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Solving the Capacitated Vehicle Routing Problem with Environmental Criteria Based on Real Estimations in Road Transportation: A Case Study

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Abstract

One of the most important objectives in company logistics is the optimization of goods distribution considering the whole value chain. There are many algorithms to optimise the capacitated vehicle routing problems (CVRP) associated to problems of road transportation. The objective function of those problems usually involves distance, cost, number of vehicles, or profits, among others. In this contribution we also take into account environmental costs. Here, we want to manage environmental costs estimations based on surveys about road transportation crossing rural areas having valuable biological and natural stock. Thus, we develop some variants (AWEC) to traditional heuristic algorithms, such as those of Clarke and Wright or Mole and Jameson, in which we include environmental cost estimates in real scenarios in Spain. This raises the value of the global objective function, but permits a more realistic cost estimate that includes not only the internal costs involved in the problem but also the related externalities. Finally, we discuss several solutions to a real case in the agribusiness sector in Navarre (Spain).

Keywords: Capacitated Vehicle Routing Problem; Environmental Criteria, Heuristics, Transport surveys.

1. Introduction

Nowadays, there is increasing concern across the world over the environmental impact of business management decisions. Many of those decisions affect the transport and logistics sector and the agribusiness sector is not an exception. This has led to detailed analysis of transport externalities, which has given rise to the sustainable mobility concept (European Commission, 1998). This term covers all the various environmental and social impacts that are generated by business logistic activities. This paper bases its theoretical foundation on the report written by the

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authors, among others, for the Spanish Ministry of Transport on the optimisation of routes incorporating safety and environmental measures (ETMOL, Pintor *et al.*, 2005)

The environmental externalities generated by transport activities in Europe have a tremendous impact on the economy of every European country, with economic costs amounting to 8% of the Gross Domestic Product in 2000 in the EU-15 (INFRAS/IWW, 2000). The most important source of negative environmental externalities is road transport, which generates 90% of the external costs of all forms of transport (Betancor and Nombela, 2003). Road freight, moreover, causes 30% of the external costs generated by transport activities (European Environment Agency, 2010). It is therefore important to incorporate these ideas and concerns in daily route management in companies, by searching for good quality routes to offset the environmental costs. Such routes will be classed as sustainable routes.

This paper analyses route-building using pertinent variants of traditional algorithms (Clarke and Wright, 1964; Mole and Jameson, 1976) for the Capacitated Vehicle Routing Problem (Toth and Vigo, 2002), including the implementation of new costs apart from the classic ones, such as distances or delivery expenses. These new costs are related to the assessment of the environmental damage caused by logistic activities along with the introduction of new safety rules in vehicle loading and unloading processes. Safety costs are easier to estimate than environmental costs, because the former ones are closely related to very well-known safety measures, while the latter ones require complex computations to obtain monetary estimates of the negative environmental impact of transport and logistics. Safety cost estimations in Spanish transport focus on absenteeism and the workplace accident rate (Bayo, 2003). In contrast, environmental cost estimation must be linked to specific geographical areas, and requires data on the exact delivery policies for each vehicle (ECMT, 2003; Carlow, 2001). We are going to introduce both costs in our optimisation model to solve logistic problems but the most important ones are the environmental costs (5% versus 28% roughly speaking, according to ETMOL project (Pintor *et al.*, 2005)). For that reason, we have paid more attention to environmental costs in the current paper.

1.1. Definition of the Problem

Algorithms with Environmental Criteria (AWEC) were constructed to address the need for solutions to real problems in delivery companies or logistic carriers. First of all, the authors highlight the importance of designing an algorithm which optimises distribution costs along with *the costs associated to environmental impact*. We outline the costs involved in the current problem as follows:

Costs I: We define these costs as the *traditional logistic costs associated to the usual delivery process in transportation,* i.e. the fuel cost, the vehicle maintenance cost and the staff cost, among others, are the main kinds of costs included in this section.

Costs II: We define this cost as the *added expenditure associated to environmental damage caused by logistic activities*. This environmental damage can be classified according to its origin: pollution, noise, congestion and wear and tear on infrastructure. We will also consider in this section the safety cost as the *added expenditure due to extra voluntary safety measures carried out by the company manager in normal delivery activities*. Such measures are usually highly recommended but not compulsory and therefore not always applied. These measures are painstakingly described in ETMOL project (Pintor *et al.*, 2005) and include, among others, the following actions: scheduled vehicle inspections, fuel and lubricant checks on vehicles, continuous maintenance policies, or good driving practices.

2. Literature Review for the CVRP

The Capacitated Vehicle Routing Problem (CVRP) (Table 1) has been described as the most common management problem in food, fuel and retail goods distributors. Our literature review revealed several different approaches to the CVRP. A good update of various heuristic methods appears in Van Breedam's (2001) paper. Other traditional papers about heuristic algorithms are Gaskell (1967), Golden, *et al.* (1977) and Bodin and Berman (1979). The most interesting reference in the VRP bibliography is Toth and Vigo (2002) which provides a good list of excellent algorithms to solve the CVRP. Other reviews of the VRP are the following: Golden and Assad (1991) and Cordeau *et al.* (2007).

We seek to design directly applicable algorithms to solve routing problems in real companies. Constructive methods have been shown to be applicable in the solution of real problems in the logistic activities of many companies (Guillén, 2003). These methods were thoroughly analyzed during the 1960s and 1970s, and found to give satisfactory results for small-scale problems. The most important constructive method is Clarke and Wright's (1964) algorithm (CWS algorithm) which defines a saving function to decide which nodes should be incorporated to the routes in construction. Some commercial applications generate routes, sequentially or simultaneously, using that method. Nevertheless, sequential methods based on savings are quicker than other constructive algorithms, although the total distance of their routes is much greater. Thus, alternative methods were devised: various procedures are described in Wren and Holliday (1972), Gillet and Miller (1974) or Gaskell (1967). Finally, Mole and Jameson's (1976) algorithm appeared as a natural generalization of the CWS algorithm with good properties for the solution of real cases.

Table 1. Characteristics of CVRP (it is called VRP-SE01 when environmental costs are also considered)

Characteristics of CVRP	Options for the CVRP
Fleet size	Multiple vehicles
Fleet composition	Homogeneous or Heterogeneous
Vehicle origin	Single Depot
Demand type	Known Deterministic Demand
Demand location	In each node
Network type	Non-oriented
Maximum time per route	None
Activities	Deliveries only
Costs	Fixed vehicle costs and variable route costs
Constraints	Safety requirements Time distribution constraints
Objective	Minimise distribution costs (Costs I) and environmental costs (Costs II)

Similarly, the use of metaheuristics in VRP became popular during the nineties. Two of the most important papers on the use of heuristics and metaheuristics were Gendreau, *et al.*'s (1994), which introduced the Tabu Route algorithm, and Laporte *et al.* (2000), which includes a thorough discussion of classical and modern heuristics. Nevertheless, the main source of current information about metaheuristics is Toth and Vigo (2002). Some ideas for AWEC were taken from the previous references. Other algorithms that need to be taken into account in the construction of our method are the GRASP procedures (Feo and Resende, 1989; Feo and Resende, 1995), which are iterative randomized sampling techniques that provide a solution to the problem with each iteration.

3. Environmental Problems in Transportation

The consideration of environmental costs is essentially changing the transportation policy in developed countries, especially those within the European Union. The new environmental sensitivity in today's societies and governments has been described in several studies, such as INFRAS/IWW and UNITE (INFRAS/IWW, 2004; Betancor and Nombela, 2003; Sansom *et al.*, 2001). The European Conference of Ministers of Transport (1998) urged European Governments to develop new instruments to incorporate externalities and environmental costs in transport management accounting. Similarly, Weintraub and Romero (2006) have also highlighted the need to use environmental criteria in the development of OR models in Agriculture. Therefore, environmental concerns have highlighted the importance of sustainable transport design.

Amongst the gamut of environmental costs associated with mobility and transportation, we will focus our attention on two; namely, noise and polluting emissions. One reason for selecting these particular causes of environmental damage is because they are important components of the transportation cost function: near 60% of the total average of cost freight in the EU. (INFRAS/IWW, 2004). Furthermore, they have widely been studied in the European arena and we can use some of the findings in our study of road transport problems in Spain. Unlike safety, which we analyzed in ETMOL project (Pintor *et al.*, 2005) in the Spanish context, environmental studies have often been conducted on a European level. We have therefore made use of these studies and applied them to the Spanish transport setting. We will portray these environmental costs in the following subsections.

3.1. Road transport noise impact

The road transport noise is a topic that has been widely analyzed in many cases. Unfortunately, there are no European standards to assess noise impact (Verhoef, 1994). Nevertheless, Quinet (2004) highlighted the importance of external cost estimates for transport policy decisions. Furthermore, the quantification of environmental externalities involves many uncertainties and heavily depends on the temporal and regional conditions. Thus, we will adopt the main noise estimates in the INFRAS/IWW (2004) study to select the costs to be incorporated in the design of our algorithms AWEC. This study was chosen for the reliability of the data and the richness of the results and the fact that it is the most complete existing study of noise and polluting emissions (Tables 2 and 3). Thus, we consider these to be reliable noise cost estimates (Table 2, shaded cells) and use INFRAS/IWW average costs for the implementation of the AWEC algorithms.

Table 2. Comparison of noise cost estimates in the INFRAS and UNITE studies

Values	INFRAS (2004)	UNITE (2003)
Average costs[(1)]	€ /1,000 Tm-Km	€ /1000 Vehicle-Km
Lorry + Van	6.62	15.6 [(1)]
Van	20.40	N. A.
Lorry	2.93	N. A.
Marginal costs	€ /1000 Tm-Km	€ /1000 Vehicle-Km
Van	2.40 – 307	N. A
Lorry	0.25 – 32	N. A
Van (interurban vs urban transport)	0.71 – 92.10	N. A
Lorry (interurban vs urban transport)	1.31 – 169.47	N. A

[(1)] Also includes cars and coaches. N.A.: Not Available.

Source: Own calculations on data supplied by INFRAS/IWW (2004) and Betancor and Nombela (2003)

3.2. Impact of road transport polluting emissions.

Air pollution is a serious transport externality, which is harmful to humans, and also to flora and fauna. Generally speaking, transport vehicles release polluting agents as a consequence of fuel combustion. The increase in road traffic has brought about a rise in transport pollution, despite a reduction in pollution rates due to technical improvements in engines and fuels. Costs of air pollution are summarized in Table 3, along with the UNITE costs (Betancor and Nombela, 2003). Following the same methodology described in the noise analysis, we will make use of INFRAS/IWW (2004) to evaluate the environmental costs associated with pollution. We will employ average costs following the INFRAS study to implement pollution costs in the AWEC algorithms (Table 3, shaded cells).

Table 3. Comparison of pollution cost estimates in the INFRAS and UNITE studies

Values	INFRAS (2004)		UNITE (2003)	
Vehicle	Light Vehicle	Heavy Vehicle	Light Vehicle	Heavy Vehicle
Average costs	€ /1,000 Tm-Km		€ /1,000 Vehicle-Km	
Air Pollution	69.1	24.2	15.0	22.8
Global Warming	62.3 [(1)]	13.0 [(1)]	13.4	15.8
Nature, soils and water pollution	11.4	2.6	N. A.	N. A.
Marginal costs	€ /1,000 Tm-Km		€ /1,000 Vehicle-Km	
Air Pollution	15 - 100	33.5	N. A.	N. A.
Global Warming	8.2 - 57.4	1.8 – 12.8	N. A.	N. A.
Nature, soils and water pollution	10.9	0.8	N. A.	N. A.

[(1)] Global warming costs have been calculated with the shadow value of 140 €/Tm-CO_2. N.A.: Not Available.

Source: Own calculations on data supplied by INFRAS/IWW (2004) and Betancor and Nombela (2003)

4. Algorithms with Environmental Criteria: AWEC

Having presented the main characteristics of the new goals to be considered in AWEC algorithms, we will now describe its working philosophy. We will first of all select two families of routing algorithms to implement the cost structure described in Tables 2 and 3. We will use the average costs obtained by the INFRAS (2000, 2004) study to construct the algorithm because they provide a realistic estimation of the cost associated with environmental externalities. In light of the above considerations, therefore, in our aim to design a new algorithm, we can identify the following requisites:

- We need a constructive algorithm because it will provide an easy procedure to implement our external costs.
- We seek a versatile algorithm with a suitable number of tuning parameters.
- We seek an algorithm that is transparent in the sense that it will readily reveal the effects of the external costs considered.

4.1. Selection of the baseline algorithms

Taking into account the need to find an appropriate constructive algorithm in which to test the implementation of external costs, we chose the Mole and Jameson's (1976) procedure because it satisfies the three prerequisites described above. Viewing this algorithm as a generalization of Clarke and Wright's (1964) procedure (CWS algorithm), we will now describe it in the following way.

Mole and Jameson's algorithm (MJ algorithm) (1976). This algorithm is based on the CWS algorithm and it is described as a generalization of the savings algorithm. The CWS algorithm describes the savings function as follows:

$$S(A,B) = d_{OA} + d_{OB} - d_{AB} \qquad (1)$$

where point O is the depot and points A and B are any pair of nodes in network Ω corresponding to the set of customers to be visited, and the variable d describes the distance between its two subindices which represent two different points of Ω. Clearly $S(A,B) = S(B,A),\ with\ 1 \le A,B \le N$, being N the total number of nodes of Ω. The sequential MJ procedure will present the steps described below:

1) Choice of position for an additional node C.

i) Calculate the generalized extramileages starting from nodes A and B and aiming to add node C (we call this function the modified strain):

$$MST_C(A,B) = d_{AC} + d_{BC} - \lambda d_{AB} \qquad with \quad \lambda \ge 0 \quad (2)$$

If it is satisfied that strain $ST_C(A,B)$ is a feasible distance (it has a positive value), where strain is defined as $ST_C(A,B) = d_{AC} + d_{BC} - d_{AB}$ (this strain is calculated for different nodes C having fixed nodes A and B), then go to the next step. Otherwise, select a different pair of points A and B.

ii) Find the position *(I, J)* to add node C satisfying the following criterion:

$$MST_C(I,J) = \underset{A,B \text{ where } ST_C(A,B) \text{ is feasible}}{Min} MST_C(A,B) \qquad (3)$$

2) <u>Selection of the next node to be added to the route in formation</u>.

i) Calculate the modified savings function:

$$MSAV_C(A,B) = \mu d_{1C} - MST_C(A,B) = \mu d_{1C} + \lambda d_{AB} - d_{AC} - d_{BC} \qquad (4)$$

ii) Find the node K to be included in the route in the next iteration, with C satisfying the vehicle capacity constraint:

$$MSAV_K(L,M) = \underset{C \text{ feasible}}{Max} MSAV_C(I,J) \qquad (5)$$

3) <u>Use of r-opt methods</u>**.** Once the nodes have been grouped, an appropriate method to re-sort nodes should be implemented: r-opt procedures are the best (Laporte, 2007). We will use the 2-opt or 3-opt methods.

4.2. Implementation and parameters of the AWEC algorithms: the rationale.

Knowing the behavior and main characteristics of Mole and Jameson's (1976) procedure (MJ algorithm), let us describe the way in which we are going to implement the external costs due to noise and environmental damage. Thus, the AWEC algorithms will proceed through in five phases.

1) <u>Data introduction</u>. The following data are required to implement the algorithm:
    a. Number of nodes, apart from the depot
    b. Coordinates x and y for each node, the real road network and the traveling times
    c. Demand associated to each node, depot included
    d. Capacity of each vehicle and number of vehicles. All vehicles have the same characteristics (Homogeneous fleet)
    e. Maximum speed of each vehicle according to road category of delivery route (urban, two-way road, dual carriageway or motorway)
2) <u>Calculation of nodes which are inserted in a new route</u>. In this phase we calculate the insertion cost functions α and β, when we try to insert node *k* between nodes *i* and *j*:

$$\alpha(i,j,k) = d_{ik} + d_{jk} - \lambda d_{ij} \qquad (6)$$
$$\beta(i,j,k) = \mu d_{1k} - \alpha(i,j,k) \qquad (7)$$

These formulae are the functions (2) and (4) as depicted in Mole and Jameson's algorithm where *i* and *j* are two fixed nodes of the network Ω and *k* is a candidate node to be implemented in the current route. In fact, following our notation $\alpha(i,j,k) = MST_k(i,j)$. These steps are undertaken to obtain estimates of the best values of the parameters λ and μ for each iteration of the current procedure. This is also known as a parameter tuning process. We will not take the traditional values recommended by Mole and Jameson; we will instead sweep the parameter square at each iteration of the algorithm, using steps of 0.1 in each parameter interval [0,1]. We will therefore be testing the parameter square using a representative network of 100 points. Since this test has no effect on problem size, it does not increase the computational complexity of the algorithm.

3) <u>Nodes introduction in the route created in the phase 2</u>. Formulae (6) and (7) are used to add more nodes to any existing route. This process is iterated as long as there are any unassigned nodes, any vehicles with available loading space and any drivers with available driving time. After having distributed the

load among the vehicles, the trucks with incomplete loads are checked to see if smaller vehicles can be found to perform the same delivery task.

4) Optimization of route solution using 2-opt or 3-opt techniques. Once we have calculated a potential route solution, we apply 2-opt or 3-opt optimization techniques. The choice of 2-opt or 3-opt depends on the complexity or the size of the problem.
5) Solution display. Eventually, the algorithm displays the final route solutions along with the main optimization values: distances and costs.

4.3. Main description of the structure of the AWEC algorithms.

The costs used to be implemented in the preceding steps are internal distance-related costs (including also costs related to safety measures) and environmental costs. The first type of costs is usually calculated employing a logistic software, such as Optrak (www.optrak.com), knowing previously the real data given by a company whose distribution process we want to analyze. The second one is calculated using the INFRAS (2004) study which provide different environmental costs according to a classification of roads or motorways, their characteristics (slope, width, traffic intensity,…) and the typology of the surrounding landscapes (urban or rural areas, high or low populated regions, national parks, …). Thus, the data provided by the INFRAS (2004) study and those provided by the company to analyze, are used to calculate the final costs of the whole distribution process.

Thus, the construction of the AWEC algorithms is based in the selection of a baseline procedure (CWS or MJ algorithms) to solve a distribution problem in a company. Later, an objective function which considers the distance-related costs along the environmental costs (provided by INFRAS, 2004) is optimized using the selected baseline procedure. It is really important to highlight that the environmental costs given by INFRAS depending strongly on the geographical area in which they have been calculated. Therefore, the new objective function designed in this way is really different to the objective function which does not consider environmental costs. That is the main characteristics of our method.

5. Solving a Real Case in the Agribusiness Sector: Computational Results

We are going to use AWEC algorithms in order to solve the logistic problems related to a canning company situated in Navarre (Spain), called Company H (this is the company nickname for discretion reasons). This firm cans and delivers frozen food (mainly vegetables) around Spain and southern Europe. Traditionally, the food canning industry breaks down vegetable canning into six categories: 1) Root Vegetables, 2) Leafy Vegetables, 3) String Beans, 4) Fresh Pack, 5) Dry Pack, 6) Specialty Vegetables. Company H is devoted to production and distribution of frozen vegetables, in a single or pooled way. The number of workers amounts to seven hundred during peak production. Company H is sited in Pamplona, Navarre (Spain).

Having described the AWEC algorithms, we will now describe the delivery routing problem of Company H in its plant in Pamplona. Company H has hired a logistic carrier LC1 to perform its delivery activities. We have obtained the delivery data of the logistic carrier LC1 in the surroundings of Pamplona (Navarre, Spain). The carrier gave us the option of optimizing ten different cases of final product delivery in cases P1-P10. We will show the outcomes for the first case only for brevity reasons. We chose the P2 case for being one of the most representative.

5.1. Data collection for case P2

Case P2 involves a delivery activity for which Company H uses up to seven vehicles the characteristics of which are described in Table 4, including their speed on urban streets, trunk roads and highways. Table 6 gives delivery route data including the depot and customers to visit. These data for all customers include Cartesian coordinates, demand, area (customer situated in the same town or village belongs to the same area), and road access (which takes a value of 1 if there is a direct access, and 0 otherwise). We used Cartesian coordinates to find the Cartesian distances and updated them using the circuity factors portrayed by Ballou *et al.* (2002). In this way we estimated the real distances between customer nodes.

5.2. Solving case P2

After the introduction of problem P2 in the AWEC algorithms using Mole and Jameson's procedure as the baseline method, we obtained the outcomes given in Table 5, in which we depict the final solution of the problem. We then calculated the costs associated to that solution in Table 8 for case P2.

Thus, from Tables 6 and 7, we can observe the characteristics of the AWEC solutions and costs for problem P2. In Table 7, we have calculated the internal costs (fixed, driver,…) according to the information and the data provided by Company H using the Optrak software (www.optrak.com). Most of those costs are affected by the structure and length of the provided route solution. We attained a good vehicle filling percentage with a large cost increment due to environmental impact and a moderate increase in costs associated to the implementation of safety measures.

Using the same procedure, we solved the complete list of ten cases P1-P10. The average costs associated to these cases are portrayed in Table 8. Comparing the P2 problem with the overall outcome, it can be seen that the results are similar for environmental costs and rather diverse for safety measures. We also compared the performance of the AWEC algorithms with different baseline methods for ten instances drawn from Augerat (1995) with the best known solutions (Faulin et al, 2011).

The solutions previously shown could be clearly improved, but they represent a first step towards routing solutions including external costs in addition to traditional distance costs. Finally, the solutions to P2 were presented to one of the managers of Company H, who considered the results very positive on the whole and in some cases eligible for implementation in other real logistic activities.

Table 4. Vehicle characteristics for the test problem P2

Truck	Capacity (kg)	Urban way speed (km/h)	Road speed (km/h)	Highway speed (km/h)
1	5,000	40	70	90
2	5,000	40	70	90
3	5,000	40	70	90
4	3,500	45	75	95
5	3,500	45	75	95
6	3,500	45	75	95
7	2,000	50	80	100

Table 5. Results obtained with the AWEC algorithms using Mole and Jameson's method as the baseline for test problem P2.

Route	Truck Class (kg)	Load (kg)	Filling percentage (%)	Distance (km)	Time (min)	Driving time (min)	Destinations	Highway (km)
1	5,000	4,862	97.24	291	502	254	12	0
2	5,000	4,650	93.00	302	523	246	14	114
3	5,000	4,005	80.10	240	375	208	8	0
Total	15000	13517	90,11	833	1400	708	34	114

6. Conclusions and Recommendations

According to our previous discussion, we highlight the importance of the present analysis in routing optimization in real companies. The following are the pooled conclusions based on an analysis of the outcomes in the above section and in the EMTOL project (Pintor *et al.,* 2005).

6.1. Conclusions about the properties of the AWEC algorithms

i. The AWEC algorithms quickly yield a solution to routing problems with less than 100 nodes (maximum time: 2 minutes).
ii. The AWEC algorithms calculate an average cost increase of 5% over the baseline cost when safety measures are implemented. This percentage increase, estimated net of transport related environmental costs, can be easily supported by logistics companies.
iii. When environmental costs are included and safety costs ignored, however, the AWEC estimates a 28% average increase in relation to the baseline case. This is a very high cost for companies to afford without public funding.

Table 6. Characteristics of the depot and destinations for test problem P2

Node	Destination	Coord_X (km)	Coord_Y (km)	Area	Highway	Demand (kg)
1	Pamplona (Depot)	83	115	1	1	0
2	Tudela I	87	27	2	1	142
3	Tudela II	87	26	2	1	80
4	Tudela III	86	27	2	1	988
5	Tudela IV	86	25	2	1	564
6	Tudela V	86	26	2	1	233
7	Tudela VI	87	25	2	1	443
8	Tudela VII	86	24	2	1	67
9	Castejon I	78	54	3	0	456
10	Castejon II	79	53	3	0	67
11	Corella I	70	31	4	0	76
12	Corella II	70	32	4	0	24
13	Corella III	70	33	4	0	233
14	Corella IV	69	30	4	0	65
15	Corella V	71	29	4	0	1,234
16	Corella VI	71	30	4	0	1,254
17	Corella VII	72	31	4	0	1,157
18	Cintuenigo I	68	27	5	0	654
19	Cintuenigo II	66	26	5	0	67
20	Cascante I	79	17	6	0	56
21	Cascante II	80	16	6	0	23
22	Cascante III	81	18	6	0	345
23	Cascante IV	79	18	6	0	644
24	Cascante V	79	16	6	0	444
25	Cascante VI	78	16	6	0	1,078
26	Peralta I	69	58	7	0	1,868
27	Peralta II	70	58	7	0	78
28	Peralta III	70	57	7	0	87
29	Peralta IV	69	58	7	0	675
30	Peralta V	70	58	7	0	65
31	Peralta VI	70	28	7	0	123
32	Marcilla	74	56	8	0	654
33	Villatuerta I	52	96	9	0	56
34	Villatuerta II	53	98	9	0	456
35	Villatuerta III	52	96	9	0	564

6.2. Conclusions regarding the use of the AWEC method in real companies

i. We foresee a promising outlook for optimization procedures to solve the VRP-SE01 problem (Table 1) in many transport companies and logistic carriers. The initial cost increase resulting from the implementation of safety measures is offset by a clear reduction in absenteeism, giving an average net cost in the region of 5% higher than in the baseline case. If we compare the outcomes of the two applications of the AWEC method, first using Clarke and Wright's procedure and then Mole and Jameson's algorithm, we find that the increment drops from 5% to 4%. Therefore, *our main result via the AWEC algorithms is the viability of safe routes for road transport systems*.

ii. However, our conclusions with respect to the incorporation of environmental criteria in route optimization are utterly negative, taking into account only the strictly economic concern of the company, which is to optimize deliveries. The inclusion of environmental costs (the sum of the noise impacts and the vehicle polluting emissions) increases optimization costs by around 28% in relation to the baseline scenario. Thus, public policies will be required in order to support the environmental impact of road transport. They could be based on some of the following options:
   a) Legislation requiring logistics companies to bear these costs, which could generate significant negative impacts on firms' competitiveness.
   b) Subsidies to help companies internalize environmental externalities, which could cause an increase of public expenditure.
   c) A mix of the above strategies, which might be the most plausible in the mid and long term.

Table 7. Costs of the routes generated with the AWEC algorithms using Mole and Jameson's method as the baseline for test problem P2.

Route	Fixed Cost (€)	Driver Cost (€)	Cost due to driven km (€)	Highway Cost (€)	Externalities Cost (€)	Cost/kg (€/kg)	Cost/km (€/km)	Total Cost (€)	Cost increase safety measures (%)	Cost increase externalities (%)
1	193.34	122.46	229.19	0.00	127.34	0.11	1.873	672.33	2.81	18.94
2	193.34	127.55	232.09	9.12	126.39	0.12	1.861	688.49	3.57	18.36
3	193.34	91.31	170.51	0.00	86.51	0.11	1.896	541.67	0.32	15.97
Total	580.02	341.32	631.78	9.12	340.23	0.12	1.875	1,902.47	2.81	17.88

Table 8. Average cost increases due to safety measures and environmental externalities: a comparison of AWEC algorithms with two baseline methods.

Clarke & Wright's baseline algorithm	Average increase due to safety measures	
	Without including environmental costs	Including environmental costs
Total cost	6.29 %	3.66 %
Mole & Jameson's baseline algorithm	Average increase due to safety measures	
	Without including environmental costs	Including environmental costs
Total cost	4.77%	3.48%
Clarke & Wright's baseline algorithm	Average increase due to inclusion of externality costs	
	Without applying safety measures	Applying safety measures
Total cost	29.84 %	25.98 %
Mole & Jameson's baseline algorithm	Average increase due to inclusion of externality costs	
	Without applying safety measures	Applying safety measures
Total cost	29.12 %	26.99 %

Similarly, these policies should encourage research in the abatement of noise and polluting emissions by means of technical improvements in vehicles, the development of new fuels, or new tire designs.

iii. Another important implication of the implementation of the AWEC algorithms is the need for alternatives to road transport. This means increased use of sea and rail in combination with road transportation; in other words, the optimization and management of intermodal freight transportation.

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