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A two-phases matheuristic for the home care routing and scheduling problem

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Abstract: Home care services provide care for the elderly, disabled or patients with chronic diseases. The cares are performed by nurses or unlicensed assistive personnels depending on the care to provide at the patient's home. Usually, the work routing and scheduling of the staff members are realized by an experienced nurse playing the role of the coordinator. However, this kind of manual planning has its limits as the demand tends to grow and it has to be done every day for the day after. After reviewing the existing literature on this problem, we propose a mixed-integer programming model focusing on the different types of staff member employed by home care services. The objective is to minimize the cost related to the transportation and the working hours. In order to find an optimal solution, we suggest two solving approaches : a one-phase solving method where the full data set are considered as input in order to find the best possible solution to the problem and a two-phases matheuristic in order to distinguish the scheduling of the nurses and the unlicensed assistive personnels. The approaches are then experimented on several instances of different sizes in order to compare them.

Keywords: home care, optimization, matheuristic, mixed integer linear programming, scheduling, routing, nurse, unlicensed assistive personnel

1. INTRODUCTION

In developed country, home care services are structures providing care for the elderly, or patients with chronic diseases. Home care services provide nursing and general hygiene cares at patients' homes to ensure home support for people in situation of dependency.

The general hygiene cares (personal hygiene, assisting with motion exercise,...) are generally realized by the unlicensed assistive personnels (UAP) while the nursing cares (injection, bandage, ...) are performed by the nurses.

The work routing and scheduling of the caregivers (nurses and unlicensed assistive personnel) is managed by a nurse coordinator (usually an experienced nurse). This complex organization must take into account many parameters (such as work time-window, availability of patients, ...) in order to establish the work planning for each member of the home care service organization. The planning is usually computed for the next day or for the coming weekend.

Subject to improvement both in terms of efficiency and quality, optimizing the organization of home care services has been widely studied in the scientific literature.

Since the last ten years, the number of publications related to the optimization of home care service scheduling has increased. As this optimization problem is based on a real-life situation, we can often find some similar constraints or characteristics among all the works. However, most existing researches being application based, they focus on different variants of this scheduling problem. An overview of the different constraints and characteristics considered in the past publications is given in Table 1.

Cheng and Rich (1998) consider the home health care problem as a vehicle routing problem with time window (VRPTW) with many depots and compatibility information. Their objective is to optimize the cost related to the working hours by considering full-time nurses and part-time nurses. While full-time nurses are paid for each day whether they are working the entire day or not, the part-time nurses are paid for each hour of work done. To that end, the problem aims to minimize the number of hours worked by the part-time nurses. Moreover, as full-time nurses can work overtime, the objective function aims to minimize the amount of overtime and part-time work that is scheduled.

Kergosien et al. (2009) also consider the home care problem as a multiple traveling salesman problem with time windows. They optimize the routing problem of the care staff by an integer linear programming formulation of the problem and suggests some technical improvements to increase the efficiency of the solver.

The home care services have also been considered not only as a vehicle routing problem but as a combination of vehicle routing and staff rostering with high-dependencies between both problem by Bertels and Fahle (2006). Their

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Table 1. Constraints and assumptions considered in the related works on scheduling and routing of home care service

Reference	Nurse time-window	Patient time-window	Nurse's skills	Continuity of care	Shared visits
Allaoua et al. (2013)	X	X	X		
Bertels and Fahle (2006)	X	X	X		
Braekers et al. (2016)	X	X		X	
Cheng and Rich (1998)	X	X			
Di Mascolo et al. (2014)	X	X	X		X
Eveborn et al. (2006)	X	X	X	X	X
Issaoui et al. (2015)	X		X		
Kergosien et al. (2009)	X	X	X		X
Mankowska et al. (2014)		X	X		X
Trautsamwieser and Hirsch (2011)	X	X	X	X	

work introduces the notion of qualification level owned by the nurses that is required to perform certain visits. Moreover, any violation of soft time window will be penalized by a factor proportional to the earliness or lateness. As the model is an hybrid of a rostering model and a routing model, the objective function aims to minimize the total travel time needed for the schedule and the sum of all the penalties. The authors then use a combination of linear programming, constraint programming and metaheuristics to find a solution to the problem.

Allaoua et al. (2013) have also studied the home health care problem as a vehicle routing and staff rostering problem, which is challenging because they are 2 combinatorial problems. In order to solve the problem, the authors have developed a matheuristic based on a decomposition of the previous problem into 2 problems : a set partitioning-like-problem for the rostering part and a multi-depot traveling salesman problem with time-window (MDTSPTW) for the routing part.

The dependencies between two visits have also been studied by Mankowska et al. (2014). Thanks to a sophisticated solution representation, they developed a heuristic for the health care routing and scheduling problem with interdependent services which they experimented on a set of instances that contains up to 300 patients.

Di Mascolo et al. (2014) also studied the synchronization of human resources in the home health care context. They proposed a mixed-integer linear programming formulation of the problem in order to minimize the waiting times of patients and caregivers. The authors experimented their model on some instances with up to 40 patients using CPLEX solver to measure the impact of the proportion of synchronized visits.

One of the main important aspect of the problem is the possibility to quickly generate high quality solutions. The objective is to create a schedule that allocates visits to staff members. Eveborn et al. (2006) consider that the efficiency of the planning is judged by the amount of traveling times required and how well it has succeeded in allocating all visits (defined by which care has to be provided and the set of skills required by the person performing it) to staff members. In the considered model, each patient having a list of preferred staff members (in order to provide a continuity of care), it is important to keep the number of different staff members visiting a patient as low as possible. Finally, a new assumption is taken into account in this work : some visits can require multiple staff members at the same time and therefore some staff members schedule has to be synchronized to get the different staff members at the same time at the same place occasionally.

Another work dealing with the travelling time of the staff members has been realized by Trautsamwieser and Hirsch (2011). They focus on several objectives : minimizing the travelling time of the nurse (driving + waiting time) and the dissatisfaction level of clients and nurses. In order to do so, the objective function is weighted on 7 different criteria to compute it : travelling time of nurses, overtime work done, cost of unfulfiled preferences, violations of clients and nurses soft time-windows, unpaid driving time (from nurse's homes to first and last patients) and service time of jobs covered by a higher qualification level than necessary.

The trade-off between the costs (related to transport and work) and the client convenience is also another difficult aspect to take into account. In most work, client convenience is penalized in the objective function or considered in terms of constraints. Issaoui et al. (2015) use a different procedure by optimizing 3 different objective functions : minimizing the distance traveled by nurses, maximizing the care interventions and maximizing the patient satisfaction. The metaheuristic used to solve the assignment problem is based on 3 phases : assignment scheduling first, then a search for the shortest path and finally a satisfaction refinement process.

Braekers et al. (2016) also analyse this trade-off by two objective functions : the first one minimizes the total cost (which is composed of routing and overtime costs) and the second one minimizes client inconvenience. The scheduling problem (deciding on a time schedule for a route) may be decomposed into two problems which can be solved sequentially : generating all non-dominated schedules for each individual route and generating all non-dominated solutions from the set of schedules for each route. As a single optimal solution may not exist (but several), the goal of the metaheuristic procedure is to find a set of Pareto optimal or efficient solutions. The algorithm used is based on the multi-directional local search (MDLS) framework and uses large neighborhood search (LNS) as a subheuristic.

In general, we can split the work produced into 2 main categories depending on their optimized criteria : the ones minimizing the costs (staff/transports) and the ones minimizing the traveling time/distances.

Among the researches aiming to optimize the costs, Cheng and Rich (1998) minimize the costs of work (overtime + part-time worked), Braekers et al. (2016) want to reduce the transportation costs in addition to the costs of worked hours. Finally, Bertels and Fahle (2006) minimize the costs only related to transports. On the other side, some researches focus on optimizing the distances/time travelled. Indeed, Trautsamwieser and Hirsch (2011) minimize the total duration traveled by nurse while Issaoui et al. (2015) consider the total distance travelled and Eveborn et al. (2006) add the nurse transportation time with the patient waiting time.

Finally, we can also notice that among all the works, the staff members considered are only nurses. Since home care services usually employ nurses but also unlicensed assistive personnel, the originality of our contribution is to optimize the scheduling and routing of home care services for both types of employee : nurse and unlicensed assistive personnel. To the best of our knowledge, this is the first publication to deal with both type of staff members for home care services scheduling and routing optimization.

2. MODEL DESCRIPTION

2.1 Model definition

Home care services scheduling and routing problem for several types of staff member can be defined as follows. Given a set of staff members and a set of jobs to be performed at patient location on a one day period, the goal is to find a schedule and a route for each staff member, indicating which visit to perform, in which order and at which time. Each staff member has a defined working time-window and has a start and end location, which represents actually the same place. Each staff member works for one home care service, which means he has to start his working day and finish it at his home care service affected within his working time-window. It is assumed that staff members are paid for their real working time regarding the amount of work they do. Each staff members use the same transportation mode (i.e. home care service car) during their working day. Working overtime is not allowed due to an increased cost of work. Staff members can be either nurse or unlicensed assistive personnel. Moreover, each staff member having a different salary, their cost for one hour of work may vary. It is also common that nurse get paid more (and so cost more to the company) than unlicensed assistive personnel since they graduated from a higher degree level and have higher care skills.

The time at which a staff member can start a visit is restricted by a hard-time window, specific for each visit regarding to the availability of the patient to receive his cares. The visits can be performed by only one type of staff member (e.g. an injection can be made only by a nurse), therefore some staff member-visit combinations are unfeasible. Some visits can be shared. It means that they require several staff members at the same time to perform it. However, since the staff members do not need to be present together during the entire visit, their arrival times might be slightly different, without overcoming a certain limit (usually few minutes).

Two characteristics are considered in the objective : minimizing the total costs of transportation and work. Minimizing the cost of work involves reducing the number of hours worked since each staff member is paid for their real working time.

2.2 Model formulation

We model the home care services scheduling and routing problem on a graph $G = (N, A)$ where N is the set of nodes and A the set of arcs. We consider a set of visits to perform $O = \{1, ..., n_v\}$ with n_v the number of visits to perform and a set of home care services $P = \{1, ..., n_p\}$ with n_p the number of home care offices. Each visit is represented by a separated node in our graph, whether two or more visits are associated with the same physical location or not. Thus, $N = O \cup P$. Using this information, the arc set is defined as follows : $A = \{(i,j) | i,j \in N, i \neq j\}$. The arc $(i,j) \in A$ has a distance d_{ij} and the cost of the trip between i and j is c_{ij} $(c_{ij} = c_{ji})$.

For each staff member $i \in S$, a working hard-time window $[\alpha_i, \beta_i]$ is known. Each staff member having a job role, the set $R = \{\mathcal{N}, \mathcal{U}\}$ represents the possible job role that can have staff member. The qualification of the staff member i is defined by the binary parameter η_i^r with $r \in R$. The cost for one minute of work for the staff member i is h_i. The time at which the nurse i finish his working day and arrive back at his home care office is the variable τ_i.

The home care services company can be located in different places and therefore have different offices. Each staff member i is working at one office $k \in P$ defined by the parameter γ_i^k.

For each visit $j \in O$, a hard-time window $[a_j, b_j]$ represents the availability of the patient to receive his care. Moreover, the staff member qualification needed to perform the job j is defined by ρ_j^r with $r \in R$. Each visit j has a length c_j in which the staff member will perform the care. Finally, the binary parameter δ_{ij} is used when 2 visits i and j need to be synchronized. The difference between the arrival times of the staff members to the visit location must not exceed d_{max}.

We consider a planning period of a single day.

In order to formulate the home care services scheduling and routing problem, we use the following decision variables :

$$x_{ij}^k = \begin{cases} 1, \text{ if staff member } k \text{ travels from } i \text{ to } j \\ 0, \text{ otherwise} \end{cases}$$

$w_k =$ Time worked by the person k in minutes

$t_{ik} =$ Arrival time of the staff member k to the visit i

$$y_i^k = \begin{cases} 1, \text{ if staff member } k \text{ is in charge of the visit } i \\ 0, \text{ otherwise} \end{cases}$$

The objective is to minimize the cost related to the work and the transport by optimizing the objective function 1 below :

$$min \sum_{i \in N} \sum_{j \in N} \sum_{k \in S} x_{ij}^k \times c_{ij} + \sum_{k \in S} h_k \times w_k \tag{1}$$

subject to :

$$y_i^k = \sum_{j \in N} x_{ij}^k \qquad \forall i \in N, k \in S \tag{2}$$

$$\sum_{k \in S} y_i^k = 1 \qquad \forall i \in O \tag{3}$$

$$\sum_{j \in O} x_{ij}^k = \sum_{j \in O} x_{ji}^k = \gamma_k^i \qquad \forall i \in P, k \in S \tag{4}$$

$$\sum_{\substack{j \in N \\ i \neq j}} x_{ij}^k = \sum_{\substack{j \in N \\ i \neq j}} x_{ji}^k \qquad \forall i \in N, k \in S \tag{5}$$

$$\alpha_k \sum_{\substack{j \in N \\ i \neq j}} x_{ij}^k \leq t_{ik} \leq \beta_k \sum_{\substack{j \in N \\ i \neq j}} x_{ij}^k \qquad \forall i \in N, k \in S \tag{6}$$

$$a_i \times y_i^k \leq t_{ik} \leq b_i \times y_i^k \qquad \forall i \in O, k \in S \tag{7}$$

$$t_{jk} \geq t_{ik} + c_i + d_{ij} + (x_{ij}^k - 1) \times M \qquad \forall i \in N, j \in O, k \in S, i \neq j \tag{8}$$

$$t_{ik} \leq \beta_k - c_i - d_{ij} \qquad \forall i \in O, j \in P, k \in S, i \neq j, \gamma_{kj} = 1 \tag{9}$$

$$-d_{max} \leq \sum_{k \in S} t_{ik} - \sum_{l \in S} t_{jl} \leq d_{max} \qquad \forall i \in O, j \in O, i \neq j, \delta_{ij} = 1 \tag{10}$$

$$\tau_k \geq t_{ik} + c_i + d_{ij} + (x_{ij}^k - 1) \times M \qquad \forall k \in S, i \in O, j \in P, \gamma_{kj} = 1 \tag{11}$$

$$w_k = \tau k - \alpha_k \qquad \forall k \in S \tag{12}$$

$$\sum_{\substack{j \in N \\ i \neq j}} x_{ij}^k = 0 \qquad i \in O, k \in S, q \in R, \eta_{kq} \neq \rho_{iq} \tag{13}$$

$$x_{ij}^k \in \{0, 1\} \qquad \forall i, j \in N, k \in S \tag{14}$$

$$w_k \in [0, 1440] \qquad \forall k \in S \tag{15}$$

$$t_{ik} \in [0, 1440] \qquad \forall i \in N, k \in S \tag{16}$$

$$y_i^k \in \{0, 1\} \qquad \forall i \in N, k \in S \tag{17}$$

Objective function (1) minimizes the total cost which is composed of the addition of traveling costs by the staff members and working costs. Constraints (2) and (3) make sure that each visit is done by one staff member. The departure and arrival of the staff members to their affected home care office is ensured by the constraint (4). The flow conservation is guaranteed by the constraint (5).

Nurses are allowed to work only during their hard time-window period which means they can visit some patients only during this period according to the constraint (6). Similarly, the constraint (7) guarantee that the visits can start only when the patient is available, so within the patient's hard time-window.

According to the constraint (8), for each job affected to a staff member, their arrival times must be separated to give enough time to the staff member to perform the previous visit and then to go from one visit to the next one. Finally, the constraint (9) guarantee that the staff member will have enough time to perform his last job and then come back to his affected home care office before the end of his working day.

The synchronized visits are guaranteed by the constraint (10). When two visits are synchronized, the difference of arrival times at the patient home cannot be higher than d_{max} minutes.

Moreover, the constraints (11) and (12) are used to compute the time really worked by each staff member during the day.

Then, the constraint (13) aim to affect to a visit a staff member who has the requested qualification to perform it.

The subtour-elimination constraint is also applied to the model.

Finally, the constraints (14) - (17) define the domains of the variables.

3. SOLVING APPROACHES

To evaluate the mathematical models of the previous section, we will use two different approaches to solve it.

3.1 Global approach

In the first solving approach, the idea is to solve our MIP-model with all the inputs in one instance. Indeed, the input of this approach are :

- All the visits contained in the set O
- All the home care offices contained in the set P
- All the staff members contained in the set S

This method is the way to be sure to find the optimal solution of the problem. However, as our problem is NP-hard (this is an extension of the TSPTW problem), the optimal solution will be found in an exponential solving time. In other words, the longer the size of the instance (size of the input parameters) will be, the longer the solving time will be.

In order to face this situation, we propose a two-phases matheuristic to solve the home care services scheduling problem.

3.2 Two-phases matheuristic

To the best of our knowledge, this is the first publication to deal with both type of staff members (nurses and unlicensed assistive personnel) for the home care services scheduling and routing optimization. In order to adapt the first and global approach to this new situation, we propose a second approach to solve the home care services scheduling and routing problem based on two phases.

The first phase will process the resolution only on the nurses and the second phase will then process the scheduling on the unlicensed assistive personnel.

In other words, the first phase will schedule the work day of all the nurses without taking into account all the constraints related to the possible synchronized visits with the unlicensed assistive personnel. Then, in order to start the second phase resolution, the output of the first phase scheduling will be considered as an input for the second phase. The second phase will then process to the scheduling of the unlicensed assistive personnel only (the nurse schedules has been done in the first phase).

The reason why the nurses are processed first and the unlicensed assistive personnel next is that the salary of the nurses is generally higher than the unlicensed assistive personnel since they have higher care skills. To that end, the costs of the nurses is higher and the priority is given to the nurses by optimizing their working time and transportation first.

To summarize, the input of the first phase will be :

- All the visits requiring a nurse to perform it
- All the home care offices contained in the set P
- All the nurses contained in the set

The output of the first phase will be a schedule for each nurses indicating which visits to perform at which time. This output will become an input for the second phase in the form of some constraints. Then, the input of the second phase will consists of :

- All the visits contained in the set O
- All the home care offices contained in the set P
- All the staff members contained in the set S
- The nurse schedules computed in the first phase

Finally, this two-phases matheuristic may present one major drawback : it might not find a solution as good as the one found with the global one-phase approach since the second phase consists of a local optimization based on the result obtained by the first phase.

4. COMPUTATIONAL RESULTS

The two solving methods proposed will now be compared on several instances of different sizes.

All the instances are composed of 2 home care offices and the staff members can work from 6.45am to 7.30pm. The visits hard-time window may have a maximum duration of one hour. The nurses have a cost defined to 50 euros/hour and the unlicensed assistive personnel to 30 euros/hour. Moreover, the parameter d_{max} indicating the maximum delay of arrival times of two staff members for a synchronized visit is 10 minutes.

To that end, the experiments have been performed on a desktop with a Intel Xeon(R) CPU E5-1603 (@ 2.80GHz) CPU with 8 Go of RAM memory. The experiments have been run using Gurobi solver (Table 2).

As the results show, the limitations of the global method (one-phase) are easily reached. Indeed, the solver cannot get an optimal solution for many instances in less than one hour. In the other hand, the two-phases matheuristic is much more efficient in terms of solving time since it is always finding a local solution faster than with the first approach.

However, the two-phases matheuristic has also a certain drawback. In the case of instance with synchronized visits, the optimal solution found is not as good as the one found with the global approach where the full data are considered as input. Instead, our two-phases matheuristic finds some good (but not always optimal solution). In contrast, the two-phases matheuristic is really fast and can find its optimal (but globally local) solution faster than the global approach as we could expect. By this advantage, it finds some good solutions even for instances with a high number of visits and staff members.

Moreover, when the instance does not imply any shared visits between staff members, the problem can then be split in two parts since the scheduling of the nurse and the unlicensed assistive personnel are totally independent. This way, we can be sure to find the optimal solution, even with the two-phases matheuristic.

Finally, even though it might not find the optimal solution to the problem, the two-phases matheuristic can be a good alternative to the home care scheduling problem when the global approach is to slow and when a metaheuristic search method would take too long to find a high quality solution. This two-phases solution approach may be preferably used on mid-size or without shared visits instances of the problem.

The solution found by the two-phases approach could then be an initial solution for a metaheuristic solving of the problem.

5. CONCLUSION

In this paper, a description of the operation of home care services that employ different types of staff member has been presented. As the nurse and unlicensed assistive personnel have their own characteristics, a MIP-model of the problem is suggested to take into account this specificity. On the basis of a daily schedule, the optimization of the model produces a work schedule which minimize the cost associated to the transportation and work. The suggested model allow the possibility to have shared visits between staff members in case the care to perform requires the presence of more than one person.

In addition, two approaches have been proposed to solve the MIP-model : a first global approach which tries to solve it with the full data of the model and a second one based on a two-phases matheuristic which process the scheduling and routing part for the nurses first and the unlicensed assistive personnel next. Computational results show the efficiency of the two-phases matheuristic which provides a great balance between quality of the solution and solving duration. Actually, the two-phases matheuristic is even

Table 2. Computationnal results and process time obtained

Instances		Global approach		Two-phases matheuristic		
Visits	Shared visits	Evaluation	Solving time (s)	Evaluation	Solving time (s)	Deviation ratio
20	0	3679.93	3.78	3679.93	1.04	0
20	1	3290.53	2.7	3290.53	0.96	0
20	5	3788.40	5.7	3788.40	4.25	0
20	10	3368.40	5.8	3368.40	1.86	0
30	0	3583	3.51	3583	2.45	0
30	1	3625.56	2.4	3625.56	2.81	0
30	5	4137.5	74	4170.40	4.47	0.78
30	10	4027.70	118	4152.5	10.74	3
40	0	4223.76	98	4223.76	8.64	0
40	1	3952.36	88.18	3952.36	17.22	0
40	5	4176.46	137	4176.46	9.81	0
40	10	4447.63	227	4454.23	18.78	0.15
50	0	4980.40	194	4980.40	20.95	0
50	1	4948.13	281.47	4948.13	117.18	0
50	5	4759.96	233	4759.96	25.9	0
50	10	$3802.81 \leq z \leq 4238.63$	>3600	4238.63	90	X
60	0	$4781.64 \leq z \leq 5383.4$	>3600	5383.4	254	X
60	1	$4597.11 \leq z \leq 5294.30$	>3600	5545.06	549.57	X
60	5	$5255.36 \leq z \leq 5585.83$	>3600	5734.43	376	X
60	10	$4985.59 \leq z \leq 6059.40$	>3600	6072.53	506	X

the most powerful method to optimize instances without shared visits. Moreover, the two-phases matheuristic is really efficient on mid-size instances when the first global method is too slow to get the optimal solution and when a metaheuristic algorithm would take too long to find a good solution. In future works, we aim to improve the two-phases matheuristic on instances with a high number of synchronized visits. In addition, since working overtime was not allowed by the model, adding this feature could be another possible extension.

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