A Novel Mixed-Integer Linear Programming Model for the Capacitated Arc Routing Problem Adapted to Roadside Management Operations

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Abstract— **Roadside management is an issue in many territories worldwide. Decision-makers face multiple challenges in finding the right combination in scheduling roadside maintenance activities while meeting several objectives, such as minimising travelled distance and time while collecting the mowed biomass for future valorisation. This work addresses the problem of planning optimal configurations for Roadside Management Operations (RMO) under tactical and operational decisions. At the tactical decision level, the allocation of resources must be carried out for each technical centre operating within the territory. At an operational level, the routing of maintenance vehicles must be scheduled. For this purpose, a Mixed-Integer Linear Programming (MILP) model is proposed to formulate a new Capacitated Arc Routing Problem (CARP) adapted to RMO (which we denote CARP-RMO). We further evaluate our proposed model with benchmark instances and well-known literature heuristics and show that our proposed optimisation approach is better performing, especially when scaling up to larger areas and multiple constraints. A case study is also presented for the area of Neufchateau, France, based on real data collected from the local operation technical centres, for which we showcase that our optimisation method can achieve good operational performance for both an optimal travel time and efficient biomass collection.**

I. INTRODUCTION

Rapid expansion of road infrastructure has led to the estimate that around 25 million kilometres of new roads will be built by 2050 [1]. Despite the positive impacts in terms of transport, roads cause considerable negative impacts on biodiversity and adjacent ecosystems, such as soil erosion and habitat destruction [2]. Therefore, proper maintenance of vegetated strips along roads, known as roadsides, is crucial to mitigate these impacts.

Challenges: However, roadside management is an issue in many territories worldwide, it can include different activities such as roadside mowing, pruning, ditch cleaning, biomass collection, etc. [2]. Decision-makers face multiple challenges in finding the right planning for these operations, this involves finding the optimal configuration of vehicle fleet, mowing equipment, and staff for multiple technical centres distributed along the network while meeting several objectives such as minimising travelled distance, the time spent on the route, and the operational costs subject to a limited annual budget [3].

This problem is further complicated by considering the heterogeneity of the road structure. Factors such as road curvature, slopes, roadside width, vegetation type and density, and the presence of equipment such as signage and safety barriers impact the performance and service times of operations. This requires an appropriate allocation of resources, adapted to the road structure.

Routing problems: From an operations research perspective, this type of problem has been addressed in the literature by vehicle routing. This type of optimisation problem can be classified according to the structure of the network. The most common case is node routing problems, where the routing is associated with vehicles performing tasks associated with points in space [4]. However, another possibility is that the tasks are associated with traversing arcs in the network, resulting in Arc Routing Problems (ARP). This is the case for Roadside Management Operations (RMO), where vehicles are required to maintain the green dependencies of the roadside along the entire length of the road.

Furthermore, to adapt to the needs of different real-life applications, the literature has proposed multiple variants of the ARP. In the roadside management context, a relevant variant to consider is the Capacitated Arc Routing Problem (CARP), which includes vehicle capacity constraints, in order to model features such as biomass collection or fuel consumption. Additionally, some features that need to be included are multiple periods, multiple depots representing the technical centres in a territory, multiple commodities representing the different sections of vegetation to be maintained, and the heterogeneity of the vehicles performing each of these operations, among others. In this work, we denote these characteristics as RMO features. However, to the best of our knowledge, the literature has not yet explored CARP applied to any type of RMO, nor has it studied a variant that can be applied to this context.

A. Related Work

Authors in the scientific domain of CARPs have studied other similar applications considering some of the features

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mentioned. The application that has been most extensively studied is municipal solid waste collection. The work presented in [5] proposes three models based on three situations: (i) using heterogeneous vehicles, (ii) the presence of multiple landfills, and (iii) both situations together. The authors in [6] presented CARP variants considering multiple commodities with multiple compartments vehicles for different types of waste that need to be separated, and a semi-periodic approach with multiple demands that must be serviced. In [7], the authors also propose a CARP with multiple vehicles to serve multiple types of wastes, but add location decisions for multiple depot and disposal sites for each type of waste. Among other applications studied under this approach, the authors in [8] designed a Mixed Integer Linear Programming (MILP) to model street sweeping operations with multiple depots, multiple periods, and different arc types, such as highways, that are only serviced at night due to traffic constraints. In [9], the problem of winter gritting is modelled considering multiple depots with a heterogeneous fleet of vehicles with different fixed costs, variable costs and capacity, but without considering task heterogeneity. The work in [10] proposed a Mixed Integer Non-Linear Programming (MINLP) for a Location Arc Routing Problem (LARP) with multiple periods, and time windows under demand uncertainty to address the problem of the location of treasury centres required for the exchange of money from a bank's branches. In [11], a MILP model is presented for post-disaster debris collection, including multiple depots located within an unconnected graph, which have a heterogeneous fleet of vehicles suited to unblock different types of roads, allowing connect the network once served.

Although these applications share some similarities in terms of the features included, especially in applications such as street sweeping and snow ploughing, the literature has not yet explored CARP variants adapted to sustainable RMO.

B. *Purpose of paper*

Therefore, this paper proposes a multi-period, multi-depot, multi-commodity, multi-demand CARP with heterogeneous vehicles adapted to RMO (which we denote CARP-RMO). Therefore, a MILP model is designed to support tactical and operational decisions such as vehicle allocation, vehicle routing, and the optimal flow of biomass collected.

This model is developed in two steps. First, a generalised form of the CARP-RMO is developed and validated using benchmark heuristics. Then, once validated, the features needed to adapt it to the requirements of roadside management are added to obtain the proposed model.

The remaining sections of the paper are structured as follows. Section II states the problem of roadside management and provides the mathematical formulation of the model. Section III presents the experimental results of the validation of the generalised CARP-RMO, experiments with multiple instances, and a real-life case study that validates the second step. Finally, the paper concludes in Section IV.

The code for the paper can be found at the following link: `https://github.com/ignaciocastaneda/IEEE-ITSC2025_CARP-RMO.git`.

II. PROPOSED METHODOLOGY

In this section, a formal statement of the problem of roadside management is presented with the notation used. Then, the mathematical formulation of the model is provided with the objective functions and constraints. Finally, the specifications of the case study selected are detailed.

A. *Statement of the problem and notation*

RMOs are carried out on a network of roads within a given territory. This network can be displayed by a directed graph $G = (N,A)$, where $N = \{0,1,\dots,n+n_d\}$ is the set of nodes, and $A = \{(i,j) : i,j \in N; i \neq j\}$ is the set of arcs represented by the roads. These roads can be separated into segments depending on the presence of vegetation at the roadside. Thus, each arc in the set A may be a required arc to be maintained or a non-required arc (traversing arc). According to the roadside infrastructure, each segment will be composed of one or more sections, each with a different length, area of vegetation, and maintenance practice. This defines the roadside typology $r \in R$. Each arc (i,j) has a distance c_{ij} and a traversing time t_{ij}; and each required arc has an additional service time t^s_{ijr} that depends on the section of the roadside r targeted.

In this territory, a technical agency is in charge of the correct roadside maintenance during the year. This facility monitors vegetation growth to ensure that it does not exceed the maximum height defined for each part of the roadside. When any of these heights are reached, maintenance operations must be performed. The sections of the roadsides that have surpassed the height limit are represented by the subset of required arcs $A_r \subset A$ so that $A_r = \{(i,j),r \mid q_{ijr} > 0\}$, where q_{ijr} represents the amount of vegetation that exceeds the height limit in the section of the roadside r at the arc (i,j). This way, each arc that doesn't need mowing has a demand equal to 0.

To carry out these activities, the technical agency has n_d technical centres located at nodes in the subset $D = \{n+1,\dots,n+n_d\}$, in charge of carrying out the maintenance operations. In this first decision-making level, the technical agency must assign the resources to each technical centre. For this, the technical agency has a fleet of vehicles $v \in V$ with types of maintenance machines $V^h \subset V$ and $V^m \subset V$. The subset V^h corresponds to machines that are only suitable for one type of section r, while those in V^m can reach the rest of the sections of the roadside, denoted by R^m.

At an operational decision-making level, each technical centre schedules the routing of its work teams to perform the required maintenance operations. This activity considers a time horizon given by periods $p \in P$, with fixed working hours per period t_{max}. At the end of each period, the work team must return to the technical centre.

Additionally, each work team must collect the biomass mowed and transport it to its respective technical centre for future recovery. Each mowing machine has a known collection capacity W_v that must be respected. When the capacity limit is reached, the work team must return to its respective technical centre to empty its capacity.

B. Mathematical formulation

This problem can be formulated as a CARP with additional RMO features, which include multiple periods, multiple depots, multiple commodities, multiple demands, and a heterogeneous fleet, resulting in the proposed CARP-RMO. Thus, in order to mathematically formulate this CARP-RMO, a dedicated MILP model is proposed. The decision variables are the following.

x_{ij}^{vp} : Integer variable that represents the number of times arc $(i,j) \in A$ is traversed by vehicle v in period p.

l_{ijr}^{vp} : Binary variable that is equal to 1 if roadside type r in arc $(i,j) \in A_r$ is served by vehicle v in time period p, 0 otherwise.

y_d^v : Binary variable that is equal to 1 if vehicle v is assigned to a depot d, 0 otherwise.

f_{ij}^{vp} : Continuous flow variable which can take on positive values when arc $(i,j) \in A$ is traversed by a vehicle v in a time period p ($x_{ij}^{vp} \geq 1$).

The optimisation model is:

$$\min Z_1 = \sum_{(i,j)\in A} \sum_{v\in V} \sum_{p\in P} c_{ij} x_{ij}^{vp} \tag{1}$$

$$\sum_{k\in\delta^+(i)} x_{ik}^{vp} - \sum_{k\in\delta^-(i)} x_{ki}^{vp} = 0, \ \forall i \in N, \forall v \in V, \forall p \in P \tag{2}$$

$$\sum_{v\in V} \sum_{p\in P} l_{ijr}^{vp} = 1, \quad \forall (i,j), r \in A_r \tag{3}$$

$$x_{ij}^{vp} \geq l_{ijr}^{vp}, \quad \forall (i,j), r \in A_r, \ v \in V, \ p \in P \tag{4}$$

$$\sum_{d\in D} y_d^v \leq 1, \quad \forall v \in V \tag{5}$$

$$\sum_{j\in\delta^+(d)} x_{dj}^{vp} \leq y_d^v, \quad \forall d \in D, \ \forall v \in V, \ \forall p \in P \tag{6}$$

$$\sum_{(i,j),r\in A_r} \sum_{p\in P} l_{ijr}^{vp} \geq \sum_{d\in D} y_d^v, \quad \forall v \in V \tag{7}$$

$$\sum_{p\in P} \sum_{v\in V^h} l_{ijr}^{vp} = 0, \quad \forall (i,j) \in A_r, \ r \in R^m \tag{8}$$

$$\sum_{(i,j),r\in A_r} q_{ijr} l_{ijr}^{vp} \leq W_v, \quad \forall v \in V, \ \forall p \in P \tag{9}$$

$$\sum_{(i,j)\in A} t_{ij}^t x_{ij}^{vp} + \sum_{(i,j),r\in A_r} t_{ijr}^s l_{ijr}^{vp} \leq t_{max}, \forall v \in V, \ \forall p \in P \tag{10}$$

$$\sum_{k\in\delta^+(i)} f_{ik}^{vp} - \sum_{k\in\delta^-(i)} f_{ki}^{vp} = \sum_{j\in\delta^+(i)} x_{ij}^{vp},$$

$$\forall i \in N \setminus D, \ \forall v \in V, \ \forall p \in P \tag{11}$$

$$f_{ij}^{vp} \leq n x_{ij}^{vp}, \quad \forall (i,j) \in A, \ \forall v \in V, \ \forall p \in P \tag{12}$$

$$f_{ij}^{vp} \geq 0, \quad \forall (i,j) \in A, \ \forall v \in V, \ \forall p \in P \tag{13}$$

Equation (1) is the objective function Z_1, which seeks to minimise the total distance travelled which is expressed as the sum of the length of each arc that has been traversed. Equation (2) ensures route continuity and flow conservation. Equation (3) states that each arc with positive demand is serviced exactly once. Equation (4) guarantees that arc (i,j) can be served by vehicle p only if it covers arc (i,j).

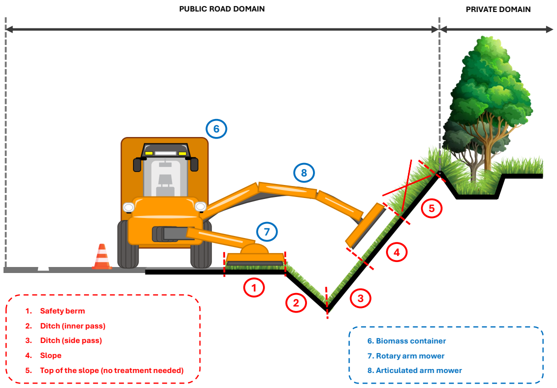

Fig. 1. Road structure illustration.

Equation (5) ensures that vehicles are assigned to only one depot. Equation (6) states that vehicles depart from their respective depot. Equation (7) prevents the allocation of vehicles that are not used. Equation (8) guarantees that vehicles in V^h can only serve one type of roadsides. Vehicle capacity is not violated on account of (9). Equation (10) is the time horizon constraint, which ensures that vehicles return to the depot before the end of the day. Finally, (11)-(13) prohibit the formation of illegal subtours.

C. Generalised model

In order to validate this model, a generalised version is proposed. This version is comparable to the CARP originally formulated by Golden & Wong in [12], and therefore applicable to the heuristics proposed by the same authors to solve this problem in [13], Path Scanning (PS) and Augment-Merge (AM). PS is a greedy algorithm that constructs routes by adding the arcs that look most promising based on a certain optimisation criterion, selecting as a solution the shortest route among the criteria. On the other hand, AM is a constructive algorithm that generates one route for each of the required arcs and then combines the overlapping routes to minimise the number of vehicles without exceeding their capacities.

To obtain the generalised version of the CARP-RMO, we need to fix a single type of roadside r, a set V of homogeneous vehicles (let $V^h = \emptyset$), a single period $p \in P$, and let $t_{max} = M$, with M a very large number.

D. Case Study

The road structure considered in this case study is represented in Fig. 1. The roadside is composed of at least a berm, but depending on the road type, it can also present a ditch and a slope. For these three sections, there is a specific maintenance policy.

This experiment is based on the spring mowing campaign carried out at the end of April in the district of Neufchâteau in the Vosges department in north-eastern France. During this campaign, the safety berm of the required roads within the network is maintained. In addition, if necessary, it is possible to perform punctual interventions in other sections.

TABLE I

COMPARISON OF EXACT RESULTS AND HEURISTICS RESULTS FOR THE GENERALISED VERSION OF THE MODEL APPLIED TO GDB INSTANCES.

Instance name	**Inputs**					**CARP-RMO**			**PS**		**AM**	
	$\lvert N\rvert$	$\lvert A\rvert$	$\lvert Ar\rvert$	$\lvert V\rvert$	W	$\lvert V\rvert$ used	Z_1 (Km)	Time (s)	Z_1 (Km) (Gap)	Time (s)	Z_1 (Km) (Gap)	Time (s)
GDB_1RM_1	12	44	8	6	5	2	168	0.03	189 (+13%)	0	168 (+0%)	0
GDB_1RM_2	12	44	17	6	5	4	295	0.01	363 (+27%)	0	315 (+10%)	0
GDB_1RM_3	12	44	26	6	5	6	383	0.03	519 (+42%)	0	407 (+6%)	0
GDB_2RM_1	22	90	18	6	50	2	209	0.04	311 (+49%)	0	231 (+11%)	0
GDB_2RM_2	22	90	36	6	50	4	303	0.08	464 (+53%)	0	381 (+26%)	0.65
GDB_2RM_3	22	90	54	6	50	6	474	0.08	731 (+54%)	0	612 (+29%)	1.23
GDB_3RM_1	32	122	24	6	70	2	143	5.21	244 (+71%)	0	185 (+29%)	0.5
GDB_3RM_2	32	122	48	6	70	4	262	12.2	488 (+91%)	0	296 (+13%)	1.6
GDB_3RM_3	32	122	73	6	70	6	382	16	836 (+119%)	0	484 (+27%)	5.94

For these operations, the technical agency of Neufchâteau has three technical centres located in the cities of Neufchâteau, Lamarche, and Mirecourt (see Fig. 2). Depending on the roads and the type of roadside to be maintained, the agency must allocate to the technical centres two different types of vehicles, rotary arm mowers ($v \in V^h$), which can only serve the safety berm ($r = 0$); and articulated arm mowers ($v \in V^m$), which can cover all sections but are best suited for punctual interventions in ditches ($r = 1$) and slopes ($r = 2$). In addition, each vehicle has a container of capacity $W^v = 10$ tonnes where the mowed biomass is stocked.

Regarding the amount of biomass on the roadsides, it is estimated that the average yield of collected biomass observed on the sites is 0.8 tonnes of raw material per kilometre [14]. Then, based on the sections of the roadside illustrated in Fig. 1, we can estimate that this amount is distributed in the ratio $1:2:1$ for $r = 0$, $r = 1$, $r = 2$, respectively.

This campaign is performed within two weeks of 5 days each within normal service hours from 8 am to 5 pm. This study considers the mowing of required roadsides during the first week, and 10 random punctual interventions for ditch and slope maintenance.

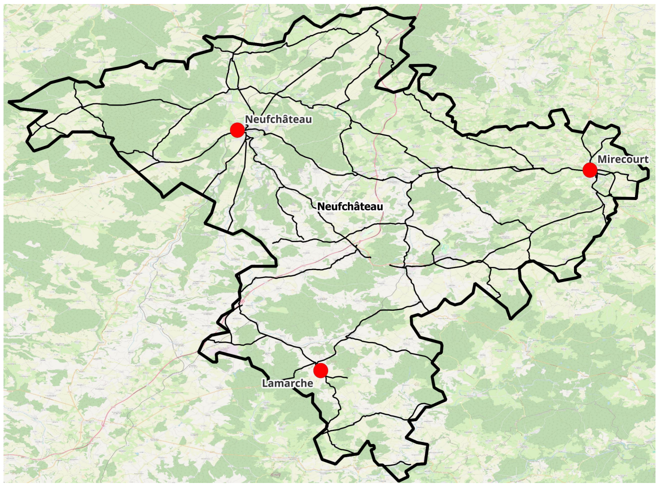

Fig. 2. District of Neufchâteau with technical centres and road network.

III. EXPERIMENTS

In this section, we first validate the proposed CARP-RMO in its generalised form by using benchmark instances adapted from the literature (see our next section, Step 1, detailed below). Then, we perform multiple scalability experiments on our proposed CARP-RMO model, as part of the lower level of the optimisation problem, and test its performance on multiple feature enhancements. Finally, to demonstrate the usefulness of the model in a real-life situation, the case study of roadside management in the district of Neufchâteau is applied.

These results were obtained using the solver Gurobi 11.0.0 in an Intel Core i7-13800H 2.50 GHz with 32 GB of RAM.

A. Step 1: Model Validation

The first data sets used in this step were adapted from the well-known benchmark instances GDB_i ($i = 1, \dots, 23$) generated in the works of Golden et al. (see [13]). These instances are defined as an undirected graph composed of a set of nodes, a set of edges, a set of homogeneous vehicles and a fixed vehicle's capacity. For this work, three instances were selected from the original set, named GDB_1, GDB_2, and GDB_3. Therefore, in order to adapt these instances to the graph proposed in this model, the original edges (i, j) were transformed into arcs in both directions, and the subset A_r was generated by a random selection of 20%, 40% and 60%, creating three new instances from each original instance, which we name GDB_iRM_j (with $j = 1, 2, 3$). For example, GDB_1RM_1 stands for an instance generated from the benchmark instance GDB_1 with a subset A_r equals to a random selection of 20% of the arcs $(i, j) \in A$. The original instances can be found in [15].

Table I presents a set of nine new instances generated from three literature instances and the results obtained by the model when using the Gurobi solver; the results of our proposed CARP-RMO are then compared against the heuristics PS and AM applied for the same network structure. The gap between the exact solution and those obtained in the heuristics is relatively low in smaller instances (see GDB_1RM_1 or GDB_1RM_3) but increases considerably as larger graphs are used, especially when PS is employed (see GDB_3RM_3). The AM algorithm manages to remain relatively

TABLE II

RESULTS OF THE STEP 2 MODEL ON THE *RM* INSTANCES GENERATED

Instance	**Inputs**										**Outputs**				
name	$\|N\|$	$\|D\|$	$\|A\|$	$\|A_r\|$	$\|A_{r=0}\|$	$\|A_{r=1}\|$	$\|A_{r=2}\|$	$\|V\|$	$\|P\|$	W	$\|V^h\|$	$\|V^m\|$	$\|P\|$ used	Z_1 **(Km)**	**Time (s)**
$RM_{13}-a$	13	2	36	8	6	1	1	6	5	40	2	1	2	238,08	22,08
$RM_{13}-b$	13	2	36	14	10	2	2	6	5	40	2	1	3	356,38	111,02
$RM_{13}-c$	13	2	36	20	14	3	3	6	5	40	3	1	3	501,9	235,84
$RM_{23}-a$	23	2	56	14	10	2	2	6	5	40	2	1	3	398,46	82,8
$RM_{23}-b$	23	2	56	20	14	3	3	6	5	40	3	1	2	434,79	287,41
$RM_{23}-c$	23	2	56	26	18	4	4	6	5	40	3	3	2	561,43	3600,02
$RM_{31}-a$	31	2	76	16	10	3	3	6	5	40	1	2	2	421,24	403,76
$RM_{31}-b$	31	2	76	22	14	4	4	6	5	40	1	2	3	498,48	1316,33
$RM_{13}-c$	31	2	76	28	18	5	5	6	5	40	2	1	3	614,48	8800,11
$RM_{48}-a$	48	2	106	22	14	4	4	6	5	40	2	1	2	520,48	1916,57
$RM_{48}-b$	48	2	106	28	18	5	5	6	5	40	2	2	3	743,1	3h
$RM_{48}-c$	48	2	106	34	22	6	6	6	5	40	3	2	3	955,72	3h

stable on medium and large instances, results being worse by a margin of 6% in the case of GDB_1RM_3 and 13% in the case of GDB_3RM_2. In terms of solution time, while applying heuristics allows for quicker results with times tending to zero, the CARP-RMO outperforms PS and AM by obtaining an optimal solution using the exact method in a slightly longer but still very low time for the tested instances.

As an example, the results of instance GDB_1RM_1 show that optimising the CARP-RMO, an optimal travelled distance of 168 kilometres is obtained using two vehicles out of the six available. The same value is achieved using AM. PS obtains a value of 189 kilometres, which is 13% higher than the optimal. In this case, all options get results immediately, which holds for instances with up to 23 nodes. However, when using larger instances, results start taking more time for CARP-RMO and AM. PS always yields results immediately, but the resulting gap is considerably higher. In the case of GDB_3RM_3, CARP-RMO takes 16 seconds to find the optimal value, AM finds a feasible solution 27% higher than the optimal in 5.94 seconds, and PS yields a solution immediately but 119% away from the optimal solution found optimising CARP-RMO with Gurobi solver.

B. Step 2: Model Scalability

In order to evaluate how the model performs as instance size increases, the CARP-RMO is implemented on graphs of different sizes. The set of $RM_i - j$ instances consists of directed graphs with i nodes ($i = 13,\dots,50$), and a number of arcs $|A|$, from which random samples are taken to form the subset A_r. These samples are denoted j, with $j = \{a,b,c\}$.

Table II shows the instances generated, with the inputs and outputs. In this step, as RMO features are considered, running times start to increase considerably. Results indicate that the solution time is also directly proportional to the number of required arcs. For the set of instances with 13 nodes, the solution times remain low, with the maximum solution time of 235.84 seconds (≈ 3.8 min) in $RM_{13} - c$. When using instances with 23 and 31 nodes, the solution times start to increase even more, especially when more required arcs are added. This is demonstrated by a comparison between $RM_{23} - a$ and $RM_{23} - c$, where increasing the number of required arcs $|A_r|$ from 14 to 26, leaving the other parameters fixed, results in a 97.7% increment in solution time. Moreover, in networks with 50 nodes, running time rises exponentially. For this reason, the notation “3h” means the best solution found after a 3-hour run. For example, the defined time limit of 3 hours was reached for $RM_{50} - b$ and $RM_{50} - c$, indicating that the best solution found is feasible but may not be optimal.

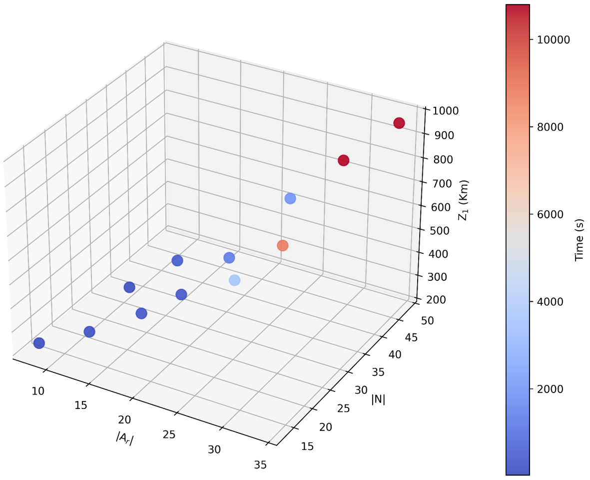

Fig. 3. 3D Representation of solutions Z_1 and execution times with respect to the number of required arcs $|A_r|$ and nodes $|N|$ in the model.

Fig. 3 shows a graphical representation of the results. Note that the solution time is directly proportional to the number of required arcs. In the model, vehicles’ capacity and time horizon constraints are subjected to capacities W_v, time horizon t_{max}, respectively, the number of vehicles $|V|$, the number of periods $|P|$, and the number of required arcs $|A_r|$. Since all the other parameters are fixed for all experiments, these constraints restrict the possible solutions as A_r increases, which decreases the number of feasible solutions, making

TABLE III

RESUME OF THE OPTIMAL PLANNING FOUND BY THE CARP-RMO APPLIED TO THE NEUFCHÂTEAU CASE STUDY.

		Day 1			Day 2			Day 3			Day 4			Total		
Technical centre	Asigned vehicles	TD (Km)	RT (hr)	BC (ton)	TD (Km)	RT (hr)	BC (ton)	TD (Km)	RT (hr)	BC (ton)	TD (Km)	RT (hr)	BC (ton)	TD (Km)	RT (hr)	BC (ton)
Neufchâteau	v_1^h	49,79	7,72	9,26	79,59	6,71	8,08	69,98	5,25	5,44	-	-	-	199,36	19,68	22,78
	v_1^m	47,38	7,32	8,39	54,58	7,07	7,99	45,91	7,2	7,62	65,74	6,92	6,76	213,61	28,51	30,76
Miercourt	v_2^m	57,95	7,23	7,1	65,19	7,25	8,71	63,22	7,2	8,32	20,52	2,62	3,14	206,88	24,3	27,27
Lamarche	v_3^m	45,01	7,1	8,48	59,22	6,3	7,56	45,7	6,14	6,56	12,19	1,6	1,92	162,12	21,14	24,52
Total		200,13	29,37	33,23	258,58	27,33	32,34	224,81	25,79	27,94	98,45	11,14	11,82	**781,97**	**93,63**	**105,33**

it more complex to find the optimal value, which is reflected in the run times.

C. Case Study Results

In this section, the results of applying the CARP-RMO to the case study of the Neufchâteau district are presented. In this case, an optimal solution was found after an 8-hour run which included all constraints mentioned dbefore. Table III shows a resume of the results obtained, suggesting an optimal configuration for the planning of roadside maintenance activities under two decision levels. In this table, the following notation has been used: (1) TD: Travelled Distance, (2) RT: Total On-Route Time (equal to travelling time plus service time), and (3) BC: Biomass Collection.

At the first tactical decision level, the vehicles were allocated. The Neufchâteau technical centre was assigned a rotary arm mower (v_1^h) and an articulated arm mower (v_1^m), while both the Miercourt and Lamarche centres were assigned only an articulated mower, v_2^m and v_3^m, respectively. This allocation indicates that the technical centre of Neufchâteau was the site with the most demand assigned to maintain, which can be reflected in the distances travelled and biomass mowed by both of its vehicles.

At the operational decision level, the routing of vehicles was scheduled in a time horizon that uses only 4 of the 5 working days currently required, indicating that minimising Z_1 is an indicator that would allow optimising this activity in practice. Despite this, the on-road times reflect that the workload is stable and evenly distributed across all technical centres, with a standard deviation of no more than two hours.

IV. CONCLUSION

In this work, a novel CARP-RMO is proposed, which provides a contribution to the CARP literature, due to their additional features related to the roadside management context. The CARP-RMO has been validated in Step 1, where optimal solutions were found at relatively low times using a solver. In Step 2, the scalability of the model was tested, indicating a good performance on short instances but struggling in larger networks, suggesting that optimisation solution methods should be explored to improve the run time. Then, a case study implementation is presented, providing a viable vehicle planning which allows to complete the tasks in fewer days than the given time horizon, demonstrating the usefulness of the proposed CARP-RMO in a real-life application. Finally, although the minimisation of Z_1 allowed to reduce the time on the road and to collect all the biomass, it would be advisable to study more indicators, such as to minimise the on-route time or the operational costs of the campaign.

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