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Packing problems in Transportation and Supply Chain: new problems and trends

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Abstract

Even if packing problems are, from their beginning, strictly linked to Transportation, the recent advances in this field (Smart City, Last Mile integration, City Logistics) and long-term planning of cross-country deliveries are forcing researchers towards a broader definition of them. In particular, while traditionally researchers mainly studied cutting and loading issues, with a special focus on the packing representation and the introduction of packing constraints like guillotine cuts, rotation and incompatibility between items, only recently they have started to consider more general issues as multi-attributes problems, rich packing problems, and uncertainty in the attributes. Aim of this work is to present the relevant literature, showing the different research directions as well as the new perspectives, with a special focus on tactical and strategic problems.

Keywords: Packing problems; uncertainty management; packing-routing; rich packing.

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1. Introduction

Even if packing problems are, from their beginning, strictly linked to Transportation, the recent advances in this field (Smart City, Last Mile integration, City Logistics) and long-term planning of cross-country deliveries are forcing researchers towards a broader definition of them. In particular, while traditionally researchers mainly studied cutting and loading issues, with a special focus on the packing representation and the introduction of packing constraints like guillotine cuts, rotation and incompatibility between items, only recently they have started to consider more general issues as multi-attributes problems, rich packing problems, and uncertainty in the attributes. Aim of this work is to present the relevant literature, showing the different research directions as well as the new perspectives, with a special focus on tactical and strategic problems.

In more details, we analyze the literature along the following directions:

- Packing-Routing problems. Traditionally packing and vehicle routing problems, even if strictly interconnected, have been considered as separate subproblems. The increasing competition and the presence of new constraints strictly correlating the two issues push the researchers to consider them as a whole, bringing to new optimization problems and methods.
- Rich and Generalized packing. The optimization of modern Supply Chain systems needs to incorporate flexible methods for addressing transportation and packing issues. After the generalization process that brought into the definition of the Rich Vehicle Routing Problems, an analogous process is recently started on packing.
- Uncertainty management. Different sources of uncertainty can affect packing problems, in particular when they act as subproblems in tactical and strategic supply-chain optimization problems, like the revenue associated with the shipping of the orders, the volume associated with the flows or the availability of certain types of containers. Recently, the researchers have started to define and deal explicitly with these sources of incertitude, both from the stochastic modeling and programming point of views, and to provide efficient methods to find accurate approximations of the stochastic solutions.

The paper is organized in three main sections, one for each research direction, giving the reader the main literature references, as well as a quick depiction of the results both in terms of solution quality and computational effort.

2. Packing-Routing problems

The efficiency of the delivery of goods is a key factor in modern business models. For this reasons a great effort was spent in the past decades to model and solve different variants of vehicle routing problems. In this process, several simplifications to the real process were usually introduced. One of the largest simplifications was the simplification of the loading of the goods, considering them mono-dimensional, even when the shape of the goods had an impact in the optimal solution. This leads to problems due to the recourse actions, which are required by the logistics staff when preparing the items for shipping. Moreover, in some applications the solution cannot be easily adapted, requiring to explicitly introduce the multi-dimensionality of the goods.

This inefficiency led in the past decade to the definition of new extensions of the standard Vehicle Routing Problem (VRP) which explicitly consider the accommodation of the items. The most studied variant is the so-called Capacitated Vehicle Routing with Two-Dimensional Loading constraints (2L-CVRP). It is an extension of the basic variant of the VRP where, given a central depot, a set of customers and the costs of a vehicle driving from the depot to a customer or between two customers, one aims to find the routes of the vehicles of the fleet minimizing the delivery costs, computed as the sum of the costs of moving from one point to the other (depot or customer). Moreover, the following constraints hold:

- The fleet of vehicles is fixed and all the vehicles are equal in terms of both maximum weight of freight that can be accommodated and two-dimensional loading space capability.

- Each route starts and terminates from and to the central depot.
- Each customer is visited once by exactly one route.
- The total weight of the items required by the customer subset assigned to each route does not exceed the vehicle capacity Q.
- For every vehicle, there exists a feasible, two-dimensional, orthogonal packing of the transported items onto the loading surface (multi-dimensional loading constraints).

Thus, the 2L-CVRP model is aimed at determining the optimal routes for executing the necessary delivery operations, as in the case of the well-known classical Capacitated Vehicle Routing Problem (Laporte, 2009; Perboli et al., 2008). Moreover, for each of the generated routes, the problem calls for the determination of a feasible two-dimensional orthogonal loading arrangement of the transported items onto the vehicle loading surface. This loading requirement is closely related to the Two-Dimensional Bin Packing Problem (2DBPP), which is the multi-dimensional packing problem involving the minimization of the number of identical rectangular bins required for packing a predetermined set of rectangular items (Crainic et al., 2008).

Iori et al. (2007) propose an exact branch-and-cut algorithm for the routing aspects, whereas the two-dimensional loading is managed by a branch-and-bound approach. The algorithm is capable to solve to optimality instances of up to 25 customers and 91 items within about one day of computational time. In order to deal with larger instances, Gendreau et al. (2008) propose a tabu-search approach for optimizing the routing characteristics, whereas feasible loading patterns are identified via a heuristic procedure based on the Touching Perimeter rule by Lodi et al., (1999). Zachariadis et al. (2009) describe a hybridization of tabu-search and guided local search which operate in parallel with a collection of heuristics for developing feasible item loadings. Other hybrid methods are developed by Leung et al. (2011) and Duhamel et al. (2011).

To our knowledge, the most innovative and effective approach for the 2L-CVRP is by Zachariadis et al. (2013). In terms of the routing aspects, they propose a local-search optimization approach, coordinated via a single-parameter policy adapting to the progress of the conducted search. Regarding the loading constraints, they are tackled via a packing heuristic which attempts to identify feasible packing arrangements for the transported goods. The packing heuristic behavior is controlled by a memory mechanism used to record the packing structures with the maximal probability of obtaining feasible loading arrangements, in order to reduce the computational effort due to the two-dimensional loading computation. The method presents a very good behavior from the point of view of efficiency, with a quite limited gap from the best knows solutions (about 1.5% in the mean) and improving several instances. The real issue of all the methods in the literature remains the computational behavior, which presents computational times up to 5000 seconds on a single-core 2.4GHz Intel workstation on the 255 customers instances.

The three-dimensional extension of the 2L-CVRP is due to Gendreau et al. (2006). The problem is referred to as the Capacitated Vehicle Routing Problem with Three-Dimensional Loading Constraints (3L-CVRP). The authors solve the examined problem via a tabu-search metaheuristic development. Further solution approaches for the 3L-CVRP model have been published by Tarantilis et al. (2009), Fuellerer et al. (2010), Ruan et al. (2011), Zhu et al. (2012), and Bortfeldt (2012).

As stated before, 2L-CVRP and 3L_CVRP tackle the basic version of Vehicle Routing problems. Some variants considering different additional constraints are defined. A vehicle routing problem with two dimensional loading constraints has been introduced by Malapert et al. (2008), examining the pick-up and delivery extension of the basic 2L-CVRP model. Another routing problem with three-dimensional packing requirements and time-window constraints is studied by Moura and Oliveira (2009). Zachariadis et al. (2012) examine an integrated routing-packing model where the items are not directly loaded in the vehicle, but need to be palletized before, called pallet packing vehicle routing problem. Finally Männel, & Bortfeldt (2013) consider a pickup and delivery problem with three-dimensional accommodation of the items and side constraints as packing stability and feasible automatic loading/unloading operations. The method is an hybrid metaheuristic, which uses a large neighborhood search for dealing with the routing part and a tree procedure to accommodate the items inside the vehicles.

According to this review, there is still a lot of work to do in integrating the multi-dimensionality with more complex and realistic versions of the Vehicle Routing problems, including pickup and delivery, hard and soft time-windows, priority of the delivery to the customers, etc. Moreover, the biggest issue of solution approaches is the computational time, which can be heavy in large instances.

3. Rich and Generalized packing

Traditionally, packing problems defined in the literature are more related to the operational level. Recently, with the introduction of packing issues in tactical and strategic problems, researchers have started to push towards the definition of generalizations and enrichments of the traditional packing problems. In the following, for reasons related to the paper length, we will focus on the latest developments on the side of mono-dimensional generalizations. For a survey of multi-dimensional packing problems, the reader can refer to Crainic et al. (2011b) and Crainic et al. (2012a), while for extensions of multi-dimensional packing problems with constraints related to the balancing of the cargo, see Baldi et al. (2012b).

The Variable Cost and Size Bin Packing problem (VCSBPP) is a generalization of the Bin Packing problem, where all items must be loaded, but bins can be chosen among several types differing in volume and cost. The total accommodation cost, computed as the total cost of the used bins, must be minimized. A number of studies have recently been dedicated to the VCSBPP. Correia et al. (2008) propose a formulation that explicitly included the bin volumes occupied by the corresponding packings, together with a series of valid inequalities improving the quality of the lower bounds obtained from the linear relaxation of the proposed model. The authors also introduce a large set of instances and use them to analyze the quality of the lower bounds. Crainic et al. (2011a) propose tight lower and upper bounds, which can be computed within a very limited computing time, and are able to solve to optimality all the instances proposed in Correia et al. (2008). The authors also present a first computational study of the sensitivity of the optimal cost with respect to the cost definition.

A special case of the VCSBPP is the Variable Size Bin Packing Problem (VSBPP) where bin costs are equal to their associated volumes. The aim of the VSBPP is then to minimize the wasted volume. Monaci (2002) presents a series of lower bounds and solution methods (both heuristic and exact) for the VSBPP. The author also introduces instance sets for the problem considering up to 500 items. His exact method is able to solve most the instances to optimality. Kang and Park (2003) develop two greedy algorithms for another special case of the VSBPP, where the unit cost of each bin does not increase as the bin volume increases, and analyze their performances on instances with and without divisibility constraints.

Being the more general problem between the two introduced, we focus on the results for the VSCBPP, which are summarized in Table 1(a). The table reports the data of 360 instances ranging from 25 to 500 items. For the mostly part of the instances the optimal solution is known, so in presenting the results of the best lower and upper bounds we compute the percentage gap with the optimal solution (or the best known lower bound, otherwise). All the tests are performed on an Intel Pentium IV 3 GHz workstation. Column 1 gives the number of items, while Column 3 and 5 give the percentage deviation from the optimal solution of the best lower and fast heuristic for the VSCBPP (Crainic et al., 2011a). For both the methods no computational result is given, being negligible (0.01 seconds in the worst case). As one can see, the gap of both lower and fast heuristic is quite limited. In particular the fast heuristic is able to achieve a precision less than 2% with a very limited computational effort. Nerveless, the heuristic is able to prove the optimality of some instances from Correia et al. (2008), as well as to improve some instances taken from the same paper.

To the best of our knowledge, the most relevant generalization of packing problems is the Generalized Bin Packing Problem (GBPP). It consists in a set of bins characterized by volume and cost and a set of items characterized by volume and profit. Moreover, the items are split into two families: the compulsory and the noncompulsory items. Whilst the compulsory items must always be loaded, the non-compulsory items might not be loaded into the bins. The goal of the GBPP is to select appropriate bins and items in order to minimize the total net cost given by the difference between the costs of the selected bins and the profits of the selected non-compulsory items (Baldi et al. 2012a). The GBPP is a generalization of many packing problems such as the Bin Packing Problem, the Variable Sized Bin Packing Problem, the Variable Cost and Size Bin Packing Problem, the Knapsack Problem, and the Multiple Knapsack Problem with and without identical capacities. This generalization provides the great advantage that the same techniques employed for solving the GBPP might be used to solve even other different packing problems. From the Transportation and Logistics point of view, the GBPP problem arises mainly in cross-continental and multi-modal transportation. Indeed, freight flows require intermediate transshipment locations, such as ports, where freight is consolidated and loaded on ships. Both exact and heuristic methods are available to solve the GBPP. In more detail, bounds and heuristics based on the generalization of the well knows Best and First Fit Decreasing heuristics are developed in Baldi et al. (2012a). A Branch and Price method is presented in Baldi et al. (2013). The method is based on a column generation lower bound and a double branching scheme.

The main results in the GBPP are summarized in Table 1(b). The results are obtained in the 900 instances presented in Baldi et al. (2012a). The instances mix different types of bins types, items profits and presence of compulsory and non-compulsory items and are computed by a Intel Pentium IV 3 GHz workstation. All the gaps are obtained by considering the optimal solutions, when known, or the best lower bound. Column 1 gives the number of items, Column 2 and 3 the gaps of the best lower bound and the best heuristic method, respectively (Baldi et al., 2012a). Finally Column 4 and 5 summarize the results of the Branch and Price presented in Baldi et al. (2013). In details, the columns report the gap between lower and upper bound and the mean computational time. Notice that computational results for LB and heuristic are not reported, being negligible (less than 0.1 seconds for the heuristic method). According to the results, the lower bound, which is based on column generation, presents a gap less than 0.08%. Moreover, in 46% of the instances the lower bound also gives the optimal objective function. The heuristic presents a good behavior, with a mean gap of 1,58%. The behavior of the Branch & Price is quite satisfactory too, with an optimality gap of 0.03% in the mean on instances up to 500 items and 5 types of bins. The counterpart of this precision is the computational effort, which is more than 2000 seconds in the largest instances.

Table 1. Computational results of state-of-the-art methods for VCSBPP (a) and GBPP (b)

N	LB	ITER-BFD
25	0.98	1.88
50	0.57	1.83
100	0.50	1.81
200	0.29	2.02
500	0.28	2.09
Overall	**0.66**	**1.93**

(a)

N	LB	C-BFD	B&P	Time B&P
25	0.15	2.31	0.00	1.94
50	0.10	2.18	0.00	66.44
100	0.05	1.50	0.02	570.44
200	0.05	1.15	0.04	1057.75
500	0.05	0.79	0.11	2175.24
Overall	**0.08**	**1.58**	**0.03**	**774.36**

(b)

4. Uncertainty management

The mostly part of the literature focused on introducing uncertainty on the arrival of the items, defining the so-called on-line versions of the classic packing problems. In particular, a lot of studies focused on the online version of the Bin Packing Problem, i.e. the variant of the Bin Packing where the items come one after the other and no knowledge (or a limited one) on the volume of the next items is given to the decision maker. In particular, the researchers studied policies for loading the items in the different bins giving results on their absolute or asymptotic behavior. Only in recent years the researchers have started to study stochastic versions of packing problems. These variants arise mainly when strategic and tactical problems must be solved and, in particular, when one has to plan the capacity of his fleet (Crainic et al. 2012b) or stochastic costs and profits are present in the problem (Perboli et al., 2012a; 2012b).

Perboli et al. (2012b) extend the standard Knapsack problem, defining the Multi-Handler Knapsack Problem under Uncertainty. This is a new stochastic variant of the Knapsack problem where, given a set of items, characterized by volume and random profit, and a set of potential handlers, we want to find a subset of items which maximizes the expected total profit. The item profit is given by the sum of a deterministic profit plus a stochastic profit due to the random handling costs of the handlers. On the contrary of other stochastic problems in the literature, the probability distribution of the stochastic profit is unknown. In the paper, a two-stage stochastic model with recursion is introduced. From a theoretical perspective, the paper shows that, under a mild assumption, the probability distribution of the maximum random profit for loading any item becomes a Gumbel distribution. Moreover, the total expected profit of the loaded items is proportional to the logarithm of the total accessibility of those items to the set of handlers and, at optimality, any item is handled by the set of handlers according to a multinomial Logit model. Table 2 presents the results over 480 instances. The instances differ in number of items, profit type, magnitude of the stochastic oscillation, and stochastic distribution type. In details, Column 1 gives the number of items. The remaining columns show, for each tested distribution (uniform and Gumbel) the mean and the variance of the percentage gap between the objective function of the two-stage model with recursion and the deterministic Logit approximation. The deterministic approximation of the stochastic model provides very promising results in negligible computing time, with a gap from a two-stage model with recourse of less than 2%. From the point of view of the computational times, the mean computational time of the two-stage stochastic model with recursion is 120 seconds, while the deterministic approximation requires less than a second, with a reduction of 2 orders of magnitude.

A similar approach was used in Perboli et al. (2012a) to derive a stochastic version of the GBPP. In this case the total net profit is still given, as in the deterministic GBPP, by the difference between the total profit of the loaded items and the total cost of the used bins, but the item profits are random variables to take into account the profit oscillations due to the handling operations for bin loading. Even in this case, the authors show that, by using some results of the asymptotic theory of extreme values (Galambos, 1978), the probability distribution of the maximum random profit of any item becomes a Gumbel (or double exponential) probability distribution and the total expected profit of the loaded items can be easily calculated. By using this result, a deterministic approximation of the S-GBPP is derived. Unfortunately, the paper gives only theoretical results and no numerical comparison between the deterministic non-linear approximation of the problem and the stochastic one is given.

In Crainic et al. (2012b) there is the first attempt to introduce a stochastic variant of the VCSBPP considering not only the renting cost of the different bins, but also their availability. In more detail, aim of the problem, named Variable Cost and Size Bin Packing problem with Stochastic Items (VCSBPSI), is, given a certain number of bin types, their costs when we book them in advance and the costs if we rent them when needed as well as the demand of goods to deliver, to decide the capacity planning in terms of bins rented in advance in order to minimize the total cost. This cost is given by the cost for booking the bins at the planning level plus the expected value of the cost due for renting the (eventual) additional bins needed in every loading scenario to actually manage the freight delivery. The source of incertitude is given by the actual availability and the volume of the freight to deliver. The authors define a two-stage model solved by means of the commercial MIP. The tests are performed over 360 instances, varying in bin types, item types (IT1, majority of the items are small, IT2 majority of items are medium sized, IT3 majority of the items are big sized), and percentage increasing of the bin costs from the first to the second level of the two-level stochastic model with recursion. The number of items available in each scenario is quite small (between 25 and 50). This limitation is due to the number of variables involved in the two-stage stochastic model while the number of items increases. The reference machine is a Core i7-2630 workstation with a 2.0 GHz processor.

Table 2. Computational results of the deterministic approximation of the Multi-Handler Knapsack Problem under Uncertainty

IT	**GUMBEL**		**UNIFORM**	
	Mean	**Var**	**Mean**	**Var**
100	1.18	0.44	1.99	1.40
1000	1.22	0.48	1.99	1.15

Table 3. Computational results of the Variable Cost and Size Bin Packing problem with Stochastic Items

		$\lvert S\rvert = 25$		$\lvert S\rvert = 50$		$\lvert S\rvert = 100$	
	α (%)	$VSS_{\%}$	**Time (s)**	$VSS_{\%}$	**Time (s)**	$VSS_{\%}$	**Time (s)**
IT1	**5**	3.11	126.49	2.85	334.61	2.41	246.22
	10	2.91	308.51	2.86	813.25	1.76	639.08
	20	2.25	210.21	1.71	813.82	1.28	819.09
	40	1.17	126.86	0.51	162.59	0.64	254.36
IT2	**5**	2.62	206.24	1.97	777.22	1.83	831.67
	10	2.79	390.10	2.23	738.96	1.44	837.06
	20	1.49	70.10	1.93	248.30	0.67	639.43
	40	1.36	222.37	0.68	579.32	0.32	825.96
IT3	**5**	3.43	246.66	3.26	846.85	2.31	900.76
	10	2.62	128.16	2.44	139.30	1.47	744.46
	20	1.84	220.44	1.49	795.81	0.37	900.18
	40	0.60	510.99	0.69	900.23	0.34	902.09

Table 3 gives the comparison of the results of the two-stage stochastic model with recursion with the Monte Carlo simulation of the first level decisions obtained by substituting to the stochastic values their mean. For each number of second-level scenarios (25, 50, and 100, respectively), item types, and percentage increasing of the bin costs from the first to the second stage of the two-stage stochastic model ( ), we give:

- the percentage Value of the Stochastic Solution, i.e., the percentage gap between the objective function of the two-stage stochastic model with recursion and the Monte Carlo simulation of the mean deterministic solution.
- The computational time needed to compute the Monte Carlo simulation of the mean deterministic solution.

No computational times are given for the two-stage model, because it reaches in mainly all the instances its time limit of 15 minutes.

The data show how already with 25 scenarios the results become quite stable. Moreover, the VSS is relevant, if we think to packing problem, while the costs for renting the bins are not changing a lot from the first to the second stage. When the spread of the costs is increasing (more than 10%), it becomes easy even for the deterministic model using the mean values of the uncertain parameters to determine the goof first-stage decisions. From the computational point of view, the computational times are quite big. More detailed results are presented by the same authors in Crainic et al. (2012b). The analysis show how packing problems, due to their solution symmetry property, not only are more difficult to solve than other combinatorial problems even in their stochastic counterpart, but that new extensions of traditional measures for evaluating the expected value of the stochastic solution are needed (Maggioni, & Wallace, 2012).

5. Conclusions

The optimization of modern transportation and supply chain demands to push the research in different directions from the more traditional ones. This is true in particular for the packing field, which was for a long time mainly related to the loading/unloading operations only. In recent years, the scenario has started to change towards problems able to come additional aspects of the packing problems. In this paper we gave a quick depiction of the new trends related to the emerging packing problems in Transportation and Logistics, showing the limits of the current approaches and possible directions of research.

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