally, they introduced the constraint that newly arrived orders were composed of only one type of product. Zhang et al. (2017) studied the minimization the maximum completion time, also known as the turnover time of all orders, but also reported the average idle time per picker and the average workload. Chen et al. (2018) studied the minimization of the service time of a single order. In this case, they considered a multiple-block warehouse with narrow aisles. Also, they studied the possibility that orders could be split in several batches and that batches could be modified during picking. Similarly, Hojaghania, Nematian, Shojaiea, & Javadi (2019) studied the minimization of the maximum turnover time and the idle time of pickers in a warehouse with different zones within the warehouse, each of them assigned to a picker. Zhang, Zhang, & Zhang (2021) studied a pondered objective function which includes the minimization of completion time needed to pick and delivery the orders, together with the minimization of the total delivery cost. The assignment of batches to pickers follows a first available picker rule. Shavaki & Jolai (2021) studied the minimization of the transportation cost of orders and jointly solved the delivery planning, by proposing two mathematical models, solved with a solver, which included: the assignment of trucks to docks, the departure time, and the route of the truck. Finally, Gil-Borrás et al. (2021) studied the minimization of picking time, the minimization of the completion time, and the minimization of the differences in the workload balance among pickers in a single-block warehouse.

4.4.2. Online order batching and routing problem with multiple pickers (OOBRPMP)

We have classified into this category those works in which the batching and routing tasks are optimized in a scenario with dynamic order arrival and multiple pickers (see Table 13). In this case, the only paper found (Leung, Lee, & Choy, 2020) studied the minimization of the total travel time in a real scenario. They proposed a Genetic Algorithm which integrates the solution to the batching and routing tasks. They also considered the existence of multiple pickers (up to 18). Their proposal was integrated into a software system to manage the warehouse.

4.4.3. Online order batching, sequencing, assigning, and routing problem with multiple pickers (OOBSARPMP)

We have classified under this category the works in which batching, assigning, and routing tasks are optimized in a scenario with dynamic arrival of orders and multiple pickers (see Table 13). Specifically, Zhang, Wang, & Huang (2016) studied the minimization of the total service time, while maximizing the number of orders delivered without exceeding a predefined due date. In this paper, the sequencing and assigning tasks were inspired by a previous strategy for other problem introduced in Pratap, Nayak, Cheikhrouhou, & Tiwari (2015). Particularly, they proposed several heuristic rules that combine the urgency of a batch and the workload balance of idle pickers. The arrival of orders is studied on a 2-hour time horizon. Later, Duda & Stawowy (2019) studied the minimization of the number of pickers together with the minimization of the distance traveled in an online scenario. To that aim, the authors introduced a weighted function that combines the two previous objectives. They proposed a Mixed-Integer Programming model to jointly solve the batching, sequencing, assigning, and picker routing tasks. The authors also proposed a heuristic approach based on Variable Neighborhood Search for solving the problem when the size of the instance is large. They considered an 8-hour time horizon. Schrotenboer, Wruck, Vis, & Roodbergen (2019) simultaneously studied the minimization of the total travel time and the picking cost through the use of a combined objective function. They proposed different Mixed-Integer Programming models to jointly solve the batching, sequencing, assigning, and routing tasks. The authors also proposed a constructive procedure together with an Adaptive Large Neighborhood Search heuristic for the problem. Additionally, in this paper, the authors integrated the restocking of returned products into regular order picking routes. Finally, Cao, Zhou, Lin, & Zhou (2023) studied a multi-block scenario with the existence of heterogeneous pickers in terms of capacity and picking speed. In this case, the authors optimized a combined objective function which considered the picking time and the penalty associated to the delay with respect to a due date.

4.5. Synthesis of the review

In Section 4, we have reviewed and classified 125 papers (110 JCR / 15 SJR) related to Order Batching. In Fig. 4, we present a bar chart in which all publications are classified per year and category of problems. Additionally, in Fig. 5, we show another bar chart in which we can compare the number of papers per problem variant.

Table 13
Publications related to Online Order Batching Problem with Multiple Pickers in a JCR/SJR indexed journal.

Online Order Batching Problem with Multiple Pickers (OOBPMP)

Publication	Objective Function							Routing		Batching & Assigning	
	Distance	Picking Time	Cost	Turnover Time	Completion Time	Workload Balance	Others	Type of algorithm	Algorithm	Type of algorithm	Algorithm
Yu & De Koster (2009)					✓			H	SS	H	QNT
Van Nieuwenhuyse & De Koster (2009)					✓			H	SS	H H	FTWB VTWB
Rubrico et al. (2011)					✓			H	SS	H	SDI+ MRS
Zhang et al. (2017)				✓				H	SS	H	SEED+ HRBA
Chen et al. (2018)					✓			H H	SS LG	H H H	GAS FTWB VTWB
Hojaghania et al. (2019)				✓				H	SS	H H	ACO ABC
Gil-Borrás, Pardo, Alonso-Ayuso, & Duarte (2019)					✓			H H H	SS LG CO	H	BVNS
Alipour, Mehrjedrdi, & Mostafaeipour (2020)					✓			H H	SS LG	H	ILS
Zhang et al. (2021)			✓		✓			H	SS	H	C&W
Shavaki & Jolai (2021)			✓					H	SS	H H H	HBS SVA GA
Gil-Borrás et al. (2021)		✓			✓	✓		H	SS	H	MS+ VND

Online Order Batching and Routing Problem with Multiple Pickers (OOBRPMP)

Publication	Objective Function							Routing & Batching & Assigning	
	Distance	Picking Time	Cost	Turnover Time	Completion Time	Workload Balance	Others	Type of algorithm	Algorithm
Leung et al. (2020)	✓							H	GA

Online Order Batching, Sequencing, Assigning, and Routing Problem with Multiple Pickers (OOBSARPMP)

Publication	Objective Function							Routing		Batching & Sequencing & Assigning	
	Distance	Picking Time	Cost	Turnover Time	Completion Time	Workload Balance	Others	Type of algorithm	Algorithm	Type of algorithm	Algorithm
Zhang et al. (2016)					✓			H	SS	H H	SEED C&W
Duda & Stawowy (2019)	✓						✓	E H	MM VNS	H H	MM VNS
Schrotenboer et al. (2019)		✓	✓					E H	MM ALNS	E H	MM ALNS
Cao et al. (2023)		✓					✓	H H	RSM CO	H H H	HISH ILS SEDD

Acronym key (alphabetically ordered) · **Type of algorithm:** Exact (E); Heuristic (H). **Algorithm:** Adaptive Large Neighborhood Search (ALNS); Ant Colony Optimization (ACO); Artificial Bee Colony (ABC); Basic Variable Neighborhood Search (BVNS); Clarke & Wright (C&W); Combined (CO); Fixed Time Window Batching (FTWB); Genetic Algorithm (GA); Green Area Strategy (GAS); Heuristic Based on Similarity (HBS); Hybrid Iterated local Search algorithm embedded with Heuristic rules (HISH); Hybrid Rule-Based Algorithm (HRBA); Iterated Local Search (ILS); Largest Gap (LG); Mathematical Model (MM); Multistage Rescheduling strategy (MRS); Multi-Start (MS); Queueing Network Theory (QNT); Routing Strategy based on Manhattan distance (RSM); Saving (SV); Seed (SEED); Seed algorithm based on Earliest Due Date (SEDD); S-Shape (SS); Steepest Descent Insertion (SDI); Variable Neighborhood Descent (VND); Variable Neighborhood Search (VNS); Variable Time Window Batching (VTWB).

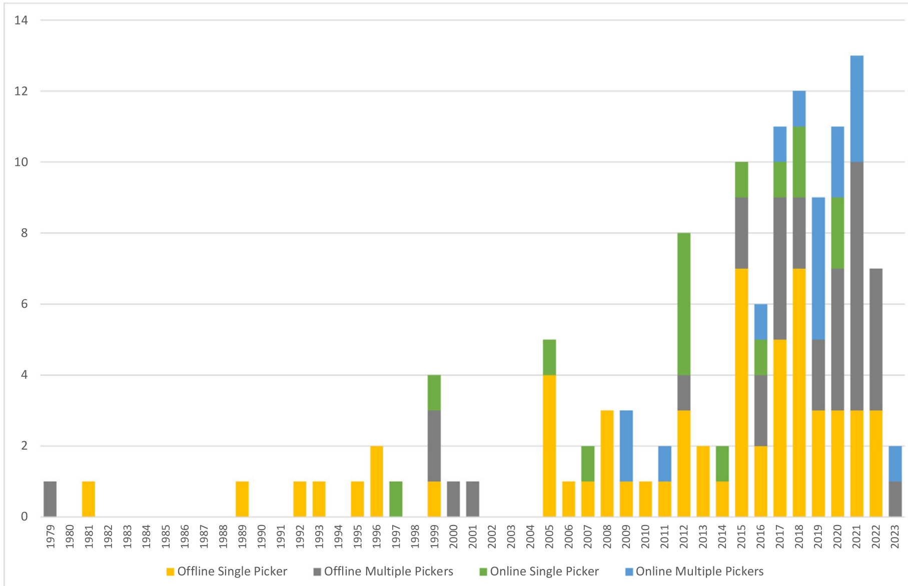

Fig. 4. Publications reviewed classified by year and grouped by category.

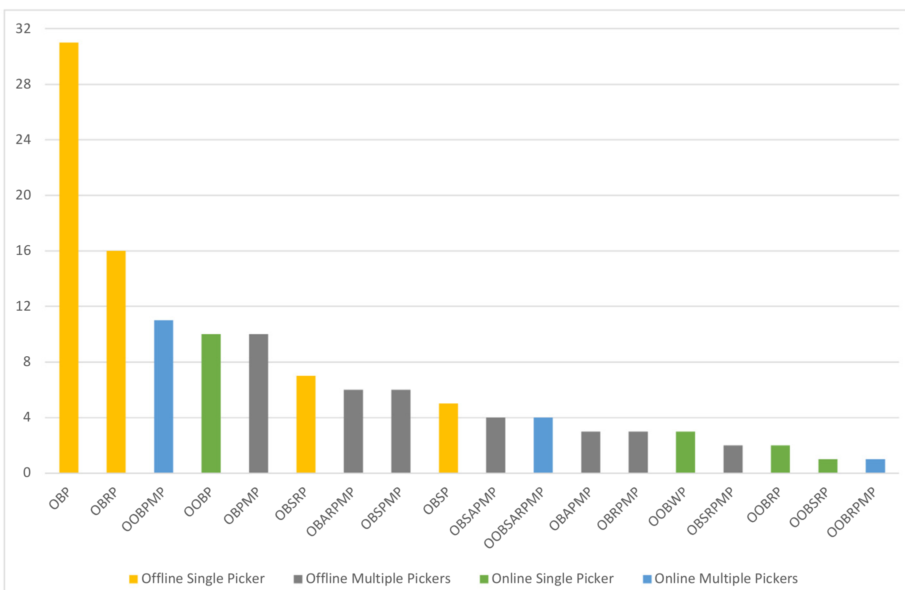

Fig. 5. Publications reviewed classified by order batching variant and grouped by category.

As a first conclusion of the analysis performed, we observe that among the 36 variants of order batching problems identified in the taxonomy introduced in Fig. 3, 18 of them have never been tackled in the literature. Among the studied variants, we observe that 47.20% of the papers deal with offline single-picker variants, 27.20% of the papers deal with offline multiple-pickers variants, 12.80% of the papers deal with online single-picker variants, and 12.80% of the papers deal with online multiple-pickers variants.

Furthermore, the offline variants of the problem have been studied further than the online ones (93 papers vs 32 papers). Similarly, single-picker variants have been studied further than multiple-pickers ones (75 papers vs 50 papers). The most studied variant is the offline version of the Order Batching Problem with a single picker, where the problem consists of the batching task only (31 papers).

As far as the warehouse studied is concerned, the most studied warehouse is a rectangular-shaped warehouse with a single depot and a single block (composed of parallel aisles) to perform the picking operation. Particularly, we have found 94 out of the 125 papers reviewed using this warehouse model. However, other authors studied different warehouse configurations, such as multiple blocks, irregular shapes, or storage at different heights, among others. Furthermore, 15 papers studied semi-automated warehouses.

All the papers compiled in this review achieve the routing and batching tasks. However, only 31 papers study the sequencing task, 16 papers study the assigning task, and 3 papers study the waiting task.

A large number of papers explore the use of more than one routing strategy. In particular, all the papers reviewed include any kind of heuristic / metaheuristic strategy for the routing task. Among them, the S-Shape method is the most popular one (i.e., it was used in 62 out of 125 papers). On the other hand, 34.40% of the papers additionally propose the use of an exact approach, mainly based on a mathematical model or dynamic programming.

As far as the batching task is concerned, metaheuristics are the most common strategies to tackle the task (61.60% of the studied papers included at least a metaheuristic method). However, simpler heuristics such as: seed, savings, and FCFS methods, are also very popular (36.80% of the studied papers included at least a heuristic method). Finally, 27.20% of the articles studied proposed the use of any kind of exact method (usually a mathematical model). The sequencing and assigning tasks are usually handled together with the batching strategy. The waiting task has been little explored in the literature despite the fact that it has been shown to have a profound impact on the overall performance of the picking algorithms.

5. Conclusions and open issues

In this survey, we review the order batching family of optimization problems. This family compiles a group of well-known optimization problems related to the picking of orders in a warehouse, having in common that they consider the batching policy during the picking process. That is, orders received in a warehouse are grouped into batches before starting the picking process. We have properly defined the family of problems denoted as order batching problems, and we have identified the main tasks that have to be addressed to solve each particular variant of the problem within the order batching family. Then, we have proposed a taxonomy to classify all order batching problems. To the best of our knowledge, this is the first time a taxonomy to classify the order batching variants has been proposed. Following the proposed taxonomy, we have reviewed the previous literature related to order batching and classified all JCR and SJR papers found in the literature using the aforementioned taxonomy, on the basis of the particular problem tackled in each paper. Finally, for each reference identified in the literature, we have briefly highlighted the strategies proposed for each of the main tasks associated to solve the problem variant handled in the paper. Next, we state our conclusions, open issues, and future research opportunities.

5.1. Conclusions

Order batching problems have been extensively studied by the scientific community in the last forty years, since the batching policy within a warehouse has been demonstrated to be a very effective strategy to perform the task of picking orders. As it happens with many scientific disciplines, practitioners in the field often handle simplified variants of interesting real problems to illustrate the performance of their algorithms instead of more realistic scenarios. Furthermore, it is common to find literature with simple variants of problems but very large data sets (or with very large instances within them) that are often unrealistic for the problem handled. In this sense, we believe that some of the variants related to order batching studied in the state of the art, such as the simple OBP (an offline variant with a single picker) which is the most studied variant in the literature, represents mainly a theoretical problem that helps practitioners to propose and validate new algorithms and ideas further than a real problem on its own. In contrast, online variants with multiple pickers are probably the most general versions of order batching and the closest ones to real-world scenarios related to order batching. It is important to remark that the offline version of order batching problem is a specific case of the online one, which can be considered as the general problem. Similarly, let us remember that the single-picker version of the problem is a specific case of the multiple-pickers one. Therefore, solving more general variants of the problem also provides solutions to the specific ones.

Despite the fact that it is possible to find more than a hundred publications related to order batching in top-level journals, as far as we know, practitioners have never introduced a proper taxonomy to clearly identify the gaps or the particular problem variant they are handling. This fact has obstructed researchers to identify previous works in the literature directly connected to their research, and therefore many articles lack a proper comparison of their findings with other previous proposals.

Proposing a taxonomy which classifies all order batching variants tackled in the previous literature is not an easy task. Any taxonomy might result incomplete when considering an exceptional / specific piece of work, and the criteria included in it are always full of controversy. However, there are some relevant aspects that are clearly identifiable in the literature of order batching problems such as: offline / online, single / multiple pickers, or the objective function being optimized. In this sense, we have tried to propose a taxonomy that gathers the characteristics of an optimization problem: constraints, variables, and objective functions. Furthermore, the proposed taxonomy is easily extensible, mainly by adding new constraints, variables, or objective functions.

From our point of view, there are two main groups to classify any order batching problem: Simple or Joint. We denote as “Simple” to any variant of the problem that only handles the batching task (i.e., the optimization is restricted to the values of the variables that determine the batching). Similarly, we denote as “Joint” to any variant of order batching that handles the batching task together with one or more additional tasks (i.e., optimization is not restricted to the variables that determine the batching, but also the variables that determine sequencing, routing, assigning, or waiting).

The most outstanding variants of the order batching problems, attending to the relevance, novelty, and number of references related to them, are the simple variants of order batching problems: simple Order Batching Problem, simple Order Batching Problem with Multiple Pickers, simple Online Order Batching Problem, simple Online Order Batching Problem with Multiple Pickers. Additionally, there are some relevant joint versions such as: joint Order Batching, Sequencing, and Routing Problem, or joint Order Batching and Routing Problem. On the other hand, 18 out of the 36 identified variants of the problem have never been tackled. This is especially relevant in the case of the online variants of the problem.

As a final conclusion, we would like to highlight that order batching problems are a growing family of optimization problems of high economic interest for the industry. Given the large recent interest in related problems, the main objective of this paper is to set the foundations of order batching and organize the current state of the art of this family of problems, so the related literature can grow up properly, avoiding repetitions and establishing a clear comparison framework for future research proposals.

5.2. Open issues and future research opportunities

In this section, we highlight the main open issues related to order batching problems, including the gaps identified in the literature, the most realistic variants of the problem, the most influential tasks to address, and the most promising algorithmic strategies.

In the near future, practitioners interested in any problem related to order batching should start by identifying the particular gap in the taxonomy proposed in this review, which they are trying to cover. Moreover, any previous work on the variant discussed should be included in the literature review, and the new approach should be adequately compared with the previous ones. Since the taxonomy is designed to grow, in case of necessity, we also invite practitioners to extend it with new constraints, objective functions, or variables (tasks), making clear the new contribution to the literature. As we can observe from the taxonomy proposed and the classification of previous works, many variants of order batching remain unstudied, which opens a very large research opportunity.

Particularly, most of the joint versions of order batching problems have not been studied yet.

We suggest that the research direction should be moving from the classical and more theoretical variants of order batching to more realistic variants. Particularly, the classical and most studied approach when dealing with order batching is related to the offline version of the problem with a single picker. However, this is only a special case of the general problem, that might consider multiple pickers and an online arrival of orders to the warehouse. We suggest that practitioners in the field focus on these more realistic variants of the problem.

The batching in isolation is an interesting task from a theoretical point of view. However, when dealing with any variant of order batching problems, it is necessary to study it in combination with other tasks, such as routing, sequencing, assigning, and waiting. All the previous works in the literature consider the routing; however, since we should focus on dealing with more realistic variants, further study should be performed in relation to the sequencing and assigning (when multiple pickers are available) and waiting (when there is a dynamic arrival of orders to the warehouse). Furthermore, we have discovered that the latter has a deep influence on the performance of the overall method and is by far the least studied activity. In the future, the inclusion of other tasks such as sorting the products after picking or refilling the shelves could also be considered.

Currently, there is a large collection of algorithms, either heuristics / metaheuristics or exacts to deal with almost any of the tasks related to order batching. However, the effectiveness of the proposed strategy depends on the particular task. Furthermore, some tasks might be as hard as others computationally speaking but, in practice, they are much smaller than others (e.g., the size of the batching problem is usually larger than the size of the sequencing problem, since the number of orders is much larger than the number of batches). Moreover, the size of the instance makes some of the tasks smaller enough to be handled with exact methods. Therefore, an effort should be made to develop matheuristic algorithms which include optimal results for particular tasks in combination with other heuristic techniques for the rest of the tasks. Similarly, the routing task, given a classical warehouse design, is optimally solved in a reasonable amount of time.

Finally, there are few studies about multi-objective optimization variants of order batching problems, either considering two or more of the objective functions identified in this paper or coupling the batching task together with other optimization problems.

Appendix A. Classification of order batching papers in the literature according to the proposed taxonomy

Researchers have been proposing a wide range of optimization problems that belong to the order batching family of problems in rectangular-shaped warehouses with parallel aisles, by adding constraints, modifying the characteristics of the warehouse, or optimizing several objectives at the same time. To contribute to the literature on order batching, we have grouped all references found in the literature and reviewed in this paper under the best-known names and acronyms. Additionally, we have classified the optimization problems identified on the basis of the taxonomy intro-

Table A1
Classification of the journal papers related to Order Batching in the proposed taxonomy.

Category	Reference	Category	Reference
[Simple] / Order Batching Problem (OBP)			
OFF-SP-DI-B	Elsayed (1981)	OFF-SP-PT-B	Elsayed & Unal (1989)
OFF-SP-DI-B	Gibson & Sharp (1992)	OFF-SP-PT-B	Pan & Liu (1995)
OFF-SP-PT/DI-B	Rosenwein (1996)	OFF-SP-PT-B	De Koster et al. (1999b)
OFF-SP-DI-B	Hsu et al. (2005)	OFF-SP-PT-B	Hwang & Kim (2005)
OFF-SP-DI-B	Chen & Wu (2005)	OFF-SP-DI-B	Dukic & Oluic (2007)
OFF-SP-DI-B	Bozer & Kile (2008)	OFF-SP-PT-B	Albareda-Sambola et al. (2009)
OFF-SP-DI-B	Henn et al. (2010)	OFF-SP-DI-B	Hsieh & Huang (2011)
OFF-SP-PT-B	Henn & Wäscher (2012)	OFF-SP-PT-B	Menéndez et al. (2015)
OFF-SP-CO-B	Muter & Öncan (2015)	OFF-SP-PT-B	Pérez-Rodríguez & Hernández-Aguirre (2015)
OFF-SP-DI-B	Öncan (2015)	OFF-SP-DI-B	Koch & Wäscher (2016)
OFF-SP-PT-B	Menéndez et al. (2017b)	OFF-SP-CT-B	Lenoble et al. (2017)
OFF-SP-DI-B	Scholz & Wäscher (2017)	OFF-SP-DI-B	Cano et al. (2018)
OFF-SP-PT-B	Lenoble et al. (2018)	OFF-SP-DI-B	Žulj et al. (2018)
OFF-SP-DI-B	Van Gils et al. (2018)	OFF-SP-CT-B	Nicolas et al. (2018)
OFF-SP-DI-B	Cano (2019)	OFF-SP-DI-B	Yang et al. (2020)
OFF-SP-PT-B	Yang et al. (2021)		
[Joint] / Order Batching and Sequencing Problem (OBSP)			
OFF-SP-TA-BS	Elsayed et al. (1993)	OFF-SP-TA-BS	Henn & Schmid (2013)
OFF-SP-TA-BS	Menéndez et al. (2017a)	OFF-SP-CT-BS	Jiang et al. (2018)
OFF-SP-CO-BS	Miguel et al. (2022)		
[Joint] / Order Batching and Routing Problem (OBRP)			
OFF-SP-PT-BR	Gademann & Velde (2005)	OFF-SP-DI-BR	Ho & Tseng (2006)
OFF-SP-DI-BR	Ho et al. (2008)	OFF-SP-DI-BR	Kulak et al. (2012)
OFF-SP-DI-BR	Hong et al. (2012b)	OFF-SP-DI-BR	Matusiak et al. (2014)
OFF-SP-PT-BR	Zuniga et al. (2015)	OFF-SP-DI-BR	Cheng et al. (2015)
OFF-SP-DI-BR	Lin et al. (2016)	OFF-SP-DI-BR	Hong & Kim (2017)
OFF-SP-DI-BR	Pferschy & Schauer (2018)	OFF-SP-DI-BR	Ardjmand et al. (2019)
OFF-SP-DI-BR	Kübler et al. (2020)	OFF-SP-DI-BR	Briant et al. (2020)
OFF-SP-DI-BR	Oxenstierna et al. (2021)	OFF-SP-DI-BR	Schiffer et al. (2022)
[Joint] / Order Batching, Sequencing, and Routing Problem (OBSRP)			
OFF-SP-TA-BSR	Elsayed & Lee (1996)	OFF-SP-CO-BSR	Tsai et al. (2008)
OFF-SP-TA-BSR	Azadnia et al. (2013)	OFF-SP-TA-BSR	Chen et al. (2015)
OFF-SP-DI/CO-BSR	Pinto & Nagano (2019)	OFF-SP-CO-BSR	Miguel et al. (2019)
OFF-SP-CT-BSR	Jiang et al. (2022)		

(continued on next page)

Table A1 (*continued*)

Category	Reference	Category	Reference
[Simple] / Order Batching Problem with Multiple Pickers (OBPMP)			
OFF-MP-PT-B	De Koster et al. (1999a)	OFF-MP-DI-B	Ruben & Jacobs (1999)
OFF-MP-PT-B	Petersen (2000)	OFF-MP-PT-B	Gademann et al. (2001)
OFF-MP-PT-B	Pan et al. (2015)	OFF-MP-DI-B	Van Gils et al. (2016)
OFF-MP-PT-B	Menéndez et al. (2017c)	OFF-MP-DI-B	Cergibozan & Tasan (2020)
OFF-MP-CO-B	Yang (2022)	OFF-MP-PT-B	Zhang et al. (2023)
[Joint] / Order Batching and Sequencing Problem with Multiple Pickers (OBSPMP)			
OFF-MP-PT-BS	Hong et al. (2012a)	OFF-MP-CT-BS	Huang et al. (2018)
OFF-MP-CT-BS	Cano et al. (2021)	OFF-MP-TA-BS	Žulj et al. (2021)
OFF-MP-CT-BS	Feng & Hu (2021)	OFF-MP-CT-BS	Hofmann & Visagie (2021)
[Joint] / Order Batching and Assigning Problem with Multiple Pickers (OBAPMP)			
OFF-MP-CT-BA	Matusiak et al. (2017)	OFF-MP-CT-BA	Ardjmand et al. (2018)
OFF-MP-DI-BA	Wagner & Mönch (2022)		
[Joint] / Order Batching and Routing Problem with Multiple Pickers (OBRPMP)			
OFF-MP-CT-BR	Armstrong et al. (1979)	OFF-MP-DI-BR	Atchade-Adelomou et al. (2021)
OFF-MP-CO-BR	Yousefi Nejad et al. (2021)		
[Joint] / Order Batching, Sequencing and Assigning Problem with Multiple Pickers (OBSAPMP)			
OFF-MP-TA-BSA	Henn (2015)	OFF-MP-TA-BSA	Scholz et al. (2017)
OFF-MP-TA-BSA	Kuhn et al. (2021)	OFF-MP-TA-BSA	Srinivas & Yu (2022)
[Joint] / Order Batching, Sequencing and Routing Problem with Multiple Pickers (OBSRPMP)			
OFF-MP-DI/TA-BSR	Cano et al. (2020)	OFF-MP-TA-BSR	Cals et al. (2021)
[Joint] / Order Batching, Assigning and Routing Problem with Multiple Pickers (OBARPMP)			
OFF-MP-DI-BAR	Valle et al. (2016)	OFF-MP-DI-BAR	Valle et al. (2017)
OFF-MP-PT-BAR	Van Gils et al. (2019)	OFF-MP-DI-BAR	Valle & Beasley (2020)
OFF-MP-CT-BAR	Ardjmand et al. (2020)	OFF-MP-CT+NP-BAR	Rasmi et al. (2022)
[Simple] / Online Order Batching Problem (OOBP)			
ON-SP-TT-B	Tang & Chew (1997)	ON-SP-TT-B	Chew & Tang (1999)
ON-SP-CT-B	Le-Duc & De Koster (2007)	ON-SP-CT-B	Schleyer & Gue (2012)
ON-SP-CT-B	Henn (2012)	ON-SP-CT-B	Xu et al. (2014)
ON-SP-TT-B	Pérez-Rodríguez et al. (2015)	ON-SP-TT-B	Zhang et al. (2018)
ON-SP-TT-B	Gil-Borrás et al. (2018)	ON-SP-CT-B	Gil-Borrás et al. (2020b)
[Joint] / Online Order Batching and Waiting Problem (OOBWP)			
ON-SP-CO-BW	Bukchin et al. (2012)	ON-SP-CT-BW	Giannikas et al. (2017)
ON-SP-PT-BW	Gil-Borrás et al. (2020a)		
[Joint] / Online Order Batching, and Routing Problem (OOBRP)			
ON-SP-CO-BR	Ene & Öztürk (2012)	ON-SP-DI-BR	Li et al. (2016)
[Joint] / Online Order Batching, Sequencing, and Routing Problem (OOBSRP)			
ON-SP-PT+TT-BSR	Won & Olafsson (2005)		
[Simple] / Online Order Batching Problem with Multiple Pickers (OOBPMP)			
ON-MP-TT-B	Yu & De Koster (2009)	ON-MP-TT-B	Van Nieuwenhuyse & De Koster (2009)
ON-MP-CT-B	Rubrico et al. (2011)	ON-MP-CT-B	Zhang et al. (2017)
ON-MP-PT-B	Chen et al. (2018)	ON-MP-TT-B	Hojaghania et al. (2019)
ON-MP-CT-B	Gil-Borrás et al. (2019)	ON-MP-CT-B	Alipour et al. (2020)
ON-MP-PT-B	Zhang et al. (2021)	ON-MP-PT-B	Shavaki & Jolai (2021)
ON-MP-PT-B	Gil-Borrás et al. (2021)		
[Joint] / Online Order Batching and Routing Problem with Multiple Pickers (OOBRPMP)			
ON-MP-PT-BR	Leung et al. (2020)		
[Joint] / Online Order Batching, Sequencing, Assigning, and Routing Problem with Multiple Pickers (OOBSARPMP)			
ON-MP-PT+NO-BSAR	Zhang et al. (2016)	ON-MP-DI+NP-BSAR	Duda & Stawowy (2019)
ON-MP-PT+CO-BSAR	Schrotenboer et al. (2019)	ON-MP-PT+TA-BSAR	Cao et al. (2023)

duced in Section 3. Notice that we only consider papers published in journals indexed in the Journal Citation Reports (JCR) or the Scimago Journal & Country Rank (SJR).

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