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Variable neighborhood search approach to face-shield delivery during pandemic periods

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Abstract

In 2020, the COVID-19 pandemic and its rapid spread shook health authorities worldwide at the regional and national levels. Healthcare systems had difficulty acquiring important supplies, such as face shields, which at that time were essential for healthcare staff. The need for this material increased with the spread of the pandemic. In most areas, warehouses did not have a sufficient stock of this product. This situation has occurred in the cities and provinces of Burgos (Spain). Volunteers (citizens and small companies) owning three-dimensional printers offered themselves to manufacture face shields. These volunteers are called "makers." Similarly, different organizations (mainly Civil Protection) took charge of transport activities (delivery of material to the makers, collection of face shields, and delivery of the latter to hospitals and other entities). In this study, we were tasked with developing a system for planning and rationalizing these activities. The problems that were solved included a vehicle routing problem with different characteristics compared with other models in the literature. A previuous work described this problem, and the heuristic method used for the planning. However, it is necessary to develop tools that are as efficient as possible for similar situations. In this study, we propose a mathematical formulation of the problem and a method based on the metaheuristic strategies variable neighborhood search and greedy randomize adaptative search procedure on a multistart framework. Different tests with real instances used during the period in which these activities were conducted show that the new method improves the results obtained by the previous method as well as the commercial software.

Keywords: coronavirus; sanitary logistics; heuristic optimization; variable neighborhood search

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1. Introduction

1.1. Context

At the beginning of March 2020, a health crisis caused by SARS-CoV-2 occurred. Spain and Italy (where massive contagion started a few weeks before) were the most affected European countries in the first weeks of the pandemic (the highest rates of contagion, death, and ICU bed occupancy). Furthermore, the rapid spread of the virus revealed a scarcity of key supplies, such as protective equipment for healthcare staff. Specifically, face shields have become essential for healthcare workers, and the need to acquire sufficient numbers is critical for different authorities. This situation occurred in different regions of Spain, such as the city and province of Burgos, where there were no nearby factories manufacturing face shields or warehouses with sufficient stocks of the product. In this context, the Scientific Culture Unit (UCC in Spain) of the University of Burgos (UBU) initiated and coordinated an initiative to produce these shields and distribute them to healthcare centers and hospices. The UCC obligated certain manufacturers in the city and surrounding areas (i.e., individual citizens and small companies that owned three-dimensional printers) to manufacture face shields and contacted institutions, such as the Civil Protection, City Hall, and Red Cross, to collect, distribute, and store face shields. A small technology company (Abadía Tecnología) also collaborated to manufacture and store this item. This initiative by the UCC of the UBU was successful both for the manufacturers who responded to the request and for the quantities delivered. With respect to similar initiatives, the number of face shields delivered per citizen in Burgos and its province was seven times larger than in the rest of the Spanish territory as a whole (Table 1).

To improve the efficiency of this initiative, our research team developed a system for the daily planning of distribution tasks. This system determined the routes traveled by the members of the above-mentioned institutions to collect face shields at the homes of the manufacturers and deliver them to healthcare centers and hospices. Such deliveries have expanded to pharmacies and small- and medium-sized companies. Visits to manufacturers included the delivery of raw materials for the manufacture of face shields. The development of this system was quick, considering the circumstances and the critical nature of the situation. Pacheco and Laguna (2020) described the steps and schedule for developing, implementing, and using this system. The use of this system generated different advantages, such as time saved when planning, availability of detailed routing sheets and maps, consistency between the planned and real route times, shorter times in each route, and greater balance at stated times. The reduction in the time taken to calculate the routes to a few minutes allowed the routes to be initiated and thus finalized earlier. Furthermore, it allowed planning

Table 1
Comparison of face shields delivered in Spain and Burgos (city and province) from the last week of March to the first week of June 2020 (source: UCC-UBU)

	Population	Face shields delivered	Percentage of population with face shields
Spain	46,934,632	685,664	1.46
Burgos	355,420	37,311	10.50

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to include last-minute requests for face shields. In addition, the shorter times of each route and the balance between said times were advantageous; as explained below, it allowed the drivers to coordinate and perform other social tasks when the routes ended. Figure 1 shows the screenshots of different maps and routing sheets obtained by the system for the distribution of face shields in Burgos.

This system has been used in local and regional newspapers (Andrés, 2020; García, 2020). Moreover, the system was granted the “Innovation against the virus” initiative, which was promoted by the Regional Government of Castile and Leon, in the social and humanitarian modality, which was also shown in the national press (Antolín, 2020; Blanco, 2020).

This system consists of a graphic interface (for data entry, editing, and route visualization, as shown in Fig. 1) and an algorithm to obtain the optimal solutions, or at least the best possible solutions. The algorithm was developed as an adaptation of a previously developed commercial logistics algorithm that we already had. The resulting algorithm has been described in detail by Pacheco and Laguna (2020). The choice of adapting an already existing algorithm rather than developing an ad hoc algorithm was based on the need to have the system available immediately, considering the critical nature of the situation. As aforementioned, the manually obtained results improved and also delivered other advantages. However, it is important to investigate whether, with a longer time, the development of an ad hoc algorithm for this specific problem can generate better results than the algorithm used. It must be considered that similar situations could be repeated in the future. Therefore, developing more efficient tools is the main motivation for this work.

The present study proposes a new algorithm or method based on the metaheuristic strategies of variable neighborhood search (VNS) and greedy randomized adaptative search procedure (GRASP) on a multistart (MS) framework. Different tests, with real instances used during the period in which these activities were conducted, show that the new method improves the results obtained by the previous method as well as the results obtained by commercial software. In summary, the differences with the previous work (Pacheco and Laguna; 2020) are as follows:

- In Pacheco and Laguna (2020), the method described is a fast adaptation to this problem of methods for commercial logistics because of the circumstances mentioned. In the current work, without so much time pressure, an ad hoc tool is developed for this problem to obtain better solutions for possible similar situations in the future.
- Both methods are MS strategies that use the same constructive method and the same neighborhood structures. However, they have notable differences such as the improvement procedures or the organization of the neighborhood structures that turn out to be more efficient in the new method.
- In addition, the current work incorporates a problem formulation, tests to check the suitability/necessity of the different components, and tests to compare the solutions against commercial software and the previous method.

1.2. Characteristics of the problem

The aim of this study was to solve the problem of collecting face shields from the homes of manufacturers and delivering them to the centers that required them (healthcare centers, hospices,

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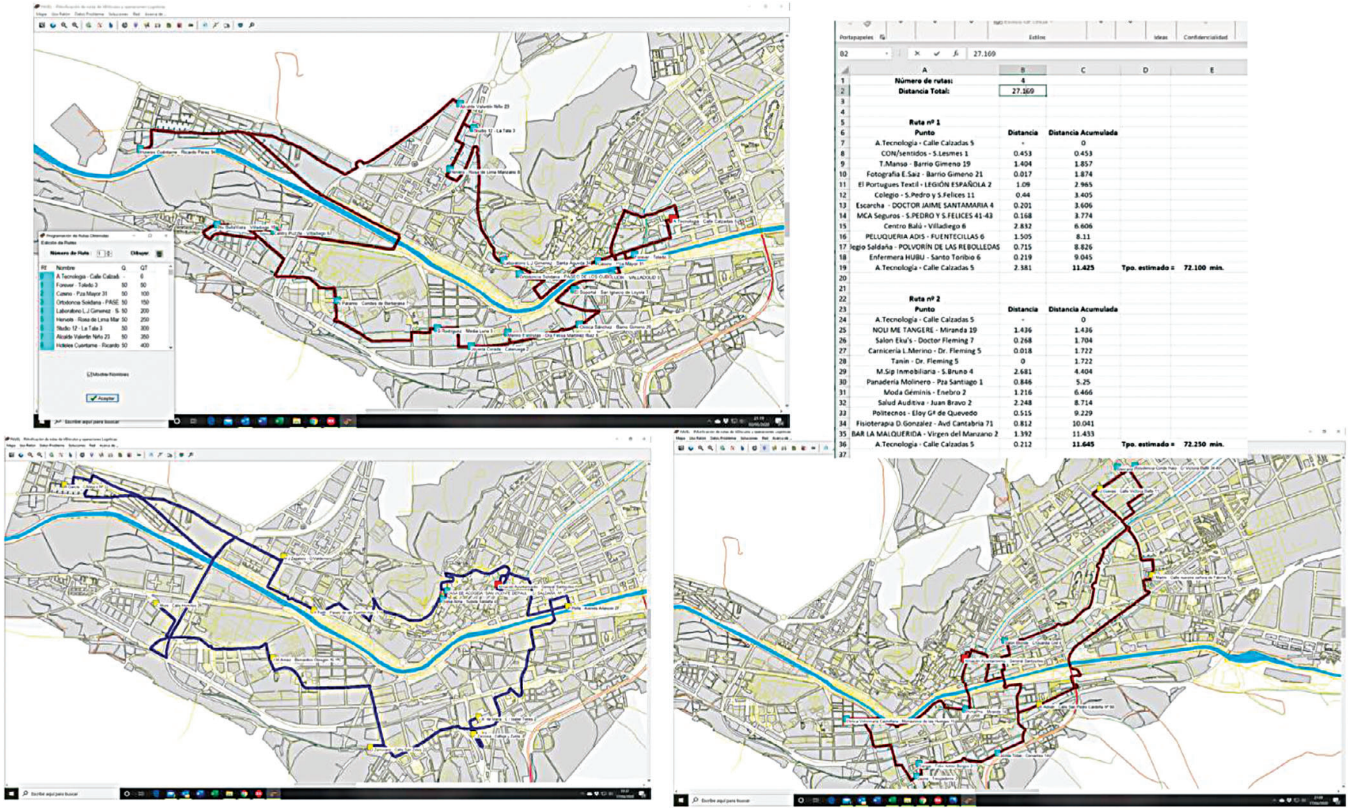

B2 27.169

	A	B	C	D	E
1	**Número de rutas:**	4			
2	**Distancia Total:**	27.169			
3					
4					
5	**Ruta nº 1**				
6	**Punto**	**Distancia**	**Distancia Acumulada**		
7	A.Tecnologia - Calle Calzadas 5	-	0		
8	CON/sentidos - S.Lesmes 1	0.453	0.453		
9	T.Manso - Barrio Gimeno 19	1.404	1.857		
10	Fotografia E.Saiz - Barrio Gimeno 21	0.017	1.874		
11	El Portugues Textil - LEGIÓN ESPAÑOLA 2	1.09	2.965		
12	Colegio - S.Pedro y S.Felices 11	0.44	3.405		
13	Escarcha - DOCTOR JAIME SANTAMARIA 4	0.201	3.606		
14	MCA Seguros - S.PEDRO Y S.FELICES 41-43	0.168	3.774		
15	Centro Balú - Villadiego 6	2.832	6.606		
16	PELUQUERIA ADIS - FUENTECILLAS 6	1.505	8.11		
17	legio Saldaña - POLVORÍN DE LAS REBOLLEDAS	0.715	8.826		
18	Enfermera HUBU - Santo Toribio 6	0.219	9.045		
19	A.Tecnologia - Calle Calzadas 5	2.381	**11.425**	**Tpo. estimado =**	**72.100 min.**
20					
21					
22	**Ruta nº 2**				
23	**Punto**	**Distancia**	**Distancia Acumulada**		
24	A.Tecnologia - Calle Calzadas 5	-	0		
25	NOLI ME TANGERE - Miranda 19	1.436	1.436		
26	Salon Eku's - Doctor Fleming 7	0.268	1.704		
27	Carniceria L.Merino - Dr. Fleming 5	0.018	1.722		
28	Tanin - Dr. Fleming 5	0	1.722		
29	M.Sip Inmobiliaria - S.Bruno 4	2.681	4.404		
30	Panaderia Molinero - Pza Santiago 1	0.846	5.25		
31	Moda Géminis - Enebro 2	1.216	6.466		
32	Salud Auditiva - Juan Bravo 2	2.248	8.714		
33	Politecnos - Eloy Gª de Quevedo	0.515	9.229		
34	Fisioterapia D.Gonzalez - Avd Cantabria 71	0.812	10.041		
35	BAR LA MALQUERIDA - Virgen del Manzano 2	1.392	11.433		
36	A.Tecnologia - Calle Calzadas 5	0.212	**11.645**	**Tpo. estimado =**	**72.250 min.**
37					

Fig. 1. Example of screenshots of maps and routing sheets obtained by our system.

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pharmacies, and small and medium companies). Thus, it is a vehicle routing problem with the following characteristics:

- More than one institution may be involved in distribution tasks. During the first few days, these tasks were conducted only through Civil Protection. Thereafter, the Red Cross and City Hall of Burgos joined, although, in the last few days, Civil Protection conducted the distribution tasks alone. For 35 days, there was only one institution involved; for 16 days, two institutions were involved, while for three days, three institutions were involved.

Therefore, the origin–destination pairs may be different for different routes. These pairs are the same for the vehicles of the same institution. However, there may be different for other institutions.

In relation to the above-mentioned factors, routes can be opened, closed, or both on the same day. For instance, the origins and destinations of Civil Protection coincided (closed routes). The same was true for the Red Cross. However, in the case of the City Hall, the starting and ending points were different (open routes). However, in the final days, the routes began in the headquarters of Civil Protection and ended in Abadía Tecnología (open routes), where the face shields were stored.

- There are no capacity restrictions because the capacity of each vehicle (van) is sufficient to carry all the face shields gathered each day.
- There are no time windows or similar constraints; collection and delivery points are available throughout the distribution period. In addition, the maximum driving time was sufficiently long.

On each route, the face-shield gathering points must be located before the delivery points. Moreover, the collected amount must be equal to or greater than the amount delivered. Spare face shields were stored at the endpoints of each route for subsequent delivery to the three largest hospitals in the city (University Hospital, Provincial Hospital, and Red Cross Hospital).

- The main target function is the minimization of the longest route's duration ("social" objective), because the drivers of each institution, in addition to distributing the face shields, perform different social tasks in collaboration with each other (transporting and assembling beds in hospices, disinfecting certain facilities, etc.). Thus, they must wait until the arrival of the last driver at their institution to begin performing the next task. Excessive time on the route for some of them would force the rest to wait. In contrast, if all drivers finish earlier, they can start the next task earlier, with all the advantages that this entails.

The use of the total distance traveled ("economic" objective) as a main target can cause an imbalance between the times of the different routes. This is evident in the real instance of April 2, 2020. With this "economic" objective, the longest route had a duration of 252 minutes, although the other three routes ended earlier (16, 17, and 107 minutes), and the drivers had to wait. Considering the "social" objective, routes of 112—115 minutes were obtained, thereby substantially reducing the waiting time. In summary, considering the "social" objective, the drivers could start the next task over two hours earlier (137 minutes) compared to when the "economic" objective was considered. Therefore, the main objective was to minimize the longest route duration, and the secondary objective was to minimize the total distance traveled.

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1.3. Contributions

This study analyzed a healthcare logistics problem based on the real problem of the daily delivery of face shields in the city and province of Burgos during the first wave of the COVID-19 pandemic. These activities were conducted between the end of March and the beginning of June 2020. Specifically, this study formulates this problem as an integer-mixed mathematical program and proposes a method based on the metaheuristic VNS strategy in an MS framework to solve this problem. The performance of this model was analyzed using 54 real instances corresponding to 54 days of face shield delivery in the city of Burgos and its surrounding areas. Computational tests showed that this new method obtained better or similar solutions than the method used to obtain the routes employed during this period (Pacheco and Laguna, 2020). It also obtained better results than two known general-purpose solvers. The tests also analyzed the need and opportunity for the different components of the method. Different results were analyzed using statistical tests. Thus, this study makes the following contributions:

- analysis of the real problem of face-shield delivery during the pandemic,
- formulation of the problem as a mixed-integer mathematical model, and
- design and development of a new solution method that improves previous models for this problem and commercial software.

The provision of 54 real instances corresponding to the daily distribution of these face shields in the city of Burgos and its surrounding areas from the end of March to the beginning of June 2020.

The remainder of the paper is organized as follows: Section 2 is devoted to a literature review. Section 3 defines the notation used and proposes the mathematical scheduling model. Section 4 describes the new MS-VNS model and its components. Section 5 presents different computational tests to analyze the performance of this new method. Finally, Section 6 presents the conclusions.

2. Literature review

2.1. State of the art of real-life health logistics problems during the COVID-19 pandemic

In addition to the previously mentioned work of Pacheco and Laguna (2020), with the appearance of the COVID-19 pandemic, other real transportation, logistics, and distribution problems have emerged, owing to the limitation of resources and unusual time pressure. Singgih (2020) considered the problem of deploying mobile laboratories that could conduct tests to address over-demand in Indonesia during the pandemic. Zhang et al. (2020) studied the problem of transporting high-risk individuals for medical isolation in epidemic areas of China, where the number of available quarantine vehicles was limited. Guevara and Peñas (2020) considered the problem of healthcare route planning for people infected with the virus to reduce its spread and the number of people infected. Gao et al. (2020) addressed a distribution problem with unmanned vehicles. Chen et al. (2020) analyzed the contactless distribution of food. Majzoubi et al. (2021) approached the problem of patient transportation. Breitbarth et al. (2021) addressed the problem of distributing healthcare materials to the homes of vulnerable people. Tsai et al. (2021) also addressed the problem of

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evacuation during emergencies. Chen et al. (2021) analyzed the use of drones in last-mile delivery. Zhao et al. (2022) addressed a similar problem using a bi-objective approach. Jiang et al. (2021) addressed the problem of fresh food distribution. Similarly, Wang et al. (2021) explored a case of interregional and intraregional emergency distribution with traffic restrictions. Tlili et al. (2022) considered the problem of managing sample collection from patients at home. Yang et al. (2022) aimed to minimize the total cost of pharmaceutical cold chain distribution. Finally, Contardo and Costa (2022) addressed the problem of the distribution of rooms (in this case, dining rooms) to optimize their use. Shen et al. (2022) reviewed healthcare logistics problems during the pandemic.

Focusing on Spanish populations and regions, there are some interesting works on the use of healthcare logistics models during the COVID-19 pandemic. Quintanilla García et al. (2021) describe a system for the distribution of medical products using drones in Valencia. Tordecilla et al. (2021) analyze the distribution of hospital supplies in Barcelona. Finally, the work of Garcia-Vicuña et al. (2022) focuses on forecasting and provisioning hospital beds in cities in the regions of La Rioja and Navarra.

2.2. *State of the art of VNS in healthcare resource logistics and management*

The VNS is a metaheuristic method used to solve combinatory and global optimization problems. Its key idea is the systematic change of neighborhoods within the local search (Mladenović and Hansen, 1997). Metaheuristic methods based on the VNS have been successfully applied to various problems and applications in healthcare resource management. Many of these contributions relate to staff schedule planning. Gomes et al. (2017), Rahimian et al. (2017), and Zheng et al. (2017) have used this strategy to solve nurse rostering problems. Recently, Lan et al. (2022) solved the physician planning and scheduling problem.

Regarding the problems of patient transportation and home healthcare planning, it is important to highlight the works of Frifita et al. (2017) and Detti et al. (2017). In the former, a VNS was used to optimize the allocation of visits to home caregivers as well as to sequence the execution of such visits. In the latter, a VNS was used to solve the real problem of nonurgent patient transportation in an Italian region, considering heterogeneous vehicles, restrictions of vehicle–patient compatibility, service quality requirements, patient preferences, and fees as a function of the vehicles on hold.

With respect to the recycling of medical waste, Zhang et al. (2022) analyzed the routing problem of medical waste vehicles with time windows to reduce risk and carbon emissions during transportation.

In a different study, Dellaert and Jeunet (2017) addressed the problem of planning surgical operations. Specifically, they developed a medium-term patient admission plan. They aimed to balance the use of resources, such as operating rooms, beds, and nursing wards. Lan et al. (2021) reviewed the main works, focusing on the applications of the metaheuristic strategy of VNS in the scope of healthcare.

Finally, with regard to works specifically related to the COVID-19 pandemic, Goodarzian et al. (2021) used VNS to solve a drug distribution problem, considering the drug production and delivery periods as a function of their perishable nature. Dai et al. (2022) proposed a planning model to guarantee that surgical operations could be performed safely during a pandemic.

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3. Notation and formulation

To formalize the problem and solution approaches, we define the following terms:

s Number of institutions
m_l : Number of vehicles used by lth the institution, $l \in \{1, 2, \ldots, s\}$
P : Set of n_1 pickup points such that $P = \{1, 2, \ldots, n_1\}$
Q : Set of n_2 delivery points such that $Q = \{n_1 + 1, n_1 + 2, \ldots, n_t\}$ and $n_t = n_1 + n_2$
O : Set of origins such that $O = \{n_t + 1, n_t + 2, \ldots, n_t + s\}$
E : Set of endpoints such that $E = \{n_t + s + 1, n_t + s + 2, \ldots, n_t + 2s\}$

That is, $nt + l$ is the starting point of the routes of institution l, and $n_t + s + l$ is their ending point.

t_{ij} : Travel time between i and j, $\forall i, j \in V$ where $V = P \cup Q \cup O \cup E$. These times already include the stop/service times at point i (if $i \in P \cup Q$).
d_{ij} : Distance between i and j $\forall i, j \in V$
p_i : Quantity picked at point $i \in P$
q_i : Quantity delivered at point $i \in Q$

The problem is formulated as follows:

$$\min \qquad Tmax \tag{1}$$

$$\min \qquad \sum_{i \in O \cup P \cup Q} \sum_{\substack{j \in P \cup Q \cup E \\ j \neq i}} \mathrm{d}_{ij} x_{ij}, \tag{2}$$

subject to

$$\sum_{j \in P \cup Q \cup E} x_{ij} \leq m_l \qquad \begin{array}{c} \forall i \in O \\ l = i - nt\text{'} \end{array} \tag{3}$$

$$\sum_{j \in O \cup P \cup Q} x_{ji'} = \sum_{j \in P \cup Q \cup E} x_{ij} \qquad \begin{array}{c} \forall l \in \{1, 2, \ldots, s\} \\ i = n_t + l \\ i' = n_t + s + l \end{array}, \tag{4}$$

$$\sum_{\substack{j \in P \cup Q \cup E \\ j \neq i}} x_{ij} = 1 \qquad \forall\, i \in P \cup Q, \tag{5}$$

$$\sum_{\substack{j \in O \cup P \cup Q \\ j \neq i}} x_{ji} = 1 \qquad \forall\, i \in P \cup Q, \tag{6}$$

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$$\sum_{l=1}^{s} h_{il} = 1 \qquad \forall\, i \in P \cup Q, \tag{7}$$

$$h_{il} \geq x_{ji} \qquad \begin{array}{c} \forall\, i \in P \cup Q \\ \forall j \in O;\ l = j - nt, \end{array} \tag{8}$$

$$h_{il} \geq x_{ij} \qquad \begin{array}{c} \forall\, i \in P \cup Q \\ \forall j \in E;\ l = j - nt - s, \end{array} \tag{9}$$

$$h_{jl} \geq x_{ij} + h_{il} - 1 \qquad \forall\, i, j \in P \cup Q;\ j \neq i, \tag{10}$$

$$u_j \geq u_i + t_{ij} - \left(1 - x_{ij}\right) \cdot (BigT) \qquad \begin{array}{c} \forall\, i \in O \cup P \cup Q \\ \forall\, j \in P \cup Q \cup E;\ j \neq i, \end{array} \tag{11}$$

$$Tmax \geq u_i \qquad \forall i \in E, \tag{12}$$

$$u_j \geq u_i + BigT - \left(1 - x_{ij}\right) \cdot (2 \cdot BigT) \qquad \forall i \in Q; \forall j \in P, \tag{13}$$

$$w_i \leq 0 \qquad \forall\, i \in O, \tag{14}$$

$$w_j \leq w_i + p_j + \left(1 - x_{ij}\right) \cdot (BigQ) \qquad \forall\, i \in O \cup P \cup Q;\ \forall\, j \in P;\ j \neq i, \tag{15}$$

$$w_j \leq w_i - q_j + \left(1 - x_{ij}\right) \cdot (BigQ) \qquad \forall\, i \in O \cup P \cup Q;\ \forall\, j \in Q;\ j \neq i, \tag{16}$$

$$x_{ij} \in \{0, 1\} \qquad \begin{array}{c} \forall\, i \in O \cup P \cup Q \\ \forall\, j \in P \cup Q \cup E;\ j \neq i, \end{array}$$

$$h_{il} \in R^+ \qquad \begin{array}{c} \forall\, i \in P \cup Q; \\ \forall l \in \{1, 2, \ldots, s\}, \end{array}$$

$$u_i \in R^+ \qquad \forall\, i \in V,$$

$$w_i \in R^+ \qquad \forall\, i \in O \cup P \cup Q$$

$$Tmax \in R^+.$$

The variable x_{ij} has a value of one if arc (i, j) is used; otherwise, its value is zero. The variable h_{il} has a value of 1 if point i is visited by a vehicle of institution l. Variable u_i indicates the time of arrival at each point i. Variable w_i indicates the remaining load in each vehicle after visiting point i. Finally, variable $Tmax$ is the longest duration among all routes.

Expressions (1) and (2) correspond to the "social objective" (minimizing the duration of the longest route) and "economic objective" (minimizing the total distance traveled), respectively. Restriction (3) ensures that for each institution, all available vehicles belonging to the institution are used. Restriction (4) ensures that for each institution, the number of vehicles leaving the starting point of the institution is equal to the number of vehicles arriving at the destination. Restrictions (5) and (6) ensure that each collection and delivery point is visited only once. Restrictions (7)–(10)

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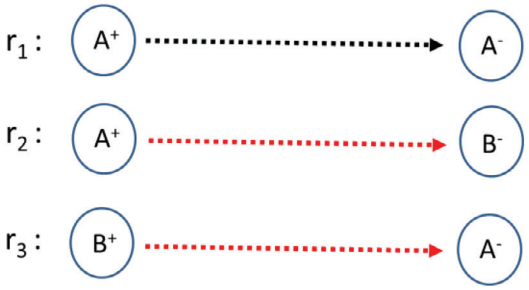

Fig. 2. “Cross” situation in routes r_2 and r_3 in red.

prevent the starting and ending points of different institutions from “cross”; specifically, they ensure that the starting and ending points of a single route are not from different institutions. This “cross” situation is depicted in Fig. 2.

Figure 2 shows examples of these two institutions. The first institution has two vehicles and the start-end pair (A^+, A^-), and the second institution has one vehicle and the start-end pair (B^+, B^-). As can be observed, the start-end pairs have “crossed” in routes r_2 and r_3. To prevent this, restrictions (7)–(10) are used. Restriction (7) ensures that each visit point is covered by a single institution. Restrictions (8) and (9) ensure that if a particular point is the first or last (respectively) visiting point of a route, it is served by an institution that corresponds to the starting or ending point of the route, respectively. Restriction (10) ensures that two consecutive visiting points along a route are served by the same institution. Moreover, restrictions (7)–(10) allow for the linearizing of variables h_{il}. Restriction (11) prevents cycles and helps to determine the value of variable u_i. Restriction (12), along with the minimization of function (1), ensures that $Tmax$ is the duration of the longest route. Restriction (13) ensures that collection points arrive before delivery points. Restrictions (14)–(16) determine the value of the variable w_i and ensure that after each visit, the balance between the number of face shields collected and delivered is positive.

4. Description of an MS-VNS method

To describe the model, we use S to represent a generic solution. Each solution S is a set of nr routes, where nr is the total number of routes; that is, $nr = \sum_{l=1}^{s} m_l$. Each route is represented as an ordered sequence of points, where the first and last points correspond to the start and end points, respectively.

For solution S, $f_1(S)$ represents the first target function (which corresponds to expression (1) of the problem formulation) and $f_2(S)$ represents the second target function (which corresponds to Equation (2)). In this problem, the first target prefers the second. Therefore, considering the two solutions S_1 and S_2, S_1 is better than S_2 if one of these two conditions occurs:

(a) $f_1(S_1) < f_1(S_2)$;
(b) $f_1(S_1) = f_1(S_2)\,\text{and}\,f_2(S_1) < f_2(S_2)$.

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Pseudocode 1. *MultiStarVNS* method.

```
Method $MultiStarVNS$(var $S_{best}$)
$iterms = 0$, $iterbestms = 0$, $S_{best} = \emptyset$
Repeat
    $iterms = iterms + 1$
    $S = Constructive(\alpha)$;
    $S = VNS(S)$
    If$S$ improves $S_{best}$ then: $S_{best} = S$, $iterbestms = iterms$
until$iterms > iterbestms + maxiterms$
```

Pseudocode 2. Procedure *Constructive*.

```
Procedure $Constructive(\alpha)$
1. Initialize $S$, $f_1(S)$ and $f_2(S)$
2. $Sel = P \cup Q$
While$Sel \neq \emptyset$ do
    begin
    3. Build $L$ the set of feasible insertions of points in $Sel$ into $S$
    4. From $L$ extract $CL$ the subset of insertions in $L$ which, if executed, would not increase the value of $f_1(S)$
    5. If$CL = \emptyset$ then$CL = L$
    6. From $CL$ extract $RCL$ the subset of the insertions that differ less than $\alpha\%$ from the best insertion (considering the increase in the duration of the corresponding route)
    7. Randomly select an insertion from $RCL$
    8. Execute the selected insertion
    9. Update $Sel$, $S$, $f_1(S)$ and $f_2(S)$
    end
```

In all operations of the different procedures that comprise the method, the following aspects must be considered to guarantee feasible solutions: all points must be visited; each point must only be visited by one vehicle/route; for each route, the collection points P must precede the delivery points Q, and the amounts collected must be greater than or equal to the amounts delivered.

As previously commented, we propose a method (named *MultiStarVNS*) that combines the VNS and GRASP (Feo and Resende, 1995) strategies on an MS framework (Martí, 2003). In each iteration, this method generates a different solution, which is subsequently improved using a procedure based on the VNS. This process ends when the stopping criterion is satisfied. Pseudocode 1 illustrates the process.

In each iteration, solution S is created using the procedure *Constructive*, and is subsequently improved by the VNS procedure. For variable S_{best}, the best solution (i.e., the output of the method) is saved. Variable *iterms* is the iteration counter, and variable *iterbestms* indicates the iteration with the best solution. The method terminates when *maxiterms* iterations occur without improving S_{best}. Subsequently, we present the two procedures that comprise our *MultiStarVNS* method: *Constructive* and *VNS*.

The construction procedure *Constructive* proposed in Pacheco and Laguna (2020) is briefly described below (Pseudocode 2).

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Pseudocode 3. Procedure VNS.

```
Procedure $VNS$(var $S$)
1. $S = VND(S)$
2. Do: $iter = 0$; $iterbest = 0$
Repeat
  3. $iter = iter + 1$
  4. $k = 0$
  Repeat
    5. $k = k + 1$
    6. $S_1 = Shaking(k, S)$
    7. $S_1 = VND(S_1)$
    8. If $S_1$ is better than $S$, then: $S = S_1$, $iterbest = iter$, $k = 0$;
  until$k = nr$
until$iter > iterbest + maxiter$
```

As indicated in Section 3, P and Q are the sets of pickup points and delivery points, respectively. To initialize solution S, routes nr were created with only the corresponding starting and ending points for each route. The distance and time for each route were initialized. The values of $f_1(S)$ and $f_2(S)$ were obtained from the distances and times of the routes. One insertion was performed in each iteration. Specifically, all possible insertions (routes and positions) of Sel (the set of non-inserted points in the subsequent steps) were analyzed. In particular, set L of feasible insertions is constructed and the CL of the solutions that do not increase the value of $f_1(S)$ is extracted. If $CL = \emptyset$, it is redefined as $CL = L$. From CL, set RCL of the insertions that differ by less than $\alpha\%$ from the best insertion is obtained, considering the time increase. From this set RCL, an insertion is randomly selected and executed. Parameter α measures the degree of avidity-randomness of the process: If $\alpha = 0$, then RCL only includes the best insertion; if $\alpha = 1$, then $RCL = CL$. This way of constructing solutions (the use of a list with the best RCL insertions and the random choice of one of them) is based on the GRASP strategy.

The VNS follows the general VNS strategy. Pseudocode 3 describes the procedure.

An initial solution is read and then improved using an improvement procedure called VND (variable neighborhood descent). Subsequently, in each step, a solution S_1 is obtained by "shaking" the current solution S (i.e., changing some elements of S). Solution S_1 is improved by the VND procedure. The "shaking" is performed with the *Shaking* procedure, which depends on parameter k: small values correspond to small shakings (the obtained solution S_1 is similar to S), and high values correspond to large shakings (S_1 is different from S). Each iteration begins with $k = 1$ and increases in the following steps. If the obtained solution S_1 improves S, then S is replaced with S_1, and $k = 1$. The iteration ends when k reaches the value of nr. The procedure ends when $maxiter$ consecutive iterations elapse without improving S.

Subsequently, we explain the improvement of the VND procedure and the *Shaking* procedure. The VND procedure is a neighborhood search method that improves the starting solution S_x. For this solution, a set of neighborhoods $N_j(S_x)$, $j = 1..jmax$ is defined, which is consecutively explored until a solution S' that improves S_x is obtained. In this case, S_x is replaced with S' and the process is restarted. The procedure ends when no solution improves S_x in any neighborhood. Pseudocode 4 describes the procedure.

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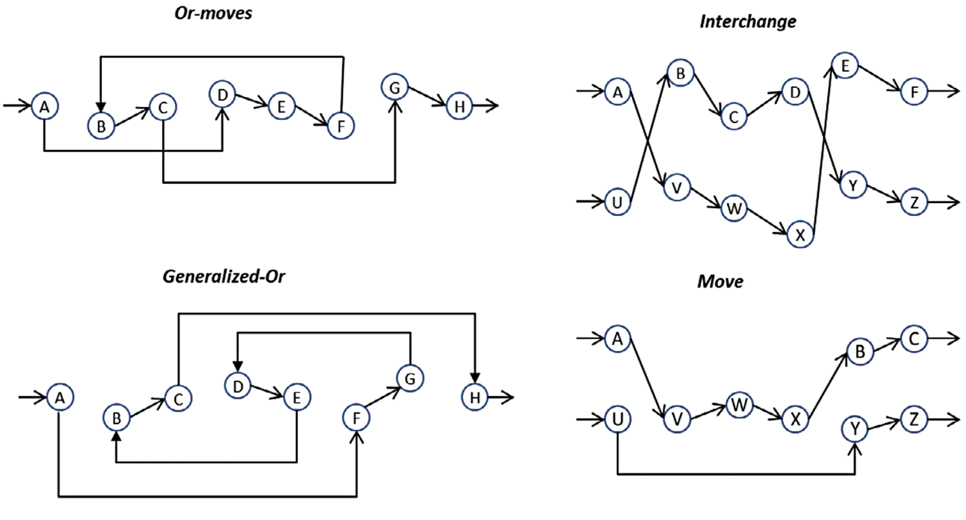
Pseudocode 4. . Procedure VND.

```
Procedure $VND$(var $S_x$)
1. $j = 0$
Repeat
    2. $j = j + 1$
    3. Determine if $S'$ is the best solution of $N_j(S_x)$
    4. If $S'$ is better than $S_x$, then: $S_x = S'$ and $j = 0$
until $j = jmax$
```


Or-moves

Interchange

Generalized-Or

Move

Fig. 3. Neighborhood movements used.

Neighborhoods consist of feasible solutions that are reached through different movements or changes made to the current solution. Different neighborhoods $N_j(S_x)$, $j = 1..jmax$ use four types of movements: *Or-moves*, *Generalized-Or*, *Interchange*, and *Move*. The *Or-moves* movements consist of exchanging two consecutive chains of points of the same route, the *Generalized-Or* movements consist of exchanging two nonconsecutive chains, the *Interchange* movements consist of exchanging two different route chains, and the *Move* movements consist of moving a chain from one route to another. These movements have demonstrated good performances in studies with similar objectives (Pacheco et al., 2013; Pacheco and Laguna, 2020). Figure 3 shows the four types of movements. Thus, in the example of *Or-moves* movements, chains B–C and D–E–F are exchanged; in the example of *Generalized-Or*, chains B–C and F–G are exchanged, with chain D–E remaining between them; in the example of *Interchange*, routes B–C–D and V–W–X are exchanged between the routes that include them; finally, in the example of *Move*, chain V–W–X changes the route.

Specifically, $N_j(S_x)$ represents the set of solutions reached from S_x with the previous movements, where the maximum size of the chains involved is j. Thus, in the example of *OR-moves*, the chains involved are B–C (size 2) and D–E–F (size 3). Therefore, the solution reached belongs to $N_3(S_x)$. Similarly, the solution that would be reached with the example of *Generalized-Or* belongs to $N_2(S_x)$

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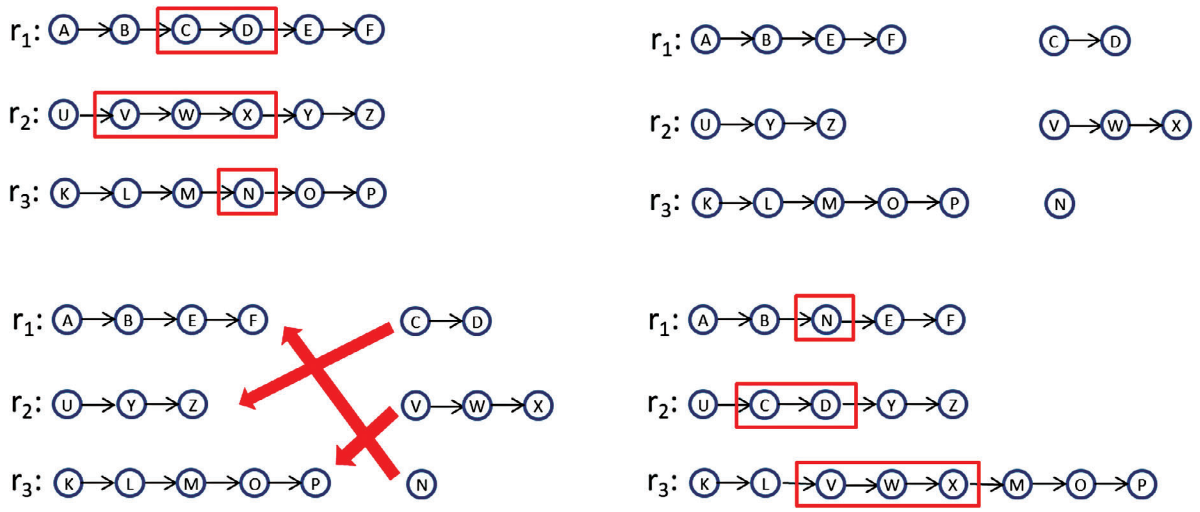

Fig. 4. Example of “shaking” with $k = 3$.

(the three chains involved are of size 2), and the solutions that correspond to the examples of *Interchange* and *Move* belong to $N_3(S_x)$. The value of *jmax* is considered as sufficiently large as to ensure that all changes of the previous types are verified ($jmax = nt - 1$). This way of structuring the neighborhoods has been chosen because it has been observed that with chains of size one, that is, N_1, significant improvements are achieved and also the cardinal of N_1 is smaller than that of N_2. In turn, the cardinal of N_2 is smaller than that of N_3. Significantly, we have observed a notable difference between the checking time of N_1 versus that of N_2. Therefore, within the *VND* procedure: first N_1 is checked, and if there is no improvement then N_2 is checked, etc.

The *Shaking*(k) typically consists of randomly choosing k routes $r_1, r_2, \ldots, r_k$, (the order is also random), selecting one chain from each of the chosen routes (also randomly) and exchanging the selected chains in the following manner: the chain of route r_1 is inserted in route r_2, the chain of route r_2 is inserted in route r_3, etc.; finally, the chain of route r_k is inserted in route r_1. Figure 4 graphically illustrates this process for $k = 3$.

In the example in Fig. 4, three routes (r_1, r_2, and r_3) are randomly selected; from route $r_1$chain C–D is extracted, from route r_2 chain V–W–X is extracted and from route r_3 chain N is extracted. These three chains were randomly selected. Chains C–D are inserted in route r_2, chains V–W–X are inserted in route r_3, and chain N is inserted in route r_1. The following observations were made:

The chains are randomly placed between positions that lead to feasible routes with respect to precedence restrictions (i.e., the collection points precede the delivery points). These feasible positions depend on whether the chain to be relocated only has (a) collection points, (b) delivery points, or (c) both. In the first case, the chain can be inserted from after the starting point to after the last collection point of the destination route. In the second case, it can be inserted from after the last collection point of the destination route to immediately before the ending point. In the third case, it can only be placed immediately after the last collection point of the destination route. Figure 3 shows three possible situations in the relocation of chains V–W–X in route r_3.

As shown in Fig. 5, in route r_3, K is the starting point, P is the ending point, L (light blue)

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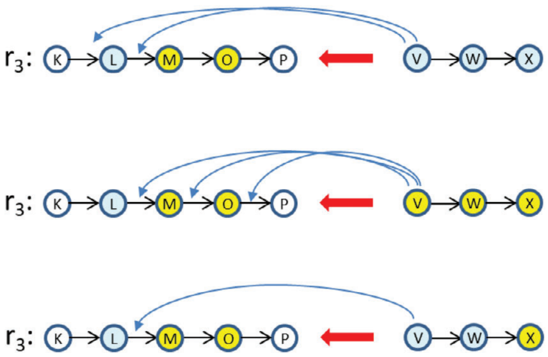

Fig. 5. Example of feasible relocations.

is the collection point, and M and O (yellow) are the delivery points. In the first case, the three points of chains V–W–X are collection points; therefore, they can be relocated after K or L. Other relocations (after M or O) would be infeasible with respect to the precedence restrictions (collection before delivery). In the second case, the three points of chain V–W–X are delivery points; therefore, they can be relocated after L, M, or O. Finally, in the last case, V and W are collection points, and X is a delivery point; thus, chain V–W–X can only be relocated after L.

This process could generate infeasible routes with respect to restrictions that require the number of face shields collected in each route to be equal to or greater than the amount delivered. To restore the feasibility, an iterative process of 0 – 1 exchanges (changing a point from one route to another) and 1 – 1 exchanges (exchanging two points on two different routes) is performed. In each step, the best exchange is searched and executed (in this case, the one that reduces infeasibility). The process ends when feasibility is recovered and is measured as follows: for each $r = 1, \ldots, nr$, $SumP(r)$ and $SumQ(r)$ are defined as the sums of the amounts collected and delivered, respectively. The infeasibility was measured using the following equation:

$$Infeasib = \sum_{r=1}^{nr} \max\left(0, SumQ\left(r\right) - SumP\left(r\right)\right).$$

The exchange that mostly reduces this infeasibility is immediately determined, and the points or points involved are inserted in the position that least increases the duration of the route from among all the feasible positions with respect to the precedence restrictions (i.e., collections before deliveries).

- Finally, it is important to demonstrate that when $k = 1$, the *Shaking* procedure consists of relocating a chain of one route to another feasible position of the same route. Pseudocode 5 describes the procedure.

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Pseudocode 5. Procedure *Shaking.*

```
Procedure Shaking($k$, $S$, var $S_1$)
1. Copy $S$ in $S_1$
2. Randomly select k indices $r_1, r_2, \ldots, r_k \in \{1, \ldots, nr\}$
3. $\forall l = 1..k$: Randomly select a chain $Ch_l$ of route $r_l$ and extract it from said route
4. $\forall l = 1..k$-1: Randomly insert $Ch_l$ in a feasible position of route $r_{l+1}$
     Randomly insert $Ch_k$ in a feasible position of route $r_1$
While $Infeasib > 0$ do
  begin
  5. Analyze all the 0 – 1 and 1 – 1 exchanges and determine which reduces $Infeasib$ the most
  6. Execute said exchange inserting the points involved in the best feasible positions
End
```

5. Computational tests

This section describes the computational tests used to evaluate the performance of the $MultiStarVNS$ method. Subsection 5.1 describes the real instances that were used to conduct these tests in the following subsections. Subsection 5.2 analyzes the fit of the parameters of this method. Subsection 5.3 explores the need for the different components of the method. Subsection 5.4 compares the results of our method with those of previous methods and commercial software. All methods, procedures, and variants were implemented using the Object-Pascal programming language and Rad Studio development framework (v10 and v11). All the tests were performed on a computer with an i9-10920X processing unit and 128 GB of RAM.

5.1. Real instances

The instances used in this section are the real instances of daily planning performed by the system described by Pacheco and Laguna (2020) from the end of March to the beginning of June 2020. This subsection presents the instances recorded from March 30 to June 8, 2020. It is important to highlight that face-shielded delivery activities began a few days earlier. In the first week, they were delivered daily (including weekends). Later, they were delivered only on weekdays. In total, 54 instances were recorded. Table 2 lists the data for these instances: the number of collection points (n_1), the number of delivery points (n_2), the number of institutions involved in the delivery (s), the number of routes involved in the delivery (m_1 and, if applicable, m_2 and m_3), the total number of face shields collected ($TotP$), and the total number of face shields delivered ($TotQ$).

As shown in Table 2, these activities were more intense in the first week, both in the number of points visited and face shields collected/delivered. Subsequently, the numbers progressively decreased. Files with these instances and a description of their formats are available at www.ubu.es/metaheuristicos-grinubumet/ejemplos-y-datos-de-problemas.

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Table 2
Description of the real instances used.

#	n_1	n_2	s	m_1	m_2	m_3	$TotP$	$Totq$
1	13	44	1	4			1775	1318
2	12	31	1	4			1350	963
3	12	41	1	4			1650	1223
4	16	18	1	4			975	467
5	11	38	1	4			1550	1104
6	16	42	1	4			2475	1309
7	10	35	1	4			1325	1105
8	15	39	1	4			2100	1202
9	15	49	1	4			1800	1454
10	14	36	1	4			1900	1087
11	14	46	1	4			1750	1286
12	13	33	1	4			1600	1031
13	13	43	1	4			750	436
14	18	47	1	4			1175	496
15	12	39	1	4			625	377
16	17	44	2	4	2		1125	428
17	8	27	2	4	2		625	286
18	12	29	2	4	2		750	297
19	8	25	2	4	2		525	269
20	11	28	2	4	2		650	276
21	10	35	2	4	2		600	346
22	10	26	2	3	2		475	262
23	10	32	2	3	2		475	306
24	10	24	2	3	2		725	206
25	9	31	2	3	2		600	324
26	13	32	2	3	2		825	342
27	8	29	2	3	2		425	264
28	12	31	3	3	1	1	775	288
29	8	27	3	3	1	1	425	274
30	11	29	3	3	1	1	550	269
31	8	28	2	3	1		450	306
32	8	20	2	3	1		550	209
33	8	26	2	3	1		525	270
34	7	18	2	3	1		500	186
35	7	24	1	3			375	248
36	6	17	1	3			375	184
37	7	22	1	3			550	232
38	9	25	1	3			600	267
39	6	20	1	3			350	191
40	9	23	1	3			525	249
41	5	19	1	3			325	191
42	8	21	1	3			350	195
43	8	27	1	3			500	253
44	7	20	1	3			350	221
45	5	18	1	3			300	160

Continued

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Table 2
(Continued)

#	n_1	n_2	s	m_1	m_2	m_3	$TotP$	$Totq$
46	4	10	1	3			225	108
47	5	15	1	2			275	136
48	7	19	1	2			450	199
49	4	14	1	2			250	133
50	6	17	1	2			350	183
51	3	12	1	2			200	123
52	6	15	1	2			375	138
53	3	10	1	2			225	107
54	5	14	1	2			350	148

5.2. Parameter Fine-tuning

As can be observed, the $MultiStarVNS$ method contains three parameters: *maxiterms* (from the main method), α (from the *Constructive* procedure), and $maxiter$ (from the VNS procedure). To determine the most suitable combination of their values, six instances were selected: two from the first days, with the largest number of points visited (instances 01 and 09); two instances from the intermediate days, where more than one institution intervened in the distribution tasks (instance 23, with two institutions; and 29, with three institutions); and finally two instances from the final days, with the smallest number of points visited (instances 51 and 53). Moreover, the $maxiter$ and *maxiterms* were established as stopping criteria. Thus, we initially set their values at $maxiter = 20$ and *maxiterms* $= 10$, and then analyzed the values of α. Specifically, we considered values that corresponded to totally random or quasi-totally random constructions ($\alpha = 0, 0.1$), quasi-deterministic constructions ($\alpha = 0.9, 0.99$), and intermediate values ($\alpha = 0.5$). The tests show that the best results were obtained with $\alpha = 0.99$. With this value of α, the values of $maxiter$ and *maxiterms* were analyzed. The tests indicated that, with values above $maxiter = 50$ and *maxiterms* $= 10$, there were barely any improvements. Furthermore, these parameters allow for quick solutions to be obtained.

5.3. Analysis of the components of the $MultiStarVNS$ method

This subsection explores the effects of the strategies used and the components of the $MultiStarVNS$ method. Specifically, we analyzed the effects of using the MS strategy and of the VND and *Shaking* procedures. The aim was to determine whether the use of this strategy and these procedures favored the results obtained. To this end, we considered three variants of our $MultiStarVNS$ in which we discarded this strategy and its components. Next, we will describe the variants.

- *Variant* 1 ("Nonmultistart"): In this variant, we discarded the MS strategy, that is, we only used the constructive method once (in this case, with $\alpha = 1$) to generate the initial solution. Specifically,

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the method consisted of only one iteration of the sequence $Constructive + VNS$. The VNS procedure ends when the stopping criterion is reached.

- *Variant* 2 ("Nonshaking"): In this variant, we discarded the *Shaking* procedure. In particular, this variant involves repeating the sequence $Constructive + VND$ until a stopping criterion is reached.
- *Variant* 3 ("Non-VND"): In this variant, we discarded the VND procedure. To this end, Step 7 of the VNS procedure was removed (Pseudocode 3).

Once these variants were implemented, the tests were designed as follows. For each instance, we first executed our $MultiStarVNS$ method and recorded the computation time used. Subsequently, the three variants described were executed, considering the computation time used by $MultiStarVNS$ as the stopping criterion. Table 3 presents the obtained results, showing the values of the two target functions (f_1 in minutes and f_2 in kilometers) for the obtained solution. Table 3 shows the computation time (C.T.) (in seconds) used by $MultiStarVNS$. The best solutions are indicated in bold.

From Table 3, the following conclusions can be drawn:

Our $MultiStarVNS$ method obtained the best solution for all instances. Moreover, the calculation time was reasonable, as it never exceeded one minute (the longest execution time was 58 seconds). This was advisable, considering the need to rapidly obtain good planning.

- *Variant* 1 obtained the best solution (matching $MultiStarVNS$) in 43 of the 54 instances. Moreover, in the 11 instances where worse results were obtained, the values of both functions were similar to those of $MultiStarVNS$. Therefore, the effect of using an MS strategy did not worsen the results and slightly improved the results in some cases.
- *Variant* 2 obtained the best solution in 12 of 54 instances. In some instances, the differences in the values of $MultiStarVNS$ were noticeable. Thus, the effect of using the *Shaking* procedure was highly positive.
- *Variant* 3 did not yield the best solution in any instance. Moreover, the results obtained were significantly different from many of the best results for each instance. The results are relatively close to the best results for some small instances. Therefore, the use of the VND procedure or a similar local search procedure is essential for obtaining quality solutions.

Employing the MS strategy and especially the use of the *Shaking* and VND procedures had a positive effect on the $MultiStarVNS$ method and seemed to be necessary to obtain quality solutions. For a clearer and more concise view of the results in Table 3, Fig. 6 is added. This chart shows the mean percentage deviations of the solutions obtained by each of the three variants with respect to $MultiStarVNS$. The left shows the gaps with respect to f_1 and the right with respect to f_2.

5.4. *VNS compared to previous methods and commercial software*

This subsection compares the performance of the proposed $MultiStarVNS$ method with that of the method proposed by Pacheco and Laguna (2020). As was previously commented, this method was designed "round the clock," adapting a previous method for commercial logistics problems. This method (*MSTabu*) uses a tabu search procedure in an MS framework and is the basis

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Table 3
Results of *MultiStarVNS* and its variants

#	*MultiStarVNS*			*Variant* 1		*Variant* 2		*Variant* 3	
	f_1	f_2	*C.T.*	f_1	f_2	f_1	f_2	f_1	f_2
1	**162.298**	**225.357**	*31.806*	**162.298**	**225.357**	162.298	228.129	206.120	282.511
2	**79.614**	**66.072**	*7.792*	**79.614**	**66.072**	84.972	80.512	90.552	89.011
3	**93.749**	**68.716**	*17.796*	**93.749**	**68.716**	94.269	72.386	98.494	82.809
4	**110.982**	**159.904**	*5.081*	110.982	161.821	110.982	161.821	142.814	229.747
5	**93.242**	**81.227**	*12.064*	93.437	83.727	96.504	90.045	103.565	107.428
6	**109.274**	**91.847**	*25.821*	**109.274**	**91.847**	**109.274**	**91.847**	118.001	116.205
7	**86.637**	**80.370**	*8.305*	**86.637**	**80.370**	87.245	82.386	97.424	104.974
8	**94.598**	**68.673**	*19.122*	**94.598**	**68.673**	94.801	69.681	101.408	85.227
9	**123.320**	**115.007**	*42.454*	**123.320**	**115.007**	124.200	116.386	135.294	143.956
10	**102.648**	**104.268**	*13.209*	**102.648**	**104.268**	103.195	105.058	113.647	133.445
11	**125.026**	**131.569**	*31.608*	**125.026**	**131.569**	**125.026**	**131.569**	142.893	164.220
12	**105.025**	**120.816**	*9.424*	105.025	121.059	105.141	122.289	117.327	156.157
13	**97.428**	**70.845**	*22.156*	**97.428**	**70.845**	97.500	72.872	107.866	85.482
14	**165.290**	**214.317**	*58.580*	**165.29**	**214.317**	165.290	215.875	216.443	293.137
15	**98.165**	**86.101**	*14.974*	**98.165**	**86.101**	98.485	89.058	108.511	111.955
16	**77.720**	**100.875**	*19.889*	**77.720**	**100.875**	78.767	104.014	92.850	133.418
17	**50.144**	**79.153**	*1.618*	**50.144**	**79.153**	50.638	82.007	54.589	81.743
18	**61.056**	**105.824**	*3.249*	**61.056**	**105.824**	62.594	104.522	63.032	109.530
19	**49.693**	**81.265**	*1.210*	**49.693**	**81.265**	**49.693**	**81.265**	52.479	89.259
20	**56.773**	**93.589**	*2.658*	**56.773**	**93.589**	59.293	95.678	71.988	122.982
21	**88.239**	**115.352**	*5.448*	**88.239**	**115.352**	88.239	116.649	104.404	145.146
22	**157.104**	**168.397**	*2.823*	157.104	168.783	157.104	168.783	171.087	196.071
23	**60.330**	**58.655**	*4.396*	**60.330**	**58.655**	**60.330**	**58.655**	65.457	66.789
24	**157.104**	**165.857**	*2.071*	**157.104**	**165.857**	157.104	165.879	181.676	194.851
25	**62.792**	**71.871**	*3.538*	**62.792**	**71.871**	62.911	72.698	67.687	86.915
26	**66.397**	**69.995**	*5.838*	**66.397**	**69.995**	71.445	82.551	71.700	88.594
27	**73.176**	**114.371**	*2.859*	**73.176**	**114.371**	78.120	119.220	86.755	142.555
28	**84.129**	**116.735**	*5.428*	**84.129**	**116.735**	84.129	123.317	114.426	140.606
29	**61.889**	**86.015**	*2.097*	**61.889**	**86.015**	62.737	87.064	67.417	104.840
30	**83.508**	**118.739**	*3.898*	**83.508**	**118.739**	83.508	119.541	110.922	141.173
31	**80.966**	**94.065**	*3.067*	**80.966**	**94.065**	**80.966**	**94.065**	96.801	108.193
32	**57.849**	**58.463**	*0.971*	**57.849**	**58.463**	**57.849**	**58.463**	62.453	69.139
33	**66.674**	**63.15**	*2.241*	**66.674**	**63.150**	69.200	66.863	69.742	67.530
34	**57.651**	**70.036**	*0.559*	**57.651**	**70.036**	58.559	71.741	63.708	83.027
35	**84.320**	**61.551**	*2.062*	**84.320**	**61.551**	84.330	61.986	86.990	68.437
36	**68.322**	**59.719**	*0.630*	**68.322**	**59.719**	**68.322**	**59.719**	80.890	83.535
37	**78.016**	**58.439**	*1.581*	**78.016**	**58.439**	80.540	60.548	82.805	62.005
38	**83.423**	**48.800**	*3.049*	83.503	51.135	83.976	51.985	86.552	58.901
39	**64.738**	**39.842**	*0.917*	**64.738**	**39.842**	**64.738**	**39.842**	68.726	49.515
40	**85.057**	**60.532**	*2.431*	**85.057**	**60.532**	**85.057**	**60.532**	88.080	66.816
41	**65.232**	**47.690**	*0.654*	65.232	48.951	66.374	46.923	69.965	54.177
42	**78.754**	**60.047**	*1.451*	78.921	60.065	79.499	61.387	81.216	64.455
43	**89.310**	**60.453**	*3.734*	**89.310**	**60.453**	**89.310**	**60.453**	92.192	64.207
44	**89.504**	**86.103**	*1.072*	**89.504**	**86.103**	91.888	92.016	96.572	100.855
45	**66.652**	**53.066**	*0.525*	**66.652**	**53.066**	74.459	64.183	73.665	67.213

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Table 3
(Continued)

#	*MultiStarVNS*			*Variant* 1		*Variant* 2		*Variant* 3	
	f_1	f_2	*C.T.*	f_1	f_2	f_1	f_2	f_1	f_2
46	**42.080**	**33.156**	*0.062*	43.017	30.485	43.423	30.756	43.017	30.485
47	**85.898**	**47.332**	*0.389*	86.438	46.111	90.614	48.480	90.231	52.499
48	**104.270**	**51.249**	*1.351*	**104.270**	**51.249**	109.108	58.658	108.653	56.304
49	**81.437**	**48.099**	*0.239*	82.169	49.258	82.874	50.115	87.783	56.792
50	**90.507**	**41.547**	*0.788*	**90.507**	**41.547**	**90.507**	**41.547**	95.614	49.748
51	**133.576**	**104.387**	*0.083*	**133.576**	**104.387**	**133.576**	**104.387**	160.868	110.450
52	**92.381**	**53.155**	*0.486*	**92.381**	**53.155**	92.581	53.289	96.174	58.044
53	**60.723**	**36.631**	*0.055*	**60.723**	**36.631**	60.777	35.386	85.313	34.499
54	**84.631**	**49.177**	*0.295*	84.790	49.142	84.852	49.780	84.905	49.815

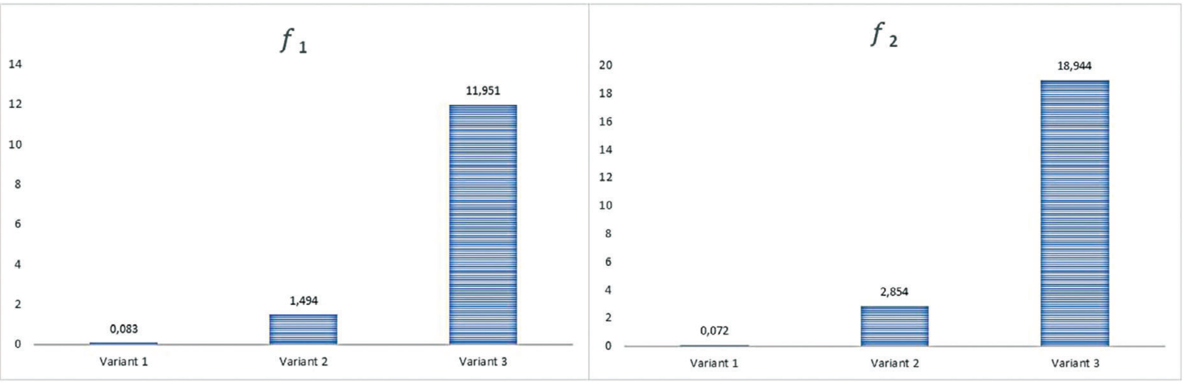

Fig. 6. Mean gaps (%) of the values of the solutions of the three variants with respect to *MultiStarVNS*.

of the system used to conduct delivery planning. Furthermore, we compared the results of the *MultiStarVNS* method with those obtained using two known commercial optimization programs, *CPLEX* (v22.1.1) and *LocalSolver* (v11.5). To conduct this comparison, the *MSTabu* method, *CPLEX*, and *LocalSolver* programs were executed in 54 real instances (for our *MultiStarVNS* method, the results obtained in Subsection 4.3 were used). The *MSTabu* method uses the computation time of *MultiStarVNS* as the stopping criterion, whereas *CPLEX* and *LocalSolver* use a computation time of 600 s. *CPLEX* uses the formulation proposed in Section 2 but aggregates the two objectives. To maintain the hierarchy between the two objectives, the first objective has a weight of 10^6 and the second has a weight of 1. We can find a short code used by *LocalSolver* to read instances and solve this problem at the following website: www.ubu.es/metaheuristicos-grinubumet/ejemplos-y-datos-de-problemas

The results are presented in Table 4. The values of the two target functions of the obtained solutions are shown for each method and software. The computation time (C.T.) (in seconds) used by *MultiStarVNS* (the same as that in Table 3) is also shown. The best solutions are indicated in bold.

From Table 4, the following conclusions can be drawn:

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Table 4
Results of *MultiStarVNS*, *MSTabu*, *CPLEX*, and *LocalSolver*

#	*MultiStarVNS*			*MSTabu*		*CPLEX*		*LocalSolver*	
	f_1	f_2	*C.T.*	f_1	f_2	f_1	f_2	f_1	f_2
1	**162.298**	**225.357**	*31.806*	162.298	228.129	167.862	237.160	163.362	217.604
2	**79.614**	**66.072**	*7.792*	**79.614**	**66.072**	90.146	90.139	84.064	64.687
3	**93.749**	**68.716**	*17.796*	93.940	72.284	104.685	91.391	97.852	67.441
4	**110.982**	**159.904**	*5.081*	115.588	190.118	110.982	161.476	113.94	84.832
5	**93.242**	**81.227**	*12.064*	93.664	83.427	103.093	106.830	96.636	79.531
6	**109.274**	**91.847**	*25.821*	**109.274**	**91.847**	120.570	117.975	111.550	91.725
7	**86.637**	**80.370**	*8.305*	87.001	80.079	179.674	85.392	90.278	73.159
8	**94.598**	**68.673**	*19.122*	94.801	69.681	105.155	88.641	113.940	84.832
9	**123.320**	**115.007**	*42.454*	124.200	116.386	126.332	116.197	128.009	112.884
10	**102.648**	**104.268**	*13.209*	103.195	105.058	115.984	140.460	107.617	105.020
11	**125.026**	**131.569**	*31.608*	**125.026**	**131.569**	141.289	165.171	127.798	127.445
12	**105.025**	**120.816**	*9.424*	105.141	122.289	108.123	126.636	106.491	114.746
13	**97.428**	**70.845**	*22.156*	97.500	72.872	106.455	89.184	101.463	70.223
14	**165.290**	**214.317**	*58.580*	165.290	215.875	178.456	252.924	166.485	210.281
15	**98.165**	**86.101**	*14.974*	**98.165**	**86.101**	102.222	96.826	99.456	80.382
16	**77.720**	**100.875**	*19.889*	78.767	104.014	88.360	130.746	81.250	101.372
17	**50.144**	**79.153**	*1.618*	50.276	79.516	52.182	83.393	54.515	76.138
18	**61.056**	**105.824**	*3.249*	62.594	104.522	65.865	116.611	66.277	102.602
19	**49.693**	**81.265**	*1.210*	**49.693**	**81.265**	54.895	102.682	53.781	79.695
20	**56.773**	**93.589**	*2.658*	57.188	91.234	63.386	101.742	60.705	90.619
21	**88.239**	**115.352**	*5.448*	**88.239**	**115.352**	91.402	130.240	92.885	113.354
22	**157.104**	**168.397**	*2.823*	157.104	168.783	157.104	169.419	161.164	166.593
23	**60.330**	**58.655**	*4.396*	**60.330**	**58.655**	91.402	120.199	65.260	59.138
24	**157.104**	**165.857**	*2.071*	157.104	165.879	157.104	166.480	161.164	165.176
25	**62.792**	**71.871**	*3.538*	62.911	72.698	69.990	85.140	66.428	68.129
26	**66.397**	**69.995**	*5.838*	68.858	76.231	72.597	99.983	70.750	68.784
27	**73.176**	**114.371**	*2.859*	75.054	123.321	81.885	136.627	78.031	118.824
28	**84.129**	**116.735**	*5.428*	84.129	123.317	96.641	140.993	89.643	113.990
29	**61.889**	**86.015**	*2.097*	62.737	85.322	65.550	96.112	65.562	84.956
30	**83.508**	**118.739**	*3.898*	83.508	119.541	88.816	138.082	88.328	116.577
31	**80.966**	**94.065**	*3.067*	**80.966**	**94.065**	89.968	116.162	85.714	93.973
32	**57.849**	**58.463**	*0.971*	**57.849**	**58.463**	59.535	63.782	63.054	58.463
33	**66.674**	**63.15**	*2.241*	67.822	63.09	69.417	63.863	70.405	62.157
34	**57.651**	**70.036**	*0.559*	**57.651**	**70.036**	58.588	71.382	61.998	67.821
35	**84.320**	**61.551**	*2.062*	**84.320**	**61.551**	84.596	61.022	88.505	60.544
36	**68.322**	**59.719**	*0.630*	**68.322**	**59.719**	71.038	59.990	73.404	59.891
37	**78.016**	**58.439**	*1.581*	80.540	60.548	79.182	59.533	82.621	58.569
38	**83.423**	**48.800**	*3.049*	83.589	50.225	83.538	49.402	86.856	50.186
39	**64.738**	**39.842**	*0.917*	**64.738**	**39.842**	65.820	44.356	69.359	39.566
40	**85.057**	**60.532**	*2.431*	**85.057**	**60.532**	85.802	141.749	89.282	61.968
41	**65.232**	**47.690**	*0.654*	66.374	46.923	66.336	51.893	71.194	49.833
42	**78.754**	**60.047**	*1.451*	79.499	61.387	79.826	61.952	82.571	57.627
43	**89.310**	**60.453**	*3.734*	**89.310**	**60.453**	90.754	62.431	93.516	60.170
44	**89.504**	**86.103**	*1.072*	91.888	92.016	91.657	92.307	95.017	89.495
45	**66.652**	**53.066**	*0.525*	68.548	52.022	67.851	55.828	70.709	53.824

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Table 4
(Continued)

#	*MultiStarVNS*			*MSTabu*		*CPLEX*		*LocalSolver*	
	f_1	f_2	*C.T.*	f_1	f_2	f_1	f_2	f_1	f_2
46	**42.080**	**33.156**	*0.062*	43.017	30.485	**42.080**	**33.156**	46.690	31.471
47	**85.898**	**47.332**	*0.389*	87.888	48.18	**85.898**	**47.332**	91.188	45.888
48	**104.270**	**51.249**	*1.351*	107.205	56.231	**104.270**	**51.249**	109.730	53.157
49	**81.437**	**48.099**	*0.239*	82.169	49.258	**81.437**	**48.099**	87.390	49.416
50	**90.507**	**41.547**	*0.788*	**90.507**	**41.547**	**90.507**	**41.547**	96.980	41.547
51	**133.576**	**104.387**	*0.083*	**133.576**	**104.387**	**133.576**	**104.387**	141.891	103.513
52	**92.381**	**53.155**	*0.486*	92.581	53.289	93.808	53.093	98.310	53.155
53	**60.723**	**36.631**	*0.055*	60.777	35.386	60.777	35.379	66.200	38.997
54	**84.631**	**49.177**	*0.295*	84.852	49.78	84.748	48.789	89.853	49.382

Table 5
Results of the Wilcoxon signed rank tests.

	n^*	W^+	W^-	*minW*	p-tail	Z score	p-tail z
MSTabu - MultiStarVNS	31	496	0	0	<0.001	4.860	<0.00001
CPLEX - MultiStarVNS	45	1035	0	0	<0.001	5.841	<0.00001
LocalSolver - MultiStarVNS	54	1485	0	0	<0.001	6.393	<0.00001

- Our *MultiStarVNS* method obtained the best solution for all instances. *MSTabu* obtained the best solution for 17 instances. In the remaining instances, although this method obtained worse solutions, it was not significantly different from the best results.
- *CPLEX* obtained the best solution for six instances. These six instances were among the smallest. In general, the solutions were clearly worse in large instances (it is worth highlighting instance 7 with 86.637 vs. 179.674 in f_1) and better in small instances (they were closer to the best solution).
- *LocalSolver* did not obtain the best solution for any instance. In general, the solutions were clearly worse than the results obtained using *MultiStarVNS*, although the differences were not significant.

To strengthen the previous conclusions from the results in Table 4, we performed rank tests to determine whether the differences in the main target function (f_1) in favor of our *MultiStarVNS* method were significant. The results of the tests are presented in Table 5, which shows, for each test, the number of instances in which there is no tie (n^*); the sum of ranks with a positive difference (i.e., the values in f_1 of *MSTabu*, *CPLEX*, and *LocalSolver* are larger than those of *MultiStarVNS*), denoted by W^+; the sum of ranks with a negative difference (W^-); the lowest values of W^+ and W^- (*minW*), with the corresponding one-tailed probability (p-tail); and the z value obtained (Z score), with the corresponding one-tailed probability (p-tail z). The results of all the tests showed significant differences in favor of the *MultiStarVNS* method.

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6. Conclusions

The coronavirus (COVID-19) pandemic spread rapidly to Italy and Spain in March 2020. In Spain, the pandemic revealed a scarcity of essential materials for these situations, such as face shields for healthcare staff and vulnerable people. This situation increased with the spread of the virus. However, initiatives were implemented in some provinces to alleviate the situation. This was the case in the province of Burgos, where the Scientific Culture Unit of its University requested "makers" (individuals and small companies who owned three-dimensional printers) to manufacture these face shields. In addition, other institutions collaborated (Civil Protection, the City Hall, and the Red Cross) in the collection and delivery of face shields. In the case of the province of Burgos, this initiative was successful, in that they supplied a considerable percentage of the population with these products (seven times more than the rest of the Spanish territory as a whole).

To improve the efficiency of these activities, a method was developed to optimize the daily distribution of face shields; specifically, we aimed to minimize the duration of the longest route, which allows the drivers to complete the routes earlier, thereby allowing them to start other social tasks earlier (e.g., assembly of beds in hospitals and hospices, disinfection, and repair of certain materials). It is important to consider that these social tasks were conducted in coordination; thus, the remaining drivers had to wait for the last driver to complete the route before pursuing their next task. The development of this method for this problem with this "social" target was performed "round the clock" (owing to these dramatic circumstances), adapting an already existing method designed for commercial logistics. Despite this hurried development, the method is advantageous, especially in saving time during planning and other social tasks.

However, it is important to investigate whether more time and less pressure will allow for the development of ad hoc methods for this "social" problem which generate better solutions, thereby improving the mentioned advantages. In this study, we developed a method based on the metaheuristic strategy of VNS in an MS framework that significantly improved both the method used in these delivery activities and the commercial software. We analyzed the convenience of the different procedures used in this method. All tests were performed on real instances used during face-shield delivery activities.

Finally, to the best of our knowledge, there is a lack of face-shield factories and warehouses in many Spanish cities. Therefore, there is a need for efficient methods (as efficient as possible) to solve this real healthcare logistics problem or similar problems, as has been demonstrated by recent experience.

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