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## The parking allocation problem for connected vehicles.

Marko Mladenovic, Said Hanafi, Thierry Delot, Gilbert Laporte, Christophe Wilbaut

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Abstract

In this paper, we propose a parking allocation model that takes into account the basic constraints and objectives of a problem where parking lots are assigned to vehicles. We assume vehicles are connected and can exchange information with a central intelligence. Vehicle arrival times can be provided by a GPS device, and the estimated number of available parking slots, at each future time moment and for each parking lot is used as an input. Our initial model is static and may be viewed as a variant of the generalized assignment problem. However, the model can be rerun, and the algorithm can handle dynamic changes by frequently solving the static model, each time producing an updated solution. In practice this approach is feasible only if reliable quality solutions of the static model are obtained within a few seconds since the GPS can continuously provide new input regarding the vehicle's positioning and its destinations. We propose a 0–1 programming model to compute exact solutions, together with a variable neighborhood search-based heuristic to obtain approximate solutions for larger instances. Computational results on randomly generated instances are provided to evaluate the performance of the proposed approaches.

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Keywords (separated by '-')

Parking allocation - 0–1 Programming - Variable neighborhood search

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Footnote Information

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# The parking allocation problem for connected vehicles

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**Abstract** In this paper, we propose a parking allocation model that takes into account the basic constraints and objectives of a problem where parking lots are assigned to vehicles. We assume vehicles are connected and can exchange information with a central intelligence. Vehicle arrival times can be provided by a GPS device, and the estimated number of available parking slots, at each future time moment and for each parking lot is used as an input. Our initial model is static and may be viewed as a variant of the generalized assignment problem. However, the model can be rerun, and the algorithm can handle dynamic changes by frequently solving the static model, each time producing an updated solution. In practice this approach is feasible only if reliable quality solutions of the static model are obtained within a few seconds since the GPS can continuously provide new input regarding the vehicle's positioning and its destinations. We propose a 0–1 programming model to compute exact solutions, together with a variable neighborhood search-based heuristic to obtain approximate solutions for larger instances. Computational results on randomly generated instances are provided to evaluate the performance of the proposed approaches.

**Keywords** Parking allocation · 0–1 Programming · Variable neighborhood search

## 1 Introduction

Drivers equipped with a Global Positioning System (GPS) device usually enter their final destination into their device. However, they rarely park their vehicles exactly

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20 at this destination point, but more likely at the most convenient available parking  
 21 slot they can find. The driving time between the desired destination and the actual  
 22 parking is known to produce several undesirable consequences, such as air pollution,  
 23 traffic congestion and stress. Detailed urbanization and transportation studies (e.g.  
 24 Shoup 2006, 1997; Gantelet and Lefauconnier 2006; Caicedo et al. 2016; Davis et al.  
 25 2010) further confirm the negative impact of massive unorganized (random) search  
 26 for parking lots in urban areas.

27 *Research motivation* One of the first authors who drew attention to the consequences  
 28 of unorganized parking was Donald Shoup. In one of his studies (Shoup 2006) he  
 29 revealed that the search for curb vacant parking slots, even though they may be  
 30 cheaper, does not pay off, because other criteria should be taken into consideration,  
 31 such as the time spent searching for parking at the curb, fuel cost of cruising, the  
 32 number of people in the car, parking duration, etc. He then proposed different pricing  
 33 techniques and advocated the use of “off-street parking” as a better alternative to a  
 34 random street search. In his other paper, (Shoup 1997), he claimed that, cumulatively  
 35 for one year, in just one district of Los Angeles around 47,000 gallons of gasoline  
 36 were burned producing 730t of CO<sub>2</sub> and taking drivers 945,000 extra miles (for a  
 37 total of 11 years) to find a vacant slot. These two papers based their observations  
 38 on data collected from the USA. Another study by Gantelet and Lefauconnier (2006),  
 39 based on European insights, reveals that drivers have a tendency to enlarge their search  
 40 radius. For example, below 15 min, the average distance to the destination is less than  
 41 200 m. When the search time exceeds 15 min, the distance becomes more and more  
 42 significant and can extend beyond 500 m (550 m on average in Lyon for a searching  
 43 time of 45 min). The authors conclude that searching for parking spaces causes traffic  
 44 congestion: between 5 and 10% of the traffic in cities and up to 60% on small streets.

45 *Existing practical solutions* Most cities have introduced some strategies to tackle this  
 46 problem. One of the most frequent is the Parking Guidance and Information (PGI),  
 47 which is displayed on roads and continuously updates neighboring parking availability.  
 48 Thus, some indoor parking zones include adaptive lighting sensors, as well as parking  
 49 space led indicators and Indoor Positioning System (IPS).  
 50 There are also a variety of start-up applications that offer drivers guidance in order to  
 51 ensure an available lot in the vicinity of their destination. For instance Parkopedia<sup>1</sup>  
 52 keeps its content up to date via its users, who get credits for every entry (update) they  
 53 make. Smartphone location feature enables apps to locate the nearest parking (mainly  
 54 public garages). If the driver desires, he can reserve a place at that parking via this  
 55 application. An example of a successful project is the ZenPark mobile application,<sup>2</sup>  
 56 which embodies these characteristics and then estimates the quantity of saved CO<sub>2</sub>, as a  
 57 mark of environmental benefit. The local authorities of Lille (France) have developed a  
 58 smart phone application containing useful real-time information called MEL.<sup>3</sup> Among

<sup>1</sup> <http://www.parkopedia.com>.

<sup>2</sup> <https://zenpark.com>.

<sup>3</sup> <http://www.lillemetropole.fr/en/mel.html>.

59 other options the users can check the availability of most parking spaces (also public  
60 garages) in the city. However, guiding options are not included.

61 *More insights* City authorities have, each in its own way, struggled with the conse-  
62 quences of massive unorganized search for available parking. Several studies show that  
63 in most cases there are sufficient parking slots for all vehicles and are concerned with  
64 the negative environmental impact of constructing more parking (Caicedo et al. 2016;  
65 Davis et al. 2010). Therefore, we focus our attention on their allocation to existing  
66 facilities in order to avoid traffic jams, reduce travel time, and so on. Furthermore, due  
67 to the availability of free slots data in public parking and the results presented in Shoup  
68 (1997), in this study we only consider public parking and not curb lots (street park-  
69 ing). Moreover, a GPS signal is available thought most modern devices with 3G/4G  
70 connections and the vehicles can exchange information with the central intelligence  
71 (server).

72 *Related work* The solutions mentioned in the previous paragraph target a single vehi-  
73 cle and allocate to it the parking that suits it best, or serves as a general guideline for  
74 currently available parking slots. However, some studies also include other vehicles in  
75 the spatial and temporal vicinity and endeavor to allocate the “globally” best parking  
76 spot to each vehicle. For example, in Delot et al. (2013) the authors examine the fairness  
77 of parking allocation in vehicular networks. As in vehicular networks it is less clear  
78 which slot would be globally best, the authors propose dissemination protocols with  
79 an encounter probability parameter. It estimates the likelihood that a vehicle is going  
80 to meet a certain event, (Cenerario et al. 2008), and shares the available information  
81 according to the encounter probability parameter. In a more recent paper, (Toutouh  
82 and Alba 2016), the other aspects of sharing data in decentralized vehicular networks,  
83 such as congestion and hazardous road situations are investigated.

84 A significant portion of articles addressing the parking issue is devoted to the  
85 problem of parking pricing. Other studies focus on Electric Vehicles (EVs) and on  
86 their specific parking needs. Some authors, such as Teodorović and Lučić (2006) and  
87 Delot et al. (2009), focus on reserving parking slots for only one vehicle at a time.  
88 Since the reservation of a parking slot is not applicable for most parking needs, we  
89 will not consider these papers. In our study, we exclusively focus on the most generic  
90 vehicle parking allocation, thus the following paragraph considers the papers that are  
91 dealing with the allocation of parking lots to a potentially very large set a vehicles.

92 So far many researchers have addressed the parking allocation problem. However,  
93 there are no standardized mathematical programming models for it, be they deter-  
94 ministic or stochastic. This is probably due to the very large number of variables and  
95 parameters that would have to be approximated and would lead to ambiguous results.  
96 This is why several authors propose various ways of defining the problem at hand. For  
97 example, Ayala et al. (2012) opt for a game-theoretic approach and model the parking  
98 allocation problem in a similar way as the stable marriage problem, and name it the  
99 parking slot assignment game problem. In Verroios et al. (2011), propose a Travel-  
100 ing Salesman Problem (TSP) variant model—the time-varying TSP. The authors also  
101 propose a number of algorithms to tackle the proposed model and group vehicles into  
102 clusters in order to improve algorithm efficiency. Recently, Roca-Riu et al. (2015)

103 proposed a mathematical programming model for the Parking Assignment Problem  
 104 (PAP) for delivery vehicles in urban distribution. The authors consider the limited  
 105 availability of parking slots in urban areas for goods delivery. They model this prob-  
 106 lem as a variant of the vehicle routing problem with time windows, because it can  
 107 be assumed that vehicles have to arrive at their destination at a predefined time in  
 108 order to satisfy the demand. The model proposed in Abidi et al. (2016) has the most  
 109 resemblance with the model we develop in this paper. The authors allocate vehicles  
 110 by taking into consideration the fact that different parking have different maximal  
 111 parking time and propose an efficient heuristic.

112 All previously mentioned articles consider in the objective function the distance  
 113 (time) as the main optimization criterion. Furthermore, Verroios et al. (2011) and Delot  
 114 et al. (2013) consider decentralized networks, i.e. networks in which information is  
 115 partially accessible by vehicles within a certain radius (see Ilarri et al. 2015 for a  
 116 detailed survey). Other papers consider that all the information is available to the  
 117 administrator (centralized system), which can then be used to propose parking lots to  
 118 vehicles. Several articles advocate the use of GPS data as input for parking guidance  
 119 (e.g. Gahlan et al. 2016; Mendez et al. 2006). However, to the best of our capabilities,  
 120 we could not find any contribution with a mathematical programming model.

121 *Contributions* In this paper, we consider a potentially very large set of  $n$  vehicles,  
 122 dispersed over a given area. The arrival time  $t'_{ij}$  ( $i = 1, \dots, n; j = 1, \dots, m$ ) to  $m$   
 123 potential parking zones can be provided by the GPS. The GPS can also compute the  
 124 walking time  $t''_{ij}$  from each parking to the drivers final destination. These data were  
 125 used to formulate a 0–1 integer programming model that allocates vehicles to parking  
 126 lots, by optimizing total travel time (from current location to parking and from parking  
 127 to destination) of all vehicles. The model is completed with the basic and necessary  
 128 constraints for any parking assignment problem: capacity and allocation constraints.  
 129 It can be regarded as a variant of the Generalized Assignment Problem (GAP), and as  
 130 such is NP-hard in the general case. Our main contributions are the following:

- 131 1. a new parking allocation LP model for a set of  $n$  connected vehicles, together with
- 132 a discussion on how to include more realistic constraints for the static PAP;
- 133 2. a complexity analysis of the proposed models; for example, it is shown that min–
- 134 sum type model possesses the integrality property, and therefore is polynomial.
- 135 However, the min–max static PAP is shown to be NP-hard;
- 136 3. a heuristic based on Variable Neighborhood Search (VNS) for it;
- 137 4. a discussion on how to extend the model to the dynamic case is provided; in fact
- 138 we propose to iteratively rerun the static model, since it appears to provide results
- 139 very fast;
- 140 5. an extensive computational analysis of exact and heuristic methods is provided.

141 *Outline* The remainder of this paper is organized as follows. Section 2 introduces both  
 142 combinatorial and mathematical programming models; Sect. 3 presents a VNS-based  
 143 heuristic for solving it. Section 4 offers comparative results between randomly parked  
 144 vehicles and the proposed model, solved both exactly and heuristically. We close the  
 145 paper with concluding remarks in Sect. 5.

146 **2 Problem formulation**

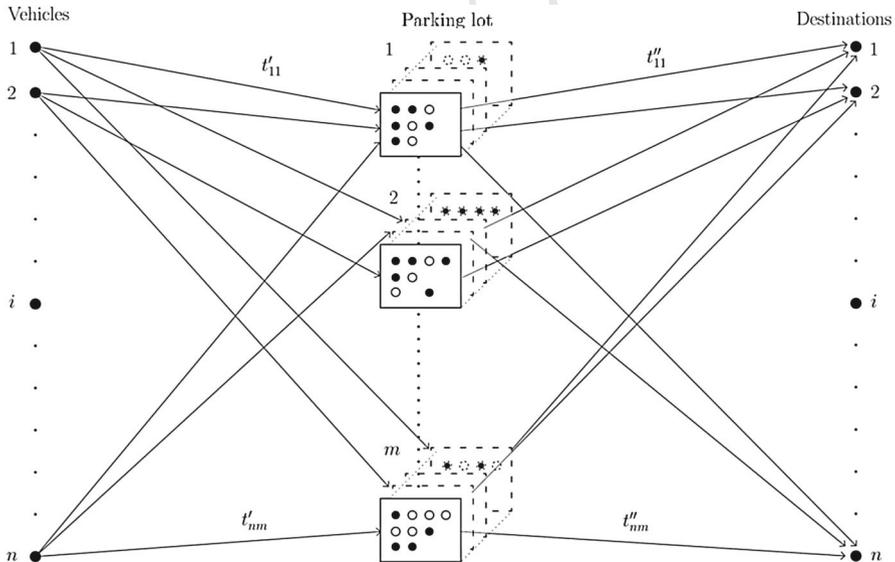
147 We first present a combinatorial formulation of the static Parking Allocation Problem  
 148 (PAP), which will be later used for developing a heuristic. We then propose a math-  
 149 ematical programming formulation which is used to solve the problem with some  
 150 commercial solver, such as CPLEX.

151 **2.1 Combinatorial formulation**

152 Assume that  $n$  connected vehicles, equipped with a GPS device, are searching for  
 153 parking slots in an urban area at time  $t_0$ . Also assume that there are  $m$  parkings  $j$ ,  
 154 each with a known total capacity  $q_j$ ,  $j = 1, \dots, m$ . Once all drivers enter their final  
 155 destinations, we are then able to determine two types of estimated times or distances  
 156 (matrices):

- 157 –  $t'_{ij}$  : estimated time needed by vehicle  $i$  to reach parking  $j$ ,  $i = 1, \dots, n$ ;  $j =$   
 158  $1, \dots, m$ ;
- 159 –  $t''_{ij}$  : estimated walking time from parking  $j$  to the final destination of driver  $i$ ,  $i =$   
 160  $1, \dots, n$ ;  $j = 1, \dots, m$ .

161 Additional input is required regarding the estimated number of free slots  $v_{jt}$  at  
 162 parking  $j$ , for each time  $t$ ,  $t = 1, \dots, T_j$ , where  $T_j = \max_i \{t'_{ij}\}$ . Note that time  $t = 1$   
 163 corresponds to  $t_0$  (see Fig. 1).



**Fig. 1** Graphical representation of the PAP; black circles in the parking column represent the occupied slots, while dotted rectangles represent different times  $t$ , and the dotted circles the occupied (available) slots at these time moments

Author Proof

164 *Objective function* Let  $x(i)$  represent the index of the parking to which vehicle  $i$  is  
 165 allocated, and let  $\mathcal{P}$  be a feasible partition of  $x = (x(1), \dots, x(n))$ . Our goal is to  
 166 determine an allocation variable  $x$  (or a partition of  $x$  into a number of groups less  
 167 than or equal to  $m$ ) that minimizes the cumulative traveling time of the vehicles from  
 168 their initial position to their destination:

$$169 \quad \min_{x \in \mathcal{P}} f = \sum_{i=1}^n (t'_{i,x(i)} + t''_{x(i),i}). \quad (1)$$

170 *Feasibility* Denote by  $b_j$  the number of used slots at parking  $j$  in the current solution  
 171  $x$ , and by  $u_{j,t}$  the remaining number of free slots at parking  $j$  at time  $t$ , regarding the  
 172 solution  $x$ . The following two properties state feasibility conditions. The first property  
 173 gives conditions on valid input data which are easy to verify.

174 **Property 1** *A problem instance has no feasible solution if one the following two*  
 175 *conditions is met:*

$$176 \quad \sum_{j=1}^m q_j < n$$

$$177 \quad v_{jt} > q_j, \quad t = 1, \dots, T_j, \quad j = 1, \dots, m.$$

178 *Proof* There is no feasible solution if the number of vehicles is larger than the number  
 179 of parking lots. Besides, the capacity  $q_j$  of each parking  $j$  should not be smaller than  
 180 the available space for any period  $t$ .  $\square$

181 The next property gives obvious feasibility conditions which depend on the solution  
 182  $x$  as well.

183 **Property 2** *The feasibility of partition  $\mathcal{P}$  is satisfied if the following two conditions*  
 184 *are met:*

185  $b_j \leq q_j$  : the number of vehicles  $b_j$  parked at parking  $j$  should be less than its  
 186 capacity  $q_j$ , for all  $j$ ;

187  $u_{jt} \leq v_{jt}$  : the number of vehicles parked at time  $t$  at parking  $j$  should be less  
 188 than or equal to the maximum allowed number  $v_{jt}$ .

189 *Estimating the number of free parking lots over time* We assume that the  $v_{jt}$  values  
 190 are known and deterministic. In other words, we assume that some statistical investi-  
 191 gation has already been performed to determine these values at each minute (or every  
 192 5 min) during the day. For example, it is well known that the random variable which  
 193 represents the time between two consecutive arrivals or departures (of vehicles) to or  
 194 from the parking is exponentially distributed ( $f(t) = \lambda e^{-\lambda t}$ ,  $t \geq 0$ ). The parameter  
 195  $\lambda$  is estimated by known statistics which use data collected by measuring inter-arrival  
 196 (or departure) times over several full days. Therefore, knowing the  $\lambda_1, \dots, \lambda_m$  values  
 197 for each parking lot  $j$  and for each time  $t$ , allows us to compute the number of free  
 198 slots  $v_{jt}$ . To conclude, the static PAP relies both on the arrival times at the parking  
 199 and at the final destination, and the number of available slots at each future moment.  
 200 The final result is an allocation variable  $x_i$ : vehicle  $i$  should go to parking  $x_i$ , and the  
 201 GPS could guide the driver to its designated parking lot.

202 *Dummy parking lot* An obvious way to avoid infeasible solutions is to introduce a  
 203 dummy parking lot  $j = 0$ . It should have a large capacity, and be very far, i.e. arrival  
 204 times  $t'_{i,0}$  are very large for all vehicles  $i$ . So whenever vehicle  $i$  cannot be parked at  
 205 any parking lot  $j = 1, \dots, m$ , it will be allocated to the dummy lot  $j = 0$ .  
 206 Note that the LP model, presented in the following section, incorporates by default the  
 207 dummy parking lot, providing feasibility for any input. In this way, we avoid infeasible  
 208 solutions and temporarily place vehicles in the dummy parking lot. Furthermore, the  
 209 dummy lot can be seen as a buffer for future allocations. Throughout of this paper, if  
 210 we refer to a solution as infeasible, this means that at least one vehicle is assigned to  
 211 the dummy lot.

212 **2.2 Mathematical programming model**

213 It is clear that the principal purpose is to allocate the best parking  $j$  to each vehicle  
 214  $i$ , minimizing the total traveling time. We introduce the binary variable  $x_{ij}$  equal to 1  
 215 if and only if such an allocation is made. The objective is to minimize the total time  
 216 traveled:

217 
$$\text{minimize } \sum_{i=1}^n \sum_{j=0}^m [t'_{ij} + t''_{ij}] x_{ij} \tag{2}$$

218 subject to

219 
$$\sum_{j=0}^m x_{ij} = 1, \quad (i = 1, \dots, n) \tag{3}$$

220 
$$\sum_{i=1}^n x_{ij} \leq q_j, \quad (j = 0, \dots, m) \tag{4}$$

221 
$$\sum_{i=1}^n \alpha_{ijt} x_{ij} \leq v_{jt}, \quad (j = 0, \dots, m, t = 1, \dots, T_j) \tag{5}$$

222 
$$x_{ij} \in \{0, 1\}, \quad (i = 1, \dots, n, j = 1, \dots, m) \tag{6}$$

223 where

224 
$$\alpha_{ijt} = \begin{cases} 1 & \text{if } t = t'_{ij} \\ 0 & \text{otherwise.} \end{cases}$$

225 Constraints 3 require that every vehicle be parked, while constraints 4 ensure that  
 226 the number of vehicles allocated to parking  $j$  does not exceed parking capacity  $q_j$ .  
 227 Constraints 5 guarantee that the capacity at each period  $t$  for each parking lot  $j$  will  
 228 be respected.

229 We introduce an additional parking lot  $j = 0$  with a large capacity,  $q_0 = n$  for  
 230 example, with sufficient slots at every future time step  $v_{0,t} = n, \forall t$ , and with larger  
 231 arrival times  $t'_{i,0} > M$ , for all  $i$  and for some  $M$ . If a feasible solution exists, then the  
 232 dummy parking will remain empty. Otherwise, some drivers would remain without  
 233 a parking slot and would be temporarily rejected. Note again that only the allocation



$$\text{minimize } f(x) = \max_{i=1, \dots, n} \sum_{j=1}^m [t'_{ij} + t''_{ij}] x_{ij} \quad (7)$$

or

$$\text{minimize } f(x, z) = z \quad (8)$$

subject to

$$\sum_{j=1}^m [t'_{ij} + t''_{ij}] x_{ij} \leq z \quad (i = 1, \dots, n), \quad (9)$$

and constraints (3)–(6). Note that, the min–max–max formulation

$$\text{minimize } g(x) = \max_{i=1, \dots, n} \max_{j=1, \dots, m} [t'_{ij} + t''_{ij}] x_{ij} \quad (10)$$

would yield the same solution as the min–max–sum formulation due to constraints (3). Indeed, the vehicle that spends the most time to reach its parking (which should be minimized—min–max–max model) is the same as the one identified in the min–max–sum model since all  $x_{ij}$  when summed up over  $j$  are equal to 0, except for one vehicle. However the min–max–sum model should be considered, since it contains  $n$  additional constraints (9), and not  $n \times m$  as for the min–max–max formulation. Note that the min–max–sum model does not possess the integrality property.

### 2.3 Upgrade to a dynamic model

Since the real-world problem is not static, our basic idea—to include time into consideration, consists of repeatedly running the static model, e.g., once every predefined time step (e.g., 1 min). By doing so, we can avoid many unpredictable situations that a static model cannot easily incorporate: (1) a driver already allocated to a parking finds free curb parking; (2) the driver decides to change his destination; (3) the GPS device stops functioning (loses signal) in some vehicles; (4) the time during which the vehicle stays at a parking lot is unpredictable, and using queuing theory in this case would be too unprecise and noisy; (5) vehicles outside of the system can occupy a previously allocated parking slot.

An elegant way to cover many such unpredictable (random) circumstances is simply to solve the problem with the new current input. In 1 min some vehicles will reach the parking they were assigned to, while others will not. In the new solution, most vehicles will keep the same final parking as in the previous solution, but it can happen that some will be reallocated to other parking lots. This is why we need to have a high-speed solution method capable of handling the dynamic nature of the problem by providing solutions of the static model more frequently, since solving the new problem cannot start before the current problem has not been solved. This way, all vehicles appearing in the input are treated with equal priority. So for example, vehicles that would have been left without a parking lot with the current input would be reinserted in the next iteration, along with all other vehicles.

### 301 3 Variable neighborhood search for parking allocation problem

302 In this section, we develop a VNS-based heuristic for the PAP. We first discuss why  
 303 a heuristic approach is useful, despite the fact that the min–sum static PAP model  
 304 possesses the integrality property (see Property 3). Then we introduce the steps of our  
 305 VNS-based heuristic, providing detailed pseudo-codes for most procedures. A survey  
 306 paper on the VNS 0–1 MIP heuristic framework can be found in Hanafi et al. (2015).

307 Another strong argument for developing a heuristic is the fact that in big cities there  
 308 could be more than 100,000 vehicles on the streets looking for a parking place. In such  
 309 cases, the model could have millions of variables and just transferring the data to the  
 310 central server would be excessively time-consuming. In such cases, even a greedy  
 311 heuristic followed by any local search heuristic could provide good quality solutions.

312 *Solution representation* We present our solution as an array, already defined in the  
 313 combinatorial formulation section:

314  $x = (x_1, \dots, x_n)$ , where  $x_i$  defines the parking lot to which vehicle  $i$  is allocated  
 315 ( $x_i \in \{1, \dots, m\}$ ).

316 In order to efficiently compute (update) objective function values associated to solu-  
 317 tions in the neighborhood of  $x$  and to check their feasibility, we keep, along with the  
 318 solution  $x$ , the following variables:

- 319 –  $f_{cur}$  : the objective function value of the current solution  $x$ ;
- 320 –  $f_v(i)$  : contribution of vehicle  $i$  to the objective function value ( $f_v(i) = t'_{i,x(i)} +$   
 321  $t''_{i,x(i)}$ );
- 322 –  $b(j)$  : the number of used parking slots at parking  $j$  in the current solution  $x$ ;
- 323 –  $u(j, t)$  : the number of free parking slots at parking  $j$  at time  $t$  in solution  $x$ .

324 *Initial solution* In order to construct an initial feasible solution we propose a *Greedy*  
 325 *add* algorithm. For each vehicle  $i$  we find its closest parking  $o(i, 1)$ ; if not feasible  
 326 (i.e., the parking is full at arrival time  $t'_{io(i,1)}$ ), the vehicle is allocated to its second  
 327 closest  $o(i, 2)$ , etc. Its steps are presented in Algorithm 1.

328 In line 3, for each vehicle  $i$ , the parking places are ranked in non-increasing order of  
 329 their distances from the vehicles. This defines the matrix  $O$ , where the element  $o(i, 1)$   
 330 represents the index of the parking lot closest to vehicle  $i$ ,  $o(i, 2)$  is its second closest,  
 331 etc. In line 4 we rank the vehicles based on the distance to their closest parking. This  
 332 permutation of the set of vehicles is denoted by  $p(i)$ . In line 5 we initialize arrays  
 333  $b$ ,  $f_v$  and  $f_{cur}$ . The allocation of each vehicle starts from line 6, following the order  
 334 obtained by the permutation  $p$ . The feasibility is checked in line 9: there should be  
 335 an available slot at parking  $j$  at time  $t$ . If it is not feasible, we try to allocate to the  
 336 next closest parking of vehicle  $i$ . If the allocation is feasible, we update the solution,  
 337 as presented in lines 12 and 13.

338 **Property 4** *The time complexity of the Greedy add algorithm is  $O(nm \log m)$ .*

339 *Proof* For each of the  $n$  vehicles, the order of all  $m$  parkings is found in line 3. Hence, its  
 340 complexity is  $O(nm \log m)$ , since ordering of array with  $m$  elements is in  $O(m \log m)$ .

**Algorithm 1** Greedy Add( $f_{cur}, x, b, u, o, f_v$ )

```

1: procedure GREEDY_ADD
2:    $u \leftarrow v$  ( $u(j, t) \leftarrow v(j, t), \forall j, t$ )
3:   Get order matrix  $O_{n \times m} = o(i, j)$ 
4:   Get order  $p(i)$  of vehicles  $o(i, 1), (o(p(1), 1) \leq o(p(2), 1) \dots)$ 
5:    $b(j) \leftarrow 0, \forall j; f_v(i) \leftarrow 0, \forall i; f_{cur} \leftarrow 0; tt \leftarrow 0$ 
6:   for  $ii = 1$  to  $n$  do
7:      $i \leftarrow p(ii);$ 
8:      $tt \leftarrow tt + 1;$ 
9:     if  $(tt > m)$  then 'No feasible solution' stop
10:     $x(i) \leftarrow o(i, tt); j \leftarrow x(i); t \leftarrow t'(i, j)$ 
11:    if  $(u(j, t) = 0$  or  $b(j) + 1 > q_j)$  goto 8
12:     $f_v(i) \leftarrow t + t''(i, j); f_{cur} \leftarrow f_{cur} + f_v(i);$ 
13:     $u(j, t) \leftarrow u(j, t) - 1; b(j) \leftarrow b(j) + 1; tt \leftarrow 0$ 
14:  end for
15: end procedure

```

341 The complexity of line 4 is then  $O(n \log n)$ . The complexity of the allocation loop  
 342 from line 6 to 14 is in  $O(nm)$  since in the worst case the vehicles will be allocated  
 343 to their furthest parking. Thus, the most time consuming operations are performed in  
 344 line 3. □

345 As mentioned earlier, we introduce a dummy parking lot to avoid generation of  
 346 infeasible solutions. Basically, the model structure does not change. However, after  
 347 introducing a dummy variable, the code would never stop in line 9 of GREEDY\_ADD  
 348 procedure, since feasibility in line 12 is always ensured by the dummy variable, if not  
 349 before. Moreover, another interesting property may be observed.

350 **Property 5** *The number of vehicles allocated to the dummy parking obtained by*  
 351 *GREEDY\_ADD is the same in the optimal solution.*

352 *Proof* Let us denote by  $\alpha(Greedy)$  and  $\alpha(Exact)$  the number of vehicles parked after  
 353 the Greedy and the Exact procedures, respectively. Due to the large values of  $t'_{i,0}, \forall i$ , we  
 354 have  $\alpha(Greedy) \geq \alpha(Exact)$ . Suppose the opposite from the claim of this property,  
 355 i.e., assume that  $\alpha(Greedy) > \alpha(Exact)$ . This means that there should be free parking  
 356 slots derived by Greedy solution equal to the difference  $k = \alpha(Greedy) - \alpha(Exact) >$   
 357  $0$ . Denote with  $i$  such a vehicle. The inner loop defined by lines from 8 to 11 of  
 358 GREEDY\_ADD excludes the possibility that  $i$  can be moved out from the dummy  
 359 parking lot. Indeed, for such a vehicle  $i$ , variable  $tt = \alpha(Greedy)$  in the pseudo-code  
 360 increases until it reaches  $m$  (there is no parking slot  $j$  in time moment  $t$  for vehicle  $i$ ).  
 361 Therefore,  $k = 0$ , which is a contradiction. □

362 This interesting property tells us that if the greedy solution includes vehicles allo-  
 363 cated to the dummy parking lot, then its number cannot be reduced by trying to get a  
 364 better solution. The better solution could possibly be obtained by allocating different  
 365 vehicles to the dummy parking lot. So, if the objective is to minimize the number of  
 366 vehicles without a parking slot, the greedy solution is optimal. This fact is another  
 367 argument for using a heuristic approach in solving a relatively simple static PAP. An  
 368 exact solution will not reduce the number of unassigned drivers.

369 *Neighborhood structures* Obviously, there can be several neighborhood structures  
 370 for this combinatorial optimization problem. Since our heuristic should be fast, in this  
 371 paper we propose two neighborhoods:

372 *Allocation* given a solution  $x$  and therefore  $(i, x_i)$  connections, for each vehicle  $i$ ,  
 373 change its parking lot  $x_i$ . The neighborhood  $N_k^{all}(x)$ , can be defined as  
 374 repeating the reallocation move  $k$  times. Therefore, the distance between  
 375 two solutions  $x$  and  $y$  is equal to  $k$  if and only if they differ in  $k$  allocations:  
 376  $x_i \neq y_i$  exactly for  $k$  vehicles; for the remaining  $n - k$  vehicles  $x_i = y_i$ ,  
 377 holds.

378 *Interchange* given a solution  $x$ , let  $(i_1, j_1)$  and  $(i_2, j_2)$  denote two vehicles parking  
 379 pairs. Assume that vehicles  $i_1$  and  $i_2$  exchange their parking places, so  
 380 that we have the pairs  $(i_1, j_2)$  and  $(i_2, j_1)$  in the new solution  $y$ . The  
 381 1-interchange neighborhood  $N_1^{int}(x)$  consists of all solutions  $y$  obtained  
 382 from  $x$  after performing such interchanges. It is clear that not all solutions  
 383 are feasible since some vehicle could arrive when all parking slots are  
 384 busy. We define the  $k^{th}$  neighborhood of  $x$ ,  $N_k^{int}(x)$ , with respect to the  
 385 interchange structure as the solutions obtained by  $k$  interchanges.

386 *Shaking* The shaking step in basic VNS consists of a random move from the current  
 387 solution  $x$  to a solution  $x' \in N_k(x)$ . We use both neighborhood structures, Allocation  
 388 and Interchange for the shaking step, with the same probability. In addition, we imple-  
 389 ment the so-called *intensified shaking* for Allocation neighborhood  $N_k^{all}(x)$ , where the  
 390 vehicle is first chosen at random and then its best identified reallocation. This step is  
 391 repeated  $k$  times to reach solution  $x'$  from  $N_k^{all}(x)$ . The complexity of this procedure  
 392 is obviously  $O(m)$ .

393 *Allocation Local search* We perform local search using a reallocation neighborhood  
 394 structure. Given a feasible solution  $x$ , every vehicle tries to change its parking to every  
 395 other parking. It is clear that the cardinality of  $N_1^{all}(x)$  is  $n \times m$ . However, we can  
 396 significantly reduce it in the following way: reallocate vehicles just to  $r_v$  (a parameter)  
 397 their closest parking ( $r_v < m$ ).

398 In the reduction strategy used during the preprocessing, we need to rank distances  
 399 (or times)  $t'_{ij} + t''_{ij}$  in non-decreasing order of their values, for each vehicle  $i$  and each  
 400 parking  $j$ : we thus obtain the order of parking facilities  $o(i, j)$ ,  $j = 2, \dots, m$ , for each  
 401 vehicle  $i$ . Note that the matrix  $O$  has already been introduced for the Greedy\_Add  
 402 algorithm. A detailed description of our local search is provided in Algorithm 2.

403 The input variables in Reallocate\_LS, beside those already introduced earlier  
 404 in Greedy\_Add are

- 405 – *first* : a Boolean variable which defines whether the first or the best improvement
- 406 strategy is implemented in the LS;
- 407 – *r<sub>v</sub>* : an integer value that defines how many parking we will try to change with the
- 408 current one, for any vehicle, following their distance order.

409 The basic loop starts at line 3. It is repeated until no improvement can be obtained  
 410 in the reallocation neighborhood  $N_1^{all}(x)$ . For each vehicle  $i$ , its current parking  $jj$  (at  
 411 time  $tt$ ) is replaced with the parking  $j$  (at time  $t$ ). The feasibility of this reallocation

**Algorithm 2** Reallocate LS( $x, f_{cur}, f_v, b, o, r, u, first$ )

```

1: procedure REALLOCATE_LS
2:   improve  $\leftarrow$  true
3:   while improve do
4:     improve  $\leftarrow$  false
5:     for  $i = 1$  to  $n$  do
6:        $jj \leftarrow x(i)$ ;  $tt \leftarrow t'(i, jj)$ ;  $f_{new} \leftarrow f_{cur} - f_v(i)$ 
7:       for  $j = o(i, 1)$  to  $o(i, r)$  do
8:          $t \leftarrow t'(i, j)$ ;
9:         if ( $u(j, t) > 0$  &  $b(j) + 1 \leq q_j$ ) then
10:           $f_{new} \leftarrow f_{new} + t + t''(i, j)$ 
11:          if  $f_{new} < f_{cur}$  then
12:             $f_{cur} \leftarrow f_{new}$ ; improve  $\leftarrow$  true
13:             $x(i) \leftarrow j$ ;  $f_v(i) \leftarrow t'(i, j) + t''(i, j)$ 
14:             $b(j) \leftarrow b(j) + 1$ ;  $u(j, t) \leftarrow u(j, t) - 1$ 
15:             $b(jj) \leftarrow b(jj) - 1$ ;  $u(jj, tt) \leftarrow u(jj, tt) + 1$ 
16:            if ( $first$ ) return
17:          end if
18:        end if
19:      end for
20:    end for
21:  end while
22: end procedure

```

412 is checked in line 9; whether a better solution is found or not is checked in line 11.  
 413 If the move is not feasible, or if there is no improvement, vehicle  $i$  remains at the  
 414 same parking lot. Otherwise the solution  $x$  is updated, together with arrays  $f_v$ ,  $b_j$  and  
 415 matrix  $U$ . If the first improvement strategy is implemented, the procedure returns the  
 416 improved values in line 16.

417 The number of iterations of LS is not known in advance and thus we do not know  
 418 the worst-case complexity of this algorithm. However, we can find the complexity of  
 419 one iteration of Reallocate\_LS. The following property is obvious:

420 **Property 6** *The number of calculations of one Reallocate\_LS iteration is*  
 421 *bounded by  $O(rn)$ .*

422 *Interchange Local search* This local search uses  $N_1^{int}(x)$  neighborhood described  
 423 earlier. Detailed pseudo-code is given at Algorithm 3.

424 Note that in Interchange\_LS we have two vehicles ( $i_1$  and  $i_2$ ) and two corre-  
 425 sponding parking ( $j_1$  and  $j_2$ ), but four different times:

- 426  $t_1$  : the time at which vehicle  $i_1$  arrives at its current parking  $j_1$ ;
- 427  $t_2$  : the time at which vehicle  $i_2$  arrives at its parking  $j_2$ ;
- 428  $t_3$  : the time at which vehicle  $i_1$  arrives at parking  $j_2$ , and
- 429  $t_4$  : the time moment at which vehicle  $i_2$  arrives at parking  $j_1$ .

430 We need to interchange the vehicle-parking pair ( $i_1, j_1$ ) with ( $i_2, j_2$ ) to obtain the  
 431 ( $i_1, j_2$ ) and ( $i_2, j_1$ ) allocations for each feasible pair of vehicles  $i_1$  and  $i_2$ . This move  
 432 is not possible if both vehicles are already at the same parking in solution  $x$  (condition  
 433  $j_1 \neq j_2$  at line 9). Note that we do not need to include the capacity constraints  $\leq q_j$   
 434 here, since vehicles just exchange their parking lots. However, it can happen that at

**Algorithm 3** Interchange LS( $i, j, t, jj, x, t'', tt, b, u, f_v, first$ )

---

```

1: procedure INTERCHANGE_LS
2:   improve  $\leftarrow$  true
3:   while (improve) do
4:     improve  $\leftarrow$  false
5:     for  $i_1 = 1$  to  $n - 1$  do
6:        $j_1 \leftarrow x(i_1)$ ;  $t_1 \leftarrow t'(i_1, j_1)$ 
7:       for  $i_2 = i_1 + 1$  to  $n$  do
8:          $j_2 \leftarrow x(i_2)$ 
9:         if  $j_1 \neq j_2$  then
10:           $t_2 \leftarrow t'(i_2, j_2)$ ;  $t_3 \leftarrow t'(i_1, j_2)$ ;  $t_4 \leftarrow t'(i_2, j_1)$ 
11:          if ( $u(j_2, t_3) > 0$  &  $u(j_1, t_4) > 0$ ) then
12:             $f_{new} \leftarrow f_{cur} - f_v(i_2) - f_v(i_1)$ 
13:             $f_{v1} \leftarrow t'(i_1, j_2) + t''(i_1, j_2)$ ;  $f_{v2} \leftarrow t'(i_2, j_1) + t''(i_2, j_1)$ 
14:             $f_{new} \leftarrow f_{new} + f_{v1} + f_{v2}$ 
15:            if  $f_{new} < f_{cur}$  then
16:               $f_{cur} \leftarrow f_{new}$ ; improve  $\leftarrow$  true
17:               $u(j_1, t_1) \leftarrow u(j_1, t_1) + 1$ ;  $u(j_2, t_2) \leftarrow u(j_2, t_2) + 1$ 
18:               $u(j_1, t_4) \leftarrow u(j_1, t_4) - 1$ ;  $u(j_2, t_3) \leftarrow u(j_2, t_3) - 1$ 
19:               $x(i_1) \leftarrow x(i_2)$ ;  $x(i_2) \leftarrow j_1$ 
20:               $f_v(j_1) \leftarrow f_{v1}$ ;  $f_v(i_2) \leftarrow f_{v2}$ 
21:              if first return
22:            end if
23:          end if
24:        end if
25:      end for
26:    end for
27:  end while
28: end procedure

```

---

435 time  $t_3$  or  $t_4$  there will be no parking place. This condition is verified in line 11. The  
 436 new solution is calculated in lines 12, 13 and 14, and if improved, it is updated in lines  
 437 16–20.

438 In terms of Interchange\_LS time complexity of, the following property is  
 439 obvious:

440 **Property 7** *The number of calculations in one iteration of Interchange\_LS is*  
 441 *bounded by  $O(n^2)$ .*

442 Despite the theoretically large number of operations, the algorithm can be very fast  
 443 due to the facts that many moves are not feasible, and that vehicles from the same  
 444 parking do not interchange. Moreover, we have implemented the first improvement  
 445 strategy, further reducing the search time.

446 *Sequential variable neighborhood descent* Variable neighborhood descent (VND) is  
 447 a deterministic variant of VNS. In its sequential version, neighborhoods are placed in  
 448 a list and used sequentially in the search. The Basic VND (BVND) returns the search  
 449 back to the first neighborhood, whenever an improvement has been detected in any  
 450 neighborhood structure from the list. For the Static PAP, our list contains two neigh-  
 451 borhood structures in the following order: reallocation and interchange. The BVND  
 452 is implemented, since Interchange LS uses the first improvement strategy. In other

453 words, the first time interchange of parking lots between two vehicles is successful,  
 454 the search resumes with reallocation. As in any other deterministic local search, VND  
 455 stops when the solution is local minimum with respect to both neighborhood structures.

456 *General variable neighborhood search* We also implemented VNS, in which the VND  
 457 heuristic is used as a local search mechanism. This VNS variant is known as General  
 458 VNS (GVNS). The basic loop contains the following tree steps: Shaking, VND local  
 459 search and Neighborhood change. Since the VNS algorithm is well known, we will  
 460 not describe it here (see Hansen et al. 2016 for a recent survey).

## 461 4 Computational results

462 The previously described heuristics were coded in Visual Studio 2012 C++. All tests  
 463 were executed on Intel Core i7-4702MQ processor with 16GB RAM running on  
 464 Windows 7 professional platform. CPLEX 12.6 was evoked via concert technology,  
 465 coded in C++ on Visual Studio 2012 and ran in parallel on all cores, while the heuristics  
 466 were sequential.

### 467 4.1 Random test instances

468 We have tested our model and the VNS-based heuristics on randomly generated test  
 469 instances. We tried to cover real-world situations as well as possible. The number of  
 470 vehicles  $n$  varies from 1000 to 90,000, while the number  $m$  of parkings is 10, 20,  
 471 30 and 50. The maximum capacity  $Q$  of each parking is equal to  $\lfloor 2n/m \rfloor$ . Then,  
 472 the actual capacity  $q_j$  is generated at random between 1 and  $Q$ , for each parking  
 473  $j$ . The drivers' positions and their destinations are generated according to a discrete  
 474 uniform distribution in the square  $S = [0, 200] \times [0, 200] \in \mathcal{R}^2$ . The parking locations  
 475 are also chosen at random within the same area  $S$ . Rectangular distances between all  
 476 drivers locations to all parking locations are used to generate the  $t'(i, j)$  distances. The  
 477 distances between parking and destinations  $t''(i, j)$  are computed in the same way.  
 478 The values of matrix  $V = (v_{jt})$  are generated in the following way. The initial values  
 479 for each parking  $j$  at time  $t_1$  are generated from a discrete uniform distribution  $v_{jt_1} \in$   
 480  $[1, q_j]$ . In order to generate more realistic instances, we generate the values  $v_{j,t+1}$   
 481 using the values  $v_{jt}$  for  $t = 1, \dots, T$  (where  $T = \max_{i=1, \dots, n} \max_{j=1, \dots, m} \{t'_{ij}\}$ ):

$$482 \quad v_{j,t+1} = v_{jt} + \gamma, \quad \gamma \in [-3, 3].$$

483 In other words, we do not allow the change in the number of free parking slots to be  
 484 greater than 3, for all parkings  $j$ .

485 Computational results are divided into two parts. We first compare the exact solu-  
 486 tions with the heuristic on small and medium size instances ( $n = 1000, 3000, 5000,$   
 487  $7000$  and  $9000$ ), for cases where dummy lots are not needed (Table 1) and were  
 488 the input does not produce feasible solutions (Table 2). We then switch to larger scale

489 instances, where the number of vehicles searching for a parking lot ranges from 10,000  
 490 to 90,000.<sup>4</sup>

#### 491 4.2 Feasible small and medium size instances

492 The feasibility of the instances is checked according to Properties 1 and 2. If an instance  
 493 is not feasible, a new one is generated. In addition, if the greedy algorithm cannot find  
 494 a feasible solution, we generate a new random instance as well. Thus, all the following  
 495 instances have feasible solutions.

496 For the number of vehicles we evaluate five possibilities:  $n = 1000, 3000, 5000,$   
 497  $7000$  and  $9000$ . As mentioned previously, for each value of  $n$ , we consider three  
 498 possible cases of parking:  $m = 10, 20$  and  $30$ . In addition, for the same  $(n, m)$  values,  
 499 we generate 10 instances. Therefore, in total we generate  $5 \times 3 \times 10 = 150$  test  
 500 instances.

501 *Comparison* We compare the results in solving static min–sum PAP of the following  
 502 methods:

- 503 – CPLEX : exact method using CPLEX solver on model (2)–(6);
- 504 – Greedy : greedy heuristic described in Algorithm 1;
- 505 – SeqVND : sequential VND-based local search, as given in Sect. 3;
- 506 – GVNS : general VNS, running maximally 10 additional seconds.

507 Average results on 10 instances, for different pairs of  $n$  and  $m$  are presented at  
 508 Table 1.

509 The third column of Table 1 provides the optimal solutions of the problem. The  
 510 next three columns report the percentage deviation from the optimal solution val-  
 511 ues obtained by Greedy, SeqVND and GVNS, respectively. The next four columns  
 512 show the corresponding running times of compared methods. Note that Greedy and  
 513 SeqVND stop naturally since they are deterministic procedures and that GVNS starts  
 514 once a solution is provided by SeqVND. Therefore, the total time GVNS spends is the  
 515 sum of SeqVND and the time provided in the GVNS column. Also note that only ten  
 516 additional seconds are allowed for GVNS.

517 The following conclusions may be drawn from Table 1. The best method is obvi-  
 518 ously the exact algorithm CPLEX. This is expected, since we intentionally propose  
 519 the basic static PAP model to be fast and “integer friendly”. The results obtained by  
 520 SeqVND local search, initialized by Greedy\_add, are very close to the optimal  
 521 ones (never larger than 0.22%), but for larger sizes this heuristic takes more time than  
 522 CPLEX. It seems that GVNS cannot easily escape from the deep local minima provided  
 523 by SeqVND. In more than 50% of the cases it was not able to improve the solution  
 524 within 10s. The solutions provided by Greedy are obtained very fast, i.e., it never  
 525 takes it more than 0.1 s. The solution quality of this algorithm depends heavily on the  
 526 instance. If there are a lot of parking slots, which never occurs in our test instances,  
 527 the solution provided by the greedy algorithm is optimal.

<sup>4</sup> The datasets are available on <https://goo.gl/H3Nu5H>.

**Table 1** Average results on ten instances for each  $n$  and  $m$ 

Parameters		Exact	% Error			Running time (s)		
$n$	$m$	CPLEX	Greedy	seqVND	GVNS	CPLEX	SeqVND	GVNS
1000	10	158,203	4.09	0.10	0.08	0.90	0.33	4.71
	20	147,250	4.43	0.16	0.14	1.21	0.55	6.43
	30	144,064	4.66	0.22	0.19	1.55	0.60	7.40
3000	10	507,136	6.28	0.08	0.08	1.98	4.41	3.13
	20	451,402	4.29	0.14	0.13	2.88	6.15	2.92
	30	432,211	4.95	0.15	0.14	4.28	8.97	4.26
5000	10	822,996	5.78	0.07	0.06	2.64	19.12	1.58
	20	728,954	3.22	0.10	0.10	4.99	29.76	2.62
	30	729,491	5.51	0.12	0.12	7.76	54.06	1.73
7000	10	1,131,207	4.94	0.22	0.22	3.62	45.75	0.85
	20	1,024,958	3.81	0.13	0.13	6.54	82.28	2.27
	30	1,005,248	4.01	0.12	0.12	8.23	133.69	0.00
9000	10	1,453,969	5.86	0.05	0.05	4.61	75.96	1.24
	20	1,329,617	4.75	0.09	0.09	9.20	120.09	0.85
	30	1,286,264	3.92	0.12	0.12	10.90	161.47	0.00

### 4.3 Infeasible small and medium size instances

We now consider instances of the same size as in the previous subsection, but allowing infeasible solutions. The vehicle number  $n$  does not exceed the total capacity of all the parking lots ( $n \leq \sum_{j=1}^m q_j$ ), but may produce an infeasible input due to current availability  $v$  per time step  $t$ . Tests are conducted on four instances for each  $n$  and  $m = 50$ . The running time of the Reduced VNS is fixed to 5 s, since in a dynamic version, the time between two runs of the static code should not be large or unpredictable. Note that RVNS does not use any local search. The neighborhood structure used for the perturbation or shaking phase is *Swap*, since *Reallocation* move has no sense in cases where there are more vehicles than parking place (see Property 5).

The results are reported in Table 2. Its second column represents the number of vehicles without a parking slot, i.e., the number of vehicles that are parked at the dummy parking. Note that, due to the Property 5, this number is equal for all tested methods. The next three columns report the objective values obtained by CPLEX, Greedy and RVNS, respectively. Columns six to eight give the corresponding computing times spent by the three methods. The last two columns, as in the previous table, provide the percentage of error for two heuristics as  $(f_{heur} - f_{exact})/f_{exact} \times 100$ .

Comparing the results with and without the dummy facility, one can conclude the following: (1) there is no significant difference in effort for obtaining the exact solution for both sets of instances; (2) as expected, RVNS performs better than Greedy for small  $n$ . For larger instances, there is not enough time to reach a higher precision.

**Table 2** Comparison of Exact, Greedy and RVNS methods on small and medium size instances with  $m = 50$  parking lots, dummy parking and different number of vehicles

$n$	# of unparked	Objective values		Running time (s)		% error			
		CPLEX	Greedy	RVNS	CPLEX	Greedy	RVNS	Greedy	RVNS
1000	3	706,592	733,584	714,842	0.58	0.02	5.00	3.82	1.17
	46	879,492	964,844	894,230	0.56	0.00	5.00	9.70	1.68
	15	743,327	800,079	759,107	0.52	0.00	5.00	7.63	2.12
	18	750,107	832,561	760,679	0.61	0.00	5.00	10.99	1.41
Average	20.50	769,879.5	832,767.0	782,214.5	0.57	0.00	5.00	8.04	1.59
3000	254	287,6571	3,138,545	2,900,863	2.19	0.02	5.00	9.11	0.84
	275	2,969,645	3,299,489	2,999,241	2.40	0.02	5.00	11.11	1.00
	64	2,230,716	2,343,062	2,253,236	1.98	0.02	5.00	5.04	1.01
	176	2,592,602	2,780,696	2,614,336	1.97	0.02	5.00	7.26	0.84
Average	192.25	2,667,383.5	2,890,448.0	2,691,919.0	2.13	0.02	5.00	8.13	0.92
5000	497	5,058,142	5,434,074	5,142,612	4.74	0.00	5.00	7.43	1.67
	564	5,312,057	5,713,841	5,410,361	4.87	0.00	5.00	7.56	1.85
	63	3,629,276	3,884,942	3,712,448	4.35	0.00	5.00	7.04	2.29
	582	5,357,472	5,862,696	5,493,064	4.61	0.02	5.00	9.43	2.53
Average	426.50	4,839,237.0	5,223,888.0	4,939,621.0	4.64	0.00	5.00	7.87	2.09
7000	757	7,279,344	7,885,014	7,505,630	7.78	0.02	5.00	8.32	3.11
	559	6,592,231	7,149,541	6,827,215	7.05	0.02	5.00	8.45	3.56
	1003	8,058,449	8,794,551	8,329,667	8.35	0.02	5.00	9.13	3.37
	773	7,518,119	8,160,985	7,793,777	7.81	0.02	5.00	8.55	3.67
Average	773.00	7,362,036.0	7,997,518.0	7,614,072.0	7.75	0.02	5.00	8.61	3.43

Table 2 continued

n	# of unparked	Objective values		Running time (s)		% error	
		CPLEX	Greedy	CPLEX	Greedy	RVNS	RVNS
9000	1549	11,283,644	12,046,312	10.32	0.03	5.00	3.05
	604	7,994,571	8,535,257	8.43	0.03	5.00	3.03
	1164	9,832,471	10,622,843	8.84	0.03	5.00	3.09
	294	7,346,493	8,177,867	14.50	0.03	5.00	6.91
Average	902.75	9,114,295.0	9,845,570.0	10.52	0.03	5.00	4.02

Uncorrected proof

**Table 3** Comparison of Exact, Greedy and RVNS methods on large size instances with  $m = 50$  parking lots, dummy parking and different number of vehicles  $n$ ; 'n/m' —no memory

$n$	# of unparked	Objective values		Running time (s)		% error			
		CPLEX	Greedy	RVNS	CPLEX	Greedy	RVNS	Greedy	RVNS
10,000	1104	10,338,915	11,212,253	10,749,531	10.67	0.03	5.00	8.45	3.97
	796	9,359,846	10,220,204	9,887,008	13.00	0.02	5.00	9.19	5.63
	313	7,868,790	8,327,986	8,176,778	12.16	0.03	5.00	5.84	3.91
	1027	10,162,548	11,060,328	10,695,966	12.48	0.03	5.00	8.83	5.25
Average	810.00	9,432,524.0	10,205,192.0	9,877,321.0	12.08	0.03	5.00	8.08	4.69
30,000	1642	25,688,032	27,225,734	27,139,640	61.82	0.08	5.00	5.99	5.65
	3	20,484,031	20,623,065	20,619,435	29.74	0.06	5.00	0.68	0.66
	1521	25,558,158	27,832,720	27,731,256	78.90	0.08	5.00	8.90	8.50
	1425	24,874,247	26,329,169	26,267,431	53.96	0.08	5.00	5.85	5.60
Average	1147.75	24,151,118.0	25,502,672.0	25,439,442.0	56.10	0.08	5.00	5.35	5.10
50,000	7569	60,307,988	66,659,792	66,421,052	252.50	0.14	5.00	10.53	10.14
	1362	38,926,503	41,748,795	41,733,403	179.12	0.11	5.00	7.25	7.21
	30	34,697,447	36,491,253	36,470,753	152.78	0.11	5.00	5.17	5.11
	2379	42,713,609	46,134,033	46,100,037	227.07	0.14	5.00	8.01	7.93
Average	2835.00	44,161,388.0	47,758,468.0	47,681,312.0	202.87	0.13	5.00	7.74	7.60
70,000	7062	n/m	7,562,6571	75,552,711	-	0.19	5.00	-	-
	6214	n/m	74,843,077	74,762,329	-	0.19	5.00	-	-
	3822	n/m	65,062,124	64,988,624	-	0.17	5.00	-	-
	6491	n/m	73,271,387	73,220,405	-	0.19	5.00	-	-

Table 3 continued

n	# of unparked	Objective values		Running time (s)		% error		
		CPLEX	Greedy	RVNS	CPLEX	Greedy	RVNS	RVNS
Average	5897.25	-	72,200,792.0	72,131,016.0	-	0.19	5.00	-
90,000	8618	n/m	97,054,560	96,997,926	-	0.25	5.00	-
	474	n/m	66,596,853	66,589,769	-	0.23	5.00	-
	9688	n/m	102,440,048	102,380,832	-	0.25	5.00	-
	1079	n/m	68,548,146	68,540,540	-	0.23	5.00	-
Average	4964.75	-	83,659,904.0	83,627,264.0	-	0.24	5.00	-

Uncorrected proof

#### 4.4 Infeasible large instances

We also compared exact and heuristic methods on instances with  $n = 10,000, 30,000, 50,000, 70,000$  and  $90,000$ , and for  $m = 50$  parking lots. Again four instances are generated for each  $n$  and  $m = 50$ . The locations of vehicles and parking lots are taken from the square  $[1000 \times 1000]$  and the location of dummy facility is set at the point with coordinates  $(1700, 1700)$ . Since the solution should be obtained within less than 5 s, among several VNS variants, we run only Reduced VNS after the Greedy initial solution (Table 3).

It appears that the time it takes to achieve the exact solution on large instances is larger than the operator (dispatcher) can wait. For the number of vehicles ranging from 10 to 50 thousand, despite the polynomial complexity of min–sum–sum PAP, the time needed is in between 10 and 250 s. Moreover, for more than 70 thousand vehicles, our PC ran out of memory (16 GB). These results confirm the necessity of a heuristic approach for solving real-life problems, even though the problem is not NP-hard. In addition, min–max–max and mix–max–sum are not polynomial problems, and heuristic approach would be even more desirable.

### 5 Conclusions

Searching for available parking lots emerges as one of the major problems in urban areas. The massive unorganized pursuit of parking spaces causes traffic congestion, financial losses, negative environmental effects, among others. Most studies on this topic base their research on simulations, due to their mostly non-deterministic input. In this paper, we have proposed a new mathematical programming model that uses arrival times to parking and destinations as input. These data can be collected by GPS devices of a set of vehicles as input. We call it the Static Parking Allocation Problem (SPAP). We showed that our min–sum–sum parking allocation model is “integer friendly” and therefore not NP-hard. However, for very large and more realistic sizes (e.g., for  $n \geq 30,000$ ), reaching the optimal solution is not decisive, either because of the time to reach it is unpredictable and too long, or due to memory overflow. Our basic model is static, but it can cover the dynamic nature of the problem by repeating its execution very often, every 5 s, for example. Therefore, it is more important to compute an approximate solution fast within a fixed time limit, rather than an exact one in unpredictable time. To guarantee that a good quality solution is obtained in each time step, we developed a VNS-based heuristic. Computational results on randomly generated test instances demonstrate that the exact solution approach is better on smaller instances, but for larger ones, the heuristic approach is more reliable because its stopping condition is the maximum execution time for the search.

Future work may follow the following directions: (i) to test our models on real parking data, including more elaborate dynamic variants; (ii) to develop a VNS heuristic and exact methods for the min–max–sum variant of PAP; (iii) to develop exact solution procedures for SPAP that would use more the problem specific knowledge and not be based on commercial solvers. In other words, trying to build a strictly polynomial exact method for SPAP, in order to reduce the time of the exact solution method.

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