Drivers' working hours in vehicle routing and scheduling

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Abstract— **Although of particular importance for many real-life applications, restrictions to drivers' working hours have only received very little attention in the vehicle routing literature. Regulations regarding drivers' working hours often have a big impact on total travel times, i.e. the time required for driving, breaks, and rest periods. In this paper we describe the regulations for drivers' working hours in the European Union. We present the Vehicle Routing Problem with Drivers' Working Hours (VRPDWH) which generalises the well-known Vehicle Routing Problem with Time Windows. We present a Large Neighbourhood Search algorithm and test cases for the VRPDWH and conclude this paper with computational experiments.**

I. Introduction

The consideration of drivers' working hours in vehicle routing and scheduling is of extraordinary importance to increase safety and punctuality in road freight transport. Motor carriers must organise the work of drivers in such a way that drivers are able to comply with the respective regulations. Due to the commitment to the just-in-time philosophy manufacturing companies increasingly request the delivery of parts and components within narrow time windows. Punctuality can only be warranted if vehicle movements are planned considering all operational constraints, in particular, restrictions to drivers' working hours.

Vehicle telematics can be used to improve the availability of information regarding vehicle position, and driving and rest periods. This information can be used to estimate arrival times at customer locations and to plan vehicle movements if decision support and planning tools are capable of considering restrictions to drivers' working hours. Despite the importance of drivers' working hours current decision support and planning tools, as well as most literature on vehicle routing and scheduling totally ignore respective regulations.

In this paper we describe the regulations for drivers' working hours in the European Union and present the Vehicle Routing Problem with Drivers' Working Hours. Furthermore, we propose a Large Neighbourhood Search algorithm capable of handling drivers' working hours.

This paper is organised as follows. First, we discuss related work on vehicle routing focusing on the literature regarding restrictions to drivers' working hours. In section III we describe how drivers' working hours are regulated in the European Union. After giving a formulation of the Vehicle Routing Problem with Time Windows (VRPTW) in section IV, we show how driving and rest periods can be scheduled and present the Vehicle Routing Problem with Drivers' Working Hours (VRPDWH) in section V. In section VI we present a Large Neighbourhood Search algorithm for the VRPDWH. Eventually, we derive test cases for the VRPDWH from the well-known benchmark problems for the VRPTW by Solomon [1] and present computational experiments performed on these test cases.

II. Related work

The VRP book edited by Toth and Vigo [2] covers the state of the art of both exact and heuristic methods for the Vehicle Routing Problem (VRP) and some of its most important variants. The Vehicle Routing Problem with Time Windows (VRPTW) is one of the best studied variants of the VRP and a comprehensive survey of the VRPTW is provided by [3]. Recent surveys on construction heuristics and metaheuristics for the VRPTW have been presented by Bräysy and Gendreau [4], [5].

Although of particular importance for many real-life applications, restrictions to drivers' working hours have only received very little attention in the vehicle routing literature. A maximum number of hours worked during a tour can be modelled similar to capacity restrictions. This approach is for example used by [6]. Only very few works have tried to address vehicle routing problems in which drivers can only work for a limited amount of time during a working day and must take a daily rest period before they are allowed to continue the tour. [7] present a Column Generation approach for a dynamic and generalised Pickup and Delivery Problem in which lunch breaks and night breaks must be taken within fixed time intervals. Drivers' working hours as regulated by the U.S. Department of Transportation have been considered by [8] who present a Column Generation approach for a rich Pickup and Delivery Problem. [8] do not consider that a daily rest periods may be taken before the maximum daily driving time is exhausted. Such "early" rest periods, however, are required in order to be able to satisfy narrow time windows at subsequent customer locations.

We are not aware of any work considering EU regulations regarding drivers' working hours. These regulations are more complicated than the regulations of the U.S. Department of Transportation as, in addition to daily rest periods, short breaks must be made after four and a half hours of uninterrupted driving.

III. Drivers' working hours

In the European Union drivers' working hours are currently regulated by EC regulation 3820/85 [9]. In February 2006 the European Parliament and the Council of the European Union have agreed on new regulations on working time, breaks, and rest periods for drivers engaged in road transport of goods and passengers [10] which will enter into force in April 2007. According to the new regulations motor carriers must organise the work of drivers in such a way that drivers are able to comply with the regulations and are made liable for infringements committed by the drivers. The new regulations are:

- After a driving period of four and a half hours a driver shall take an uninterrupted break of not less than 45 minutes, unless he takes a rest period. During a break a driver must not drive or undertake any other work.
- The daily driving time between the end of one daily rest period and the beginning of the following daily rest period shall not exceed 9 hours. A daily rest period is any period of at least 11 hours during which a driver may freely dispose of his time.
- The weekly driving time shall not exceed 56 hours.
- A weekly rest period shall start no later than 144 hours after the end of the previous weekly rest period.

Figure 1 illustrates an example of driving and rest periods for a vehicle manned by one driver. In a multiple manned vehicle, the other driver(s) may take a break on the moving vehicle whilst one driver is driving. Furthermore, the daily rest period in which the vehicle must be stationary may be reduced to 9 hours. As can be seen in figure 2, travel times for long distance haulage are significantly shorter for vehicles manned by two drivers than for vehicles manned by one driver.

In this paper we only consider the working period between two consecutive weekly rest periods and the regulations described above. Further regulations apply but they are not regarded in the remainder of this work:

- The daily driving time can be extended to at most 10 hours not more than twice during the week.
- The daily rest period may be reduced to 9 hours not more than 3 times during the week.

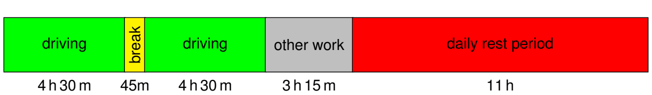

Fig. 1. Driving and rest periods

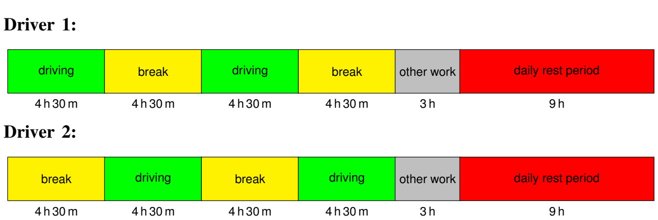

Fig. 2. Driving and rest periods for a vehicle manned by two drivers

- The break may be replaced by a break of at least 15 minutes followed by a break of at least 30 minutes.
- The daily rest period may be taken in two periods, the first of which must be an uninterrupted period of at least 3 hours and the second an uninterrupted period of at least 9 hours.
- Within each period of 24 hours (30 hours) after the end of the previous daily rest period a driver (a driver engaged in multi-manning) shall have taken a new daily rest period.

Furthermore, there are regulations regarding weekly rest periods, the maximum weekly working time, and the accumulated driving time during any two consecutive weeks.

IV. Vehicle routing with time windows

The *Vehicle Routing Problem* (VRP) concerns the distribution of goods and products to customers by a set of vehicles, which are located in a depot, are operated by a set of drivers, and perform their movements by using an appropriate road network. In particular, the solution of a VRP calls for the determination of a set of tours, each performed by a single vehicle that starts and ends at the depot, such that all the requirements of the customers are fulfilled, all the operational constraints are satisfied, and the global transportation cost is minimised. The *Vehicle Routing Problem with Time Windows* (VRPTW) is the extension of the VRP in which capacity constraints are imposed and each customer is associated with a time interval during which the service of the customer must start [11].

Let $\mathcal{C}$ denote the set of customer locations and let $\mathcal{V}$ denote the set of vehicles available. For each vehicle let $n_{(v,1)}$ and $n_{(v,2)}$ denote a node corresponding to the depot where all vehicles start and end their tour. That is, several nodes correspond to the same geographical location (the depot). Let

$$\mathcal{D}_+ := \{n_{(v,1)} \mid v \in \mathcal{V}\}$$

and

$$\mathcal{D}_- := \{n_{(v,2)} \mid v \in \mathcal{V}\}$$

and

$$\mathcal{N} := \mathcal{C} \cup \mathcal{D}_+ \cup \mathcal{D}_-$$

and

$$\mathcal{A} := \big(\mathcal{C} \cup \mathcal{D}_+\big) \times \big(\mathcal{C} \cup \mathcal{D}_-\big) \setminus \big\{(n,n) \mid n \in \mathcal{C}\big\} \cup \mathcal{D}_- \times \mathcal{D}_+.$$

Each arc $(n,m) \in \mathcal{A}$ is associated with costs c_{nm} and travel times d_{nm} that may include the time required for service at node n. Note that arcs $(n,m) \in \mathcal{D}_- \times \mathcal{D}_+$ are only used to simplify the notation and have zero costs. The capacity of the vehicles is denoted by $r^{\max}$ and each customer location $n \in \mathcal{C}$ is associated with a known resource demand r_n. Each customer $n \in \mathcal{C}$ is associated with a time interval $[t_n^{\min}, t_n^{\max}]$, called a *time window*. The vehicle must arrive at the customer location within its time window and may have to wait during the trip in order not to arrive too early. For each node $n \in \mathcal{D}_+ \cup \mathcal{D}_-$ the demand r_n is zero and the time interval $[t_n^{\min}, t_n^{\max}]$ represents the total availability during which the vehicles may be en-route.

For each arc $(n,m) \in \mathcal{A}$ the binary variable x_{nm} indicates whether node m is visited immediately after node n. For each node $n \in \mathcal{C} \cup \mathcal{D}_-$ the variable t_n represents the arrival time at the node and for each $n \in \mathcal{D}_+$ variable t_n represents the time the vehicle starts its tour. For each node $n \in \mathcal{N}$ the variable ρ_n represents the accumulated demand.

The *Vehicle Routing Problem with Time Windows* (VRPTW) is

minimise

$$\sum_{(n,m)\in\mathcal{A}} x_{nm} c_{nm} \tag{1}$$

subject to

$$\sum_{(n,m)\in\mathcal{A}} x_{nm} = \sum_{(m,n)\in\mathcal{A}} x_{mn} \text{ for all } n \in \mathcal{N} \tag{2}$$

$$\sum_{(n,m)\in\mathcal{A}} x_{nm} = 1 \text{ for all } n \in \mathcal{N} \tag{3}$$

$$\rho_n = 0 \text{ for all } n \in \mathcal{D}_+ \tag{4a}$$

$$\text{for all } (n,m) \in \mathcal{A} \text{ with } n \in \mathcal{C} \cup \mathcal{D}_+ : \tag{4b}$$

$$\text{if } x_{nm} = 1 \text{ then } \rho_m = \rho_n + r_m$$

$$\rho_n \le r^{\max} \text{ for all } n \in \mathcal{N} \tag{4c}$$

$$\text{for all } (n,m) \in \mathcal{A} \text{ with } n \in \mathcal{C} \cup \mathcal{D}_+ : \tag{5a}$$

$$\text{if } x_{nm} = 1 \text{ then } t_m \ge t_n + d_{nm}$$

$$t_n^{\min} \le t_n \le t_n^{\max} \text{ for all } n \in \mathcal{N} \tag{5b}$$

$$x_{nm} \in \{0,1\} \text{ for all } (n,m) \in \mathcal{A} \tag{6}$$

Equation (2) represents the flow conservation constraints which impose that exactly the same number of vehicles reach a node $n \in \mathcal{N}$ as vehicles depart from it. Equation (3) imposes that each node is visited exactly once. Constraints (4a), (4b), and (4c) are the capacity constraints which impose that the accumulated demand at any point in the tour of a vehicle is less or equal the capacity of the vehicle. Constraints (5a) and (5b) are the time window constraints which impose that each arrival time is within the time window at the node. Eventually, constraints (6) impose that all x_{nm} are binary.

V. Vehicle routing with drivers' working hours

In many real-life problems regulations regarding drivers' working hours must be considered when constructing tours. Therefore, the total travel time of a trip from one node to another is the sum of the pure driving time and the time required for breaks and rest periods. In order to consider drivers' working hours we use the following notation:

s_n	the service time required at node $n \in \mathcal{N}$
δ_{nm}	the pure driving time from node $n \in \mathcal{N}$ to node $m \in \mathcal{N}$
t_{weekly}	the maximum weekly driving time between two consecutive weekly rest periods
t_{daily}	the maximum daily driving time between two consecutive daily rest periods
t_{nonstop}	the maximum nonstop driving time between two consecutive breaks or rest periods
t_{rest}	the time required for a daily rest period
t_{break}	the time required for a break

In this paper we assume that service times are working periods in which drivers perform handling activities. Consequently, the service time must not be interpreted as a break and must not be part of a daily rest period. As illustrated in figure 3, the state of the driver at a customer location cannot be uniquely determined as it is possible to schedule driving and rest periods in a way such that rest periods are taken before the respective accumulated driving time is exhausted. For all nodes $n \in \mathcal{N}$ a label

$$l_n = \begin{pmatrix} l_{n,1} \\ l_{n,2} \\ l_{n,3} \\ l_{n,4} \end{pmatrix} = \begin{pmatrix} \text{arrival time} \\ \text{weekly driving time} \\ \text{daily driving time} \\ \text{nonstop driving time} \end{pmatrix}$$

can be used to represent the state of the driver at the node. The vehicle can start the service at node $n \in \mathcal{N}$ at time $l_{n,1}$ and can depart from n at time $l_{n,1} + s_n$. It may drive $t_{\text{weekly}} - l_{n,2}$ before the next weekly rest period, $t_{\text{daily}} - l_{n,3}$ before the next daily rest period, and $t_{\text{nonstop}} - l_{n,4}$ before the next break.

Although there may be very many different labels at a node, not all of them need to be considered. A label l_n

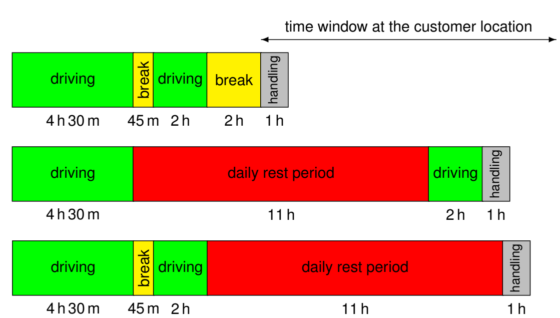

Fig. 3. Alternative driver states at a customer location

dominates another label l'_n if

$$l_{n,1} \leq l'_{n,1} \text{ and } l_{n,2} \leq l'_{n,2} \text{ and } \quad \text{(D1)}$$
$$l_{n,3} \leq l'_{n,3} \text{ and } l_{n,4} \leq l'_{n,4}$$

or

$$l_{n,1} + t_{\text{break}} \leq l'_{n,1} \text{ and } l_{n,2} \leq l'_{n,2} \text{ and } \quad \text{(D2)}$$
$$l_{n,3} \leq l'_{n,3}$$

or

$$l_{n,1} + t_{\text{rest}} \leq l'_{n,1} \text{ and } l_{n,2} \leq l'_{n,2}. \quad \text{(D3)}$$

Obviously, if a label is dominated by (D1) it doesn't need to be considered. If a label dominates another label by (D2) the vehicle may continue its tour with a break period, and after the break (D1) is satisfied. Analogously, if a label dominates another label by (D3) the vehicle may continue its tour with a daily rest period, and after the daily rest period (D1) is satisfied. Note that none of the labels corresponding to the driver states illustrated in figure 3 dominates the others.

Consider that a vehicle is supposed to travel from node $n \in \mathcal{N}$ with label l_n to a node $m \in \mathcal{N}$. As illustrated in figure 3, several labels can be determined for node m. As only working periods between two consecutive weekly rest periods are considered in this paper, it is assumed that $l_{n,2} + \delta_{nm} \leq t_{\text{weekly}}$. Otherwise, a weekly rest period would be required before reaching node m. In order to determine possible labels at node m let

$$l_m := (l_{n,1} + s_n, l_{n,2} + \delta_{nm}, l_{n,3}, l_{n,4})^T$$

and let $\mathcal{L} := \emptyset$. The recursive function illustrated in figure 4 is invoked by expand_label(l_m, δ_{nm}). First, the time the vehicle may drive uninterrupted is calculated and the label and the remaining required driving time δ are respectively adjusted. If $\delta = 0$ node m is reached and the label l_m is added to the set $\mathcal{L}$. If $\delta > 0$ and $l_{m,3} = t_{\text{daily}}$ a daily rest period is required before the vehicle may continue to travel towards m and the label is respectively adjusted. If $\delta > 0$ and $l_{m,3} < t_{\text{daily}}$ and if δ or the remaining daily driving time are less or equal t_{nonstop} a new label l'_m is generated with arrival time $l_{m,1} + t_{\text{rest}}$, zero daily driving time, and zero nonstop driving time. This new label is generated as it may be beneficial to continue with a daily rest period instead of a break. The new label is expanded by invoking expand_label(l'_m, δ). Then, the time required for a break is added to the arrival time of label l_m and the remaining required nonstop driving time is respectively adjusted. The label expansion continues with the calculation of the next driving period.

Let $l_m \in \mathcal{L}$ be a label generated as described above. The arrival time $l_{m,1}$ may be smaller than the begin of the time window $t_m^{\min}$. Therefore, for all $l_m \in \mathcal{L}$ let

$$\mathcal{L}(l_m) := \Big\{ \big(\max\{t_m^{\min}, l_{m,1}\}, l_{m,2}, l_{m,3}, l_{m,4}\big)^T,$$
$$\big(\max\{t_m^{\min}, l_{m,1} + t_{\text{break}}\}, l_{m,2}, l_{m,3}, 0\big)^T,$$
$$\big(\max\{t_m^{\min}, l_{m,1} + t_{\text{rest}}\}, l_{m,2}, 0, 0\big)^T \Big\}$$

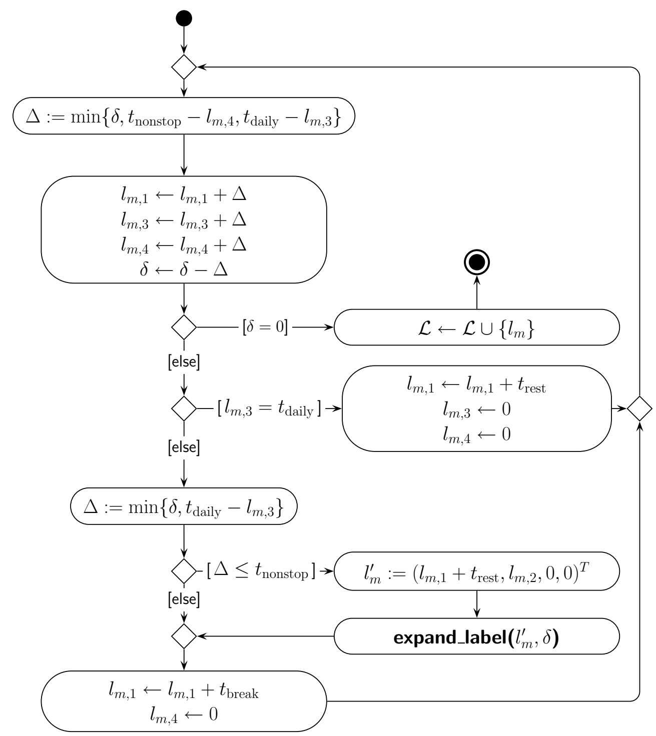

Fig. 4. Recursive function expand_label(l_m, δ)

denote a set of potential labels. Now, let $\mathcal{L}_m(l_n)$ denote the set of labels containing all

$$l \in \Big\{ l'_m \in \bigcup_{l_m \in \mathcal{L}} \mathcal{L}(l_m) \mid l'_{m,1} \leq t_m^{\max} \Big\}$$

such that no label is dominated by any other label and let l^v denote the initial label at the start of the tour of vehicle $v \in \mathcal{V}$.

The *Vehicle Routing Problem with Drivers' Working Hours* (VRPDWH) is

minimise (1)
subject to (2), (3), (4a), (4b), (4c), (6) and

$$l_{n_{(v,1)}} = l^v \text{ for all } v \in \mathcal{V} \quad \text{(5a')}$$

$$\text{for all } (n,m) \in \mathcal{A}, v \in \mathcal{V} \text{ with } n \in \mathcal{C} \cup \mathcal{D}_+ : \quad \text{(5b')}$$
$$\text{if } x_{nm} = 1 \text{ then } l_m \in \mathcal{L}_m(l_n)$$

Constraints (5a') and (5b') replace the time window constraints of the VRPTW formulation and impose that time window constraints are satisfied at each node and that drivers' working hours are satisfied for all trips.

VI. Solution approach

The difficulties in solving the VRPDWH come from three aspects. First, the VRPDWH generalises the VRPTW which already is hard to solve. Second, it is impossible to efficiently determine all possible sets of labels $\mathcal{L}_m(l_n)$. Eventually, a change at one point in the tour requires the recalculation of all labels of subsequent points in the tour.

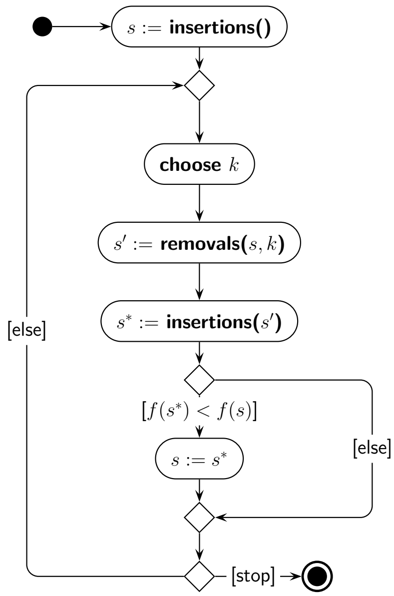

Fig. 5. Large Neighbourhood Search

In this section we propose a Large Neighbourhood Search (LNS) algorithm for the VRPDWH. LNS has been presented by [12] for the VRPTW and has proven to be well suited for rich vehicle routing problems [13], [14]. The LNS algorithm is outlined in figure 5. The basic idea is to start with an initial solution and to remove k customers from their tours. After these k customers are removed an insertion method tries to re-insert the removed customers. If the new found solution is better than the previous, the previous solution is replaced. The algorithm continues with the next iteration until some termination criterion is met.

The choice of customers to be removed in one LNS iteration can be made completely randomly or according to some appropriate *relatedness* criterion. For example, [12] proposes a relatedness criterion based on geographical distance, difference of arrival times in the current schedule, and the difference of the demand at the customer location.

The (re-)insertion of customer locations can be made by any tour construction method, e.g. the auction method proposed by [15] for the VRPTW. An iteration of the auction method can be divided into three phases which are illustrated in figure 6. In the first phase all unscheduled customers request and receive from each vehicle an insertion possibility and the costs of insertion. In order to determine whether an insertion of a customer is feasible all labels of the node preceding the customer must be expanded and all labels of succeeding nodes must be recalculated. An infinite cost is assumed if no feasible insertion is possible. In the second phase each unscheduled customer, chooses a vehicle with low incremental costs and sends a proposal for insertion to this vehicle. In phase three each vehicle which received a proposal chooses a customer for insertion to the tour. The insertion method stops if no customer can be inserted and continues otherwise.

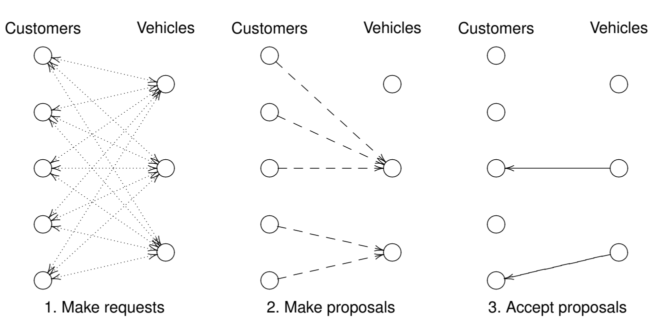

Fig. 6. Illustration of the auction method

VII. Computational Experiments

In order to perform computational experiments we modified the well-known Solomon benchmark problems for the VRPTW [1]. All values representing times in the Solomon problems are interpreted as minutes. The time windows, however, are multiplied by ten. The vehicles travel at a speed such that they can travel 5 units per hour. As a weekly rest period is required after 144 hours, the availability of all vehicles is restricted. If the time interval representing the total availability of the vehicles in the Solomon problems is greater the vehicles are given different periods of availability, each of length 144 hours. In this case, the labels must be tagged with the vehicle index and only such labels

TABLE I

Results

	0 sec		1800 sec		3600 sec	
	$\lvert\mathcal{V}\rvert$	$\sum d$	$\lvert\mathcal{V}\rvert$	$\sum d$	$\lvert\mathcal{V}\rvert$	$\sum d$
c103	17	2713.52	11	1186.56	10	1166.94
c104	15	2536.17	10	1360.39	10	1247.57
c105	19	2467.14	11	1168.05	11	1031.99
c106	19	2625.00	11	1063.61	11	1037.70
c107	18	2476.14	10	1126.10	10	1047.10
c108	17	2536.82	10	1110.42	10	1071.69
c109	13	2198.24	10	1192.47	10	1174.02
c201	25	3153.36	14	1291.64	14	1291.64
c202	25	2998.99	11	1298.27	11	1270.90
c203	24	2993.64	11	1303.02	10	1308.61
c204	16	2349.06	11	1390.67	10	1339.77
c205	25	2411.51	13	1337.66	13	1327.58
c206	24	3133.63	11	1206.87	10	1110.77
c207	22	2684.07	11	1223.27	11	1126.62
c208	22	3079.18	13	1308.01	12	1232.14
r201	15	2092.35	10	1338.95	10	1290.76
r202	18	2146.33	9	1254.65	9	1219.11
r203	14	1928.22	8	1085.67	7	1049.04
r204	13	2132.75	9	1202.16	8	1175.36
r205	10	1961.76	9	1199.13	9	1132.88
r206	11	1967.23	9	1185.57	9	1170.87
r207	15	2415.15	9	1159.65	8	1171.00
r208	9	1731.24	6	1065.69	5	908.42
r209	15	2031.26	11	1164.77	11	1102.86
r210	11	1972.78	8	1150.12	8	1058.87
r211	13	1884.35	8	1108.48	8	1067.81
rc201	17	2712.29	10	1486.77	10	1472.19
rc202	14	2253.66	12	1447.74	12	1441.00
rc203	11	2261.01	9	1381.43	9	1327.16
rc204	12	2223.21	9	1288.13	9	1244.64
rc206	14	2883.06	8	1334.98	8	1224.96
rc207	15	2934.40	9	1440.30	8	1295.47
rc208	13	2475.81	6	1127.53	6	1075.75

must be considered which have an arrival time within the availability of the vehicle. The periods of availability are distributed such that the ith vehicle becomes available at time $(i-1)\Delta$ after the begin of the total availability given in the Solomon problems. The value of Δ is such that the last vehicle becomes available 144 hours before the end of the total availability. All vehicles are manned by one driver and the following parameters are used: $t_{\text{weekly}} = 56$ hours, $t_{\text{daily}} = 9$ hours, $t_{\text{nonstop}} = 4.5$ hours, $t_{\text{rest}} = 11$ hours, and $t_{\text{break}} = .75$ hours.

Computational experiments were performed on a Intel Pentium 4 processor with 2 GHz. In order to minimise the number of vehicles first and then the total distance travelled all arcs $(n,m) \in \mathcal{D}_+ \times \mathcal{D}_-$ where given a high negative cost, such that empty tours were preferred in the LNS algorithm. In each LNS iteration $k \in [2,30]$ customers were removed from the tours. The value of k as well as the customers to be removed were chosen randomly. Table I shows the number of vehicles ($|\mathcal{V}|$) and the total distance travelled ($\sum d$) of the initial solution, the solution after 30 minutes, and the solution after 60 minutes of computation. Some problems are not listed in the table (c101, c102, rc205, and all problems belonging to the series r1 and rc1) as, due the modification of the Solomon problems, not all customers can be feasibly served in the VRPDWH problems.

VIII. Conclusions and Future Research

This paper describes how drivers' working hours are regulated in the European Union. We have shown how driving and rest periods can be scheduled considering the fact that rest periods may be taken before the respective accumulated driving time is exhausted. Such "early" rest periods are required in order to be able to satisfy narrow time windows at customer locations. To our knowledge no existing models have addressed this issue so far. In fact, only very few works have addressed regulations regarding drivers' working hours at all. This paper presents the Vehicle Routing Problem with Drivers' Working Hours which generalises the Vehicle Routing Problem with Time Windows. The same generalisations can be easily made to other variants of the VRP, e.g. the VRP with pickups and deliveries which is often used in long-distance haulage. The consideration of drivers' working hours will significantly improve the applicability of schedules as the time required for breaks and rest periods is often a significant portion of the total travel time. We proposed a Large Neighbourhood Search algorithm capable of handling drivers' working hours. Furthermore, we presented test cases for the VRPDWH derived from Solomon's benchmark problems for the VRPTW and performed computational experiments. Future research will show how the proposed algorithm competes against other solution approaches. Further research is necessary in order to consider all the regulations imposed by EU social legislation.

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