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Two variants of bi-objective Vehicle Routing Problem in Home (Health)-Care fields

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Abstract In this research paper, we consider two bi-objectives models, the Vehicle Routing Problem Preferences with Time windows, temporal dependencies, multiple structures and multiple specialties “VRPPTW-TD-2MS” and the Vehicle Routing Problem Balance with Time windows, temporal dependencies, multiple structures and multiple specialties “VRPBTW-TD-2MS”, in Home (Health)-Care “HHC” service field. In this context, The HHC services is mostly assigned to certain persons such as people who have a chronic disease or who have difficulty leaving their houses by offering them medical, social, and/or medico-social services like nursing, dressing, bathing, toileting, feeding, shopping, hygiene assistance, etc. These several services are provided by different public and private home care structures. These structures work together in coordination to provide high HHC quality for patients. Therefore, patients are not in a single structure anymore, but rather at home and need to be served by caregivers. As a result, the problem is no longer limited to the care organization, but also to the construction of optimal tours for the caregivers, the delivery of medicines, and the equipment needed for care. According to our knowledge, our work is different from those made in the literature. Our problem consists to determine the caregivers’ tours while optimizing bi-objective function, which aims to minimize the total traveling time and the total negative preference or the maximal difference workload of caregivers under set of constraints such as time window, synchronization, precedence and disjunction constraints with multiple structures and multiple caregivers’ skills. A benchmark of instances is considered from literature. Cplex (Optimization Software package) is used to solve our problems to obtain efficient solutions.

Keywords: VRPPTW-TD-2MS, VRPBTW-TD-2MS, Bi-objective, Home (Health)-Care.

1 Introduction

Some challenges related to care recipient, care provider, artifacts (equipment/technology and supplies) and health care environment (especially affective challenges, cognitive challenges, physical challenges, degraded quality, the home environment, work environment, etc.) [1] raise from the strategic, tactic and operational perspectives by the incorporation of home care in logistics and transports activities. In this context, we are interested to shed light on HHC services, which is a growing sector in the society. It becomes increasingly legitimate ([2], [3]) due to the evolution of an aging population ([4]) and the crisis context like Covid-19 [5] This sector is still witnessing numerous evolutions according to demographic, political, and economic factors. In many countries, scientific researchers place great importance on the people's satisfactions, needs and the improvement of the living conditions ([6], [7], [8]).

For several years, the scientific study has been dealing with the care organization in hospitals ([9], [10] etc.). The follow-up of some patients' health does not require their presence in the hospital. There is no need to the continuous presence of the nurse or specific materials to take care of them. In this case, the follow-up can be carried out with patients at their home. This service aims to avoid the unnecessary hospitalizations, to reduce convalescence periods and hospital infections. Some patients needs other services such as cleaning, cooking and shopping etc. These types of services are provided by different home care structures belonging to the social, medical and/or medico-social fields. Therefore, optimizing those resources (materials and human levels) is among companies' top priorities and considerable efforts. The objective of our research is to propose a model to assign patients (visits) to nurses (caregivers) and determine the routing of each caregiver. So, we are interested in designing decision support tools to provide solutions for decision-makers and to arrange vehicle routing to serve geographically distributed patients under various constraints (synchronization, precedence, disjunction, multiple structure and multiple skills) in order to minimize the total transportation time and the total negative caregiver's preference or balance their workload.

This paper begins with the problem description and a literature review of Vehicle Routing Problem's "VRP" variants based on different approaches. Modelization of the problem and experimental results will be presented in the next section.

2 Problem Description and Literature Review

2.1 Problem Description

The growing old population and the increasing demand of care take overtake the capacity of health institutions, which generates a developing trend in home care. In the Operational Research community, many authors have addressed by this issue, which interests aspects are related to VRP ([11], [12]). The VRP is considered an excellent application for different programs not only HHC but also offering different social services ([13], [14], [15], [16]). It aims to define a set of ways to manage the group of patients.

The goals may vary and depend on each context and institution. Among the most common, we can find, minimizing the cost measure (about travelling time/distance) and maximizing the preference of stakeholders (patient/ caregivers) to ensure their satisfaction level. In this context, a group of caregivers should visit a set of geographically dispersed customers (patients) respecting time windows and time-dependent constraints such as synchronization that requires more than one vehicle to serve a patient at the same time, precedence that requires a fixed order between home care workers and disjunction that means the precedence of the precedence. These couples of visits are carried out on the same patient and with two home care workers having different specialties. These home care workers can be from the same structure or from different structures. Thus, their accessibility, their skills and their structures must also be taken into account. About the service of each caregiver, each one leaves his structure and return to his starting point taking into consideration a limited number of hours per day.

2.2 Literature Review

In this section, we present a survey work related to HHC. We take a look at research work that addresses the routing problem as Vehicle Routing Problem (VRP) in the HHC context. We can find a very large number of VRP variants, which present many similarities, but differ in structures. Each problem variant is designed using parameters describing the assumptions, the constraints, and the objectives.

[17] considered the routing and/or scheduling nurses problem which minimizes the cost objective function, the total of extra time, and the part-time work that is scheduled taking into consideration time windows, breaks, multi-skills, and multi-structure constraints. They proposed two heuristic methods to solve the problem.

[18] optimized Home Health Care services respecting patients' preference, caregivers' preference and their qualifications. They solved the problem with Tabu Search and simulated annealing meta-heuristics.

[19] modelled the Home Care Crew Scheduling problem as a problem of a partitioning set with temporal dependencies and time windows constraints. The latter is solved with column generation in a Branch-and-Price framework.

[20] surveyed the vehicle tour problem with time windows and synchronization constraint. A home care environment, one depot, and a unique period are crucial elements to formulate and solve the problem. They considered three objective functions: reducing travel time, minimizing negative preference patients, or minimizing caregivers workload difference. To solve this problem, they developed a heuristic approach.

[21] developed a MILP which aims to minimize the total travel time of nurses under constraints of time windows, staff lunch breaks, patient-staff regularity, and synchronization visits between home workers. Two solvers were presented by authors to solve one instance of the model, which are: LINGO from LINDO SYSTEMS and OPL-CLPEX from ILOG Studio.

[22] respected the same considerations of [20] but they solve their problem using the LINGO of LINDO SYSTEMS solvers.

[23] tried to solve Health Care routing problem under; time windows, caregivers' skills, breaks and patients' dislikes constraints using a Variable Neighborhood Search

algorithm. Their goal is either maximizing the satisfaction level of patients/home workers or minimizing the traveling times of the caregivers.

[11] used Branch-and-Price method to solve the generalization of the Vehicle Routing Problem with Time Windows (VRPTW). Time windows, synchronization, preferences and precedence constraints are modelled as services provided to patients. Their objectives is to minimizing uncovered visits, maximizing caretaker-visit preferences and minimizing the total travelling costs.

[24] established daily home care planning with visits synchronization respecting the patients' time windows.

[25] have proposed a decision support tool based on a simulated annealing method. Their method was tested on the instances of [20] with the latest criterion.

[26] presented a case study for HHC. They developed a linear program taking into account Time Windows and caregivers' skills constraints while the main objective is to find an optimal route for visits scheduled every day.

[27] treated a chance-constrained home-caregiver scheduling and routing problem with stochastic travel and service times. The problem is modelled as a bi-objective function, which minimizes the expected total operational cost of selected routes and a penalty cost for unserved customers, subject to the following constraint: Time windows and a chance constraint. As a solution method, they combined the branch-and-price algorithm and the discrete approximation method.

[28] introduce the HHC routing and scheduling problem (HHC-RSP) for two separate services set of HHC and Home Delivery Vehicles that are affected by the different staff because of operational constraints. Consequently, the proposed MILP solved by the heuristic method suggests minimizing the total travel cost and route affectation cost for nurse and vehicle routes. The synchronization between different services considered.

[29] formulated a MIP model as new variant of "VRPTW" named "VRPTW-TD-2MS" the vehicle routing problem with time windows, time dependencies, multi-structures, and multi specialities problem. They proposed Variable Neighborhood Search; General Variable Neighborhood Search; and General Variable Neighborhood Search with Ejection Chains-based for solving their model.

[30] treated the Stochastic Districting–Staff Dimensioning–Assignment–Routing Problem, the objective is to minimize the hiring, violation of the neighbourhood constraint, and estimated travel costs. The constraints considered in this work are; skill levels of the caregivers, time window. A novel met-heuristic algorithm offered to solve the model of this problem.

[31]; [32]; [4]; [33]; [34] ; etc. have proposed relatively a complete review of the literature on Home Health Care routing and scheduling issues.

3 Modelization and Experimental Results

3.1 Modelization

We extend the mathematical modeling Vehicle Routing Problem with Time Window, Temporal dependencies, multiple structures and multiple specialties "VRPTW-TD-2MS" of [29] to deal with two bi-objective optimization models (the first model is

“VRPPTW-TD-2MS”, and the second model is “VRPBTW -TD-2MS”). The purpose of our first model is to design the least-cost routes for units caregivers (vehicles), taking into consideration the maximal preference of patients. The purpose of our second model is to design the least-cost routes for caregivers, taking into consideration the minimization of the maximal difference workload of home care workers.

Notations

$G = \bigcup_{s=1..s} (S^s, E^s)$	Undirected graph
$S^s = V^s \cup C^s$	The node set
$C^s = \{0, n_s + 1\}$	The initial and final structure s
$V^s = \{1, \dots, n_s\}$	The visit points of structure s
E^s	The edge-set for structure s
P	The set of speciality
T_{ij}^s	The travel duration
D_i^s	The time duration
$Pref_{jk}^s$	The preference measure
$[a_i^{sk}, b_i^{sk}]$	Time window preference where a_i^{sk} and b_i^{sk} respectively the earliest start time and the latest start time of visit i
p^{synch}	The set of couple of visits that are synchronized
p^{pred}	The set of couple of visits subject to precedence constraints
p^{disj}	The set of couple of visits subject to disjunction
w	The balancing variable
$W_{ijk}^s = D_i^s$	The measure is in service duration
$W_{ijk}^s = T_{ij}^s$	The measure is in traveling time
$\alpha 1, \alpha 2$	Weights of the objectives

Parameters

z_{pk}^s : A binary parameter that is equal to 1 if home care worker k from structure s has a specialty p, 0 otherwise. y_{ip}^s : A binary parameter that is equal to 1 if visit i is to be carried out by a home care worker from structure s with specialty p, 0 otherwise.

Decision variables

x_{ijk}^s : A binary decision variable that is equal to 1 if the vehicle k from structure s goes from visits i to j, 0 otherwise. t_{ik}^s : A real decision variable indicates the starting time of visit i if this latter is visited by vehicle k from structure s, 0 otherwise.

A detailed solution example for our problems is shown in the figure below:

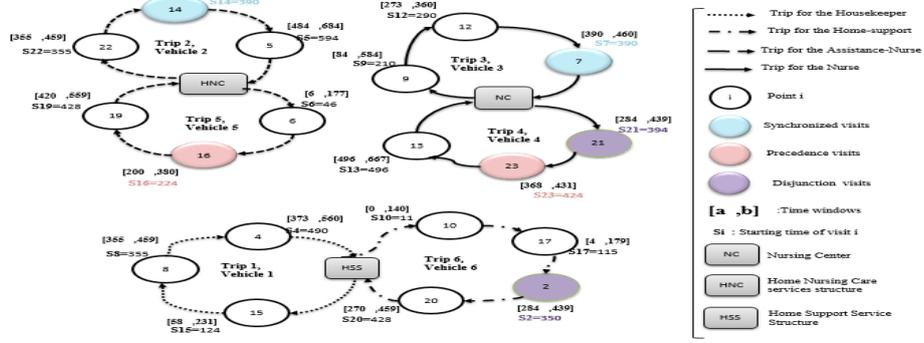


Fig. 1. Example for VRPPTW-TD-2MS or VRPBTW-TD-2MS problems.

A detailed solution example see in the (Fig. 1), for a simple instance with NC structure, HSS structure and HNC structure, hold in total 19 points (Patients or visits). Point 7 from NC structure and point 14 from HNC structure are two synchronized visits that have the same starting time of services. Point 16 from HNC structure and point 23 from NC structure are two precedence visits that visit 16 have to precede visit 23. Point 21 from NC structure and point 2 from HSS structure are two disjunction visits that have the same time windows but cannot be performed at the same time. Six caregivers with four skills carry out these visits.

The mathematical modeling of the VRPPTW-TD-2MS formulated as follows (Model 1):

$$\text{Minimize } \alpha 1 \sum_{s \in S} \sum_{k \in K^s} \sum_{(i,j) \in E^s} T_{ij}^s x_{ijk}^s + \alpha 2 \sum_{s \in S} \sum_{k \in K^s} \sum_{(i,j) \in E^s} Pref_{jk}^s x_{ijk}^s \quad (1)$$

Subject to

$$y_{ip}^s = 1: \sum_{k \in K^s} \sum_{j \in V^{s+}} y_{jp}^s x_{ijk}^s z_{pk}^s = 1 \quad \forall s \in S, p \in P^s, i \in V^s \quad (2)$$

$$z_{pk}^s = 1: \sum_{i \in V^s} x_{0ik}^s y_{ip}^s = \sum_{i \in V^s} x_{i(n_s+1)k}^s y_{ip}^s = 1 \quad \forall s \in S, k \in K^s, p \in P^s \quad (3)$$

$$y_{ip}^s z_{pk}^s = 1: \sum_{j \in V^{s+}} x_{ijk}^s y_{jp}^s = \sum_{j \in V^{s-}} x_{jik}^s y_{jp}^s \quad \forall s \in S, i \in V^s, k \in K^s, p \in P^s \quad (4)$$

$$t_{ik}^s + (D_i^s + T_{ij})x_{ijk}^s \leq t_{jk}^s + (1 - x_{ijk}^s)b_i^{sk} \quad \forall s \in S; k \in K^s; (i,j) \in E^s \quad (5)$$

$$a_i^{sk} \sum_{j \in V^s} x_{ijk}^s \leq t_{ik}^s \leq b_i^{sk} \sum_{j \in V^s} x_{ijk}^s \quad \forall s \in S; i \in V^s; k \in K^s \quad (6)$$

$$a_i^{sk} \leq t_{ik}^s \leq b_i^{sk} \quad \forall s \in S, i \in \{0, n_s + 1\}, k \in K^s \quad (7)$$

$$\sum_{k \in K^s} t_{ik}^s = \sum_{k \in K^{s'}} t_{jk}^{s'} \quad \forall (i,j) \in P^{synch}(\text{with } i \in V^s, j \in V^{s'}) \quad (8)$$

$$\sum_{k \in K^s} t_{ik}^s + D_i^s \leq \sum_{k \in K^{s'}} t_{jk}^{s'} \quad \forall (i,j) \in P^{pred}(\text{with } i \in V^s, j \in V^{s'}) \quad (9)$$

$$\sum_{k \in K^s} t_{ik}^s + D_i^s \leq \sum_{k \in K^{s'}} t_{jk}^{s'} \text{ or } \sum_{k \in K^s} t_{jk}^s + D_j^s \leq \sum_{k \in K^{s'}} t_{ik}^{s'} \quad \forall (i, j) \in P^{disj} (i \in V^s, j \in V^{s'}) \quad (10)$$

$$x_{ijk}^s \in \{0,1\} \quad \forall s \in S; k \in K^s; (i, j) \in E^s \quad (11)$$

The second model VRPBTW-TD-2MS formulated as Mixed-integer linear programming (MILP) (**Model 2**) considering the same constraints of the (**Model 1**).

$$\text{Minimize } \alpha 1 \sum_{s \in S} \sum_{k \in K^s} \sum_{(i,j) \in E^s} T_{ij}^s x_{ijk}^s + \alpha 2 w \quad (1')$$

$$\sum_{(i,j) \in E^s} W_{ijk_1}^s x_{ijk_1}^s - \sum_{(i,j) \in E^s} W_{ijk_2}^s x_{ijk_2}^s \leq w \quad \forall s \in S, k_1 \in K^s, k_2 \in K^s \setminus k_1 \quad (12)$$

The bi-objective function (1) of Model 1 is about, to minimize the total traveling time of set of vehicles and the total negative preference of patient for caregivers, the bi-objective function (1') of Model 2 is to minimize the total distance traveled by a set of vehicles and the maximal difference workload of caregivers. Constraint (2) ensures that each visit point is served by one caregiver with the corresponding specialty and the given structure. Constraint (3) states that each vehicle begins from the depot, and returns to it at the same structure. Constraint (4) ensures the equality of the inflow and outflow arcs at every point. Constraint (5) is about the time continuity constraint of routes. According to constraint (6) and (7), each vehicle of given structure must respect visits time windows and caregivers' time windows respectively. Constraints (8), (9), and (10) are about synchronization's visits, precedence's visits, and disjunction's visits, respectively, of different structures. Constraint (11) concerns the nature of the variable definition. Constraint (12) is about the balancing constraint.

The impact of our two models will be twofold: **Model 1** for the patients for their satisfaction levels and **Model 2** for the caregivers in their workload balancing while taking into account the cost criterion as a main objective.

3.2 Experimental Results

In order to test our formulated models (**Model 1** and **Model 2**), we consider the benchmark of [29] for "VRPTW-TD-2MS" and the benchmark of [20] for Vehicle Routing Problem with Time Window and Synchronization constraint "VRPTWSyn" to generate new instances, based on the same rules provided by the latter, for VRPPTW-TD-2MS and VRPBTW-TD-2MS problems. The below generated instances are clustered according to visits and vehicles number (in our data instance, we use 60 visits and 12 vehicles).

We use Cplex 12.5 coupled with C++ language to solve **Model 1** and **Model 2**.

Table 1. Solutions and computational times for the VRPPTW-TD-2MS generated instances.

Data	Weight Obj 1	Weight Obj 2	MIP	
			SOL	CPU
1-60-2 (Small)	0.9	0.1	-87.06	24.30

Time Win- dow)	0.5	0.5	-716.25	33.19
	0.1	0.9	-1352.00	24.45
1-60-3 (Med- ium Time Window)	0.9	0.1	-96.30	3600
	0.5	0.5	-787.45	878.87
	0.1	0.9	-1485.84	1129.49
1-60-4 (Large Time Win- dow)	0.9	0.1	-106.01	3598.80
	0.5	0.5	-865.12	50.02
	0.1	0.9	-1631.17	45.23

Obj1: Minimize traveling time, Obj2: Minimize Preference of customers.

Table 2. Solutions and computational times for the VRPBTW-TD-2MS generated instances.

Data	Weight Obj 1	Weight Obj 3	MIP	
			SOL	CPU
1-60-2 (Small Time Win- dow)	0.9	0.1	15.77	3600
	0.5	0.5	29.09	3597.91
	0.1	0.9	40.95	3600
1-60-3 (Med- ium Time Window)	0.9	0.1	15.82	3600
	0.5	0.5	30.35	3600
	0.1	0.9	41.78	3600
1-60-4 (Large Time Win- dow)	0.9	0.1	15.46	3600
	0.5	0.5	30.17	3596.95
	0.1	0.9	43.68	3594.64

Obj1: Minimize traveling time, Obj3: Minimize workload of caregivers.

Note that the addition of the second objective function makes the problem more complex than the traditional one. All combinations of time windows and weights objective functions, i.e. 9 test problems, are presented in these tables. The problem size is defined through the number of constraints and the number of variables, varying according to time windows classes. The objective function values from these runs are shown in the “SOL” column and the processing time values are presented in the “CPU” column. To obtain solutions as good as possible within the time limit, we solve instances with 60 minutes as a time limit. CPLEX solves Model 1 and Model 2 but when we solve some of the larger data, we find that Cplex has problems of finding solutions in a reasonable time.

4 Conclusion

Our occupation aimed to model “VRPPTW-TD-2MS” and “VRPBTW-TD-2MS” problems and solve them with Cplex. Two MILP have been formulated as bi-objective models to determine the caregivers’ tours while optimizing the objective functions minimizing the total traveling distance and the total negative preference or the maximal difference workload of home care workers. The output of our programs provides care

services to a geographically dispersed population while assigning visits to each caregiver and defining the tour of each vehicle. The set of efficient solutions (for each combination of objectives weights) have been obtained with Cplex within one hour. Note that our problems include the VRP, which is known to be NP-Hard. When we solve *Model 2*, we obtain a result with a larger CPU time. Therefore, *Model 2* is more complex than *Model 1*. For that reason, we will propose a metaheuristic method to solve these models and larger instances in shorter CPU time as future work.

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