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Coordinated Multi-criteria Scheduling of Caregivers in Home Health Care Services

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Abstract—Home health Care Services (HCS) that provides continuous and coordinated cares at patients' home. This paper addresses the problem of scheduling care activities, performed by caregivers belonging to a HCS. Care visits for the same patient might be done in some order (coordinated). The problem consists in determining a tour for all caregivers in order to optimize multiple criteria. We propose two mixed integer programming (MILP) models, each corresponding to a scheduling strategy. Numerical results are given to show the relationship between patient waiting times and caregiver working durations.

I. INTRODUCTION

THE organizational and economic problems of health care systems lead to the search of new ways and organizations. Home health Care Structures (HCS) have been proposed to provide continuous and coordinated care for patients in their homes. They were considered as a solution for reducing costs and maintaining a satisfactory quality of care services. In the French decree N°92.11.01 of October 1992 defined HCS as structures that *"ensure, at the patient's home for a limited period, but adaptable to his health condition, continuous and coordinated medical and paramedical care. These treatments differ from those usually provided by the complexity and frequency of activities"*. HCS were also defined as *"a mini network in a wider one"* [1], [2], since it requires coordination among multiple actors with different skills.

A home health care process requires a variety of organizational and clinical decisions, coordination and synchronization between various human and material resources and the participation of an important number of actors of different skills [3]. Tools for design and operations of these structures are highly needed. In this paper we propose a mixed integer programming-based decision support tool to schedule HCS caregivers' visits for patients, while taking into account the coordinated visits, i.e. the problem consists in (i) scheduling patients' care activities, and (ii) sequencing caregivers' visits, in order to minimize

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the caregivers' worked time and patients' waited time. This paper is structured as follow. First, we present relevant existing works. Then we describe the caregivers' planning and scheduling problem the mathematical formulation. Finally, numerical results are presented and analyzed.

II. LITERATURE REVIEW

An analysis of the literature review on the home health care, has allowed us to identify all issues involved. We quote from this works: methods for partitioning the geographic territory covered by caregivers, [4], [5] and [6]. Other works concern the allocation of resources to geographical area (or sub-area) [7], [8] and [9]. Papers [10], [11], [12] and [13], address communication and information's flow in home care institutions. We quote also works related to the organizing caregivers'/patients' activities, which presents our focus.

Nurses' tour problem in homecare was treated in [14], using the vehicle routing problem with time windows (VR TW). The problem is to find an optimal schedule, such that each nurse leaves from home, visits a set of patients within their time windows, takes a lunch break, and returns home, all within the nurses' time window, while minimizing both, over time for salaried nurses and part-time nurses.

The tool presented in. [15] construct the nurses' tour schedule taking into account patients availability, needs constraints, and nurses' availability. They fix in advance the days of visiting patients.

In [16] a tool to planning tours for nurses in homecare was developed using MILP, taking into account different constraints, as patients' availabilities, lunch break for nurses, travelling durations are independent of visit duration and also shared visits. The objective function was "minimizing total travelled distance".

A novel application for scheduling home caregivers was presented in [17]. The model was based on a meta-heuristic called Particle Swarm Optimization (PSO). The tool is applied to a genuine situation arising in the UK, while minimizing the travelled distance, providing that the capacity and time windows constraints of services are not violated.

In [3] the presented multi criteria method was combined of linear programming, constraint programming, and meta-heuristics for the home health care problem taking into account multiple constraints. They minimize travelling costs.

In [18], a novel approach based on VRPTW and MILP, was presented for planning and scheduling caregivers' visits in a home care institution, taking into account coordination

between caregivers and patients' availabilities, while optimizing the travelled and waited times. The tool was tested using three scenarios based on patients' locations and two situations based on patients' availabilities. In [19] the scheduling caregivers' activities problem was resolved using RCPSP and linear programming, while taking into account coordination between care activities and real life constraints. The minimized criterion was patients' waited time.

TABLE I
COMPARISON BETWEEN METHODS

	Optimized criterion	Patients' availabilities	Shared patients	Coordination	Multiple visits for patients / day	Limited patients' waiting time	Exact methods
[14]	Costs of working hours	X					X
[15]	Travel duration		X		X		X
[19]	Balancing work load	X	X				X
[16]	Travel duration	X	X				X
[17]	Travel duration	X	X		X		
[18]	(i) travelled + waited durations (ii) caregivers' worked durations	X	X	X	X		X
[19]	Patients' waited time.	X	X	X	X		X
Our approach	(i) the sum of visits' completion times (ii) the patients' waited time	X	X	X	X	X	X

Through this review, we studied works concerning nurses' scheduling and planning activities. We noted that all works cited above does not address the aspect of coordination between different providers (i.e. performing care visits in an imposed order) except in [18] and [19]. We noted also that all works proposes approaches based on caregivers' satisfying. Our goal in this paper is to develop a multi-criteria approach (two criteria), i.e. optimising caregivers' tours and limiting patients' waited time between two different visits. In table I, we summarized a comparison between some works quoted above. In the next section we describe our problem and its mathematical formulation.

III. MATHEMATICAL FORMULATION

The goal is to provide a decision tool for planning caregivers' visits, with coordination between cares.

A. Problem description and hypothesis

We consider S caregivers all belonging to the HCS. There are N patients, each stayed at his home. Each patient needs a set of care activities, each being performed by a given caregiver. As a result, each caregiver has a pre-assigned set of care activities or a set of patients to visit. Each day, a caregiver starts at HCS, visits all his patients according to a tour and finishes his tour at HCS. Each patient is available during a time window for all his cares. Different care activities of a given patient by different caregivers might need to be coordinated and be performed in a given order in order to respect his care protocol [5]. No patient can receive two cares at the same time. The goal is to minimize total patients' waiting times and the caregivers' working times. The proposed approach is deterministic, and don't take into account uncertainties of the environment, that will be taken in a further works.

This problem is related to the Vehicle Routing Problem with Time Window (VRPTW) [20]. The VRPTW problem involves a fleet of vehicles at a warehouse to serve a number of customers, at different locations, with various demands.

The objective of the problem is to find routes for vehicles, to satisfy all the customers with a minimal travel time, without violating customers' time windows [21] [22]. The VRPTW is an NP-hard problem [23] [24]. To model the problem we have considered, a set of customers <patients>, vehicles <caregivers> and a warehouse <HCS>. The goal is to find a set of routes <tours> for each vehicle <caregiver>, starting and ending at the warehouse. Each route has its set of predefined customers <patients>, and each patient has all his <care visits> performed by related vehicles <caregivers>, while respecting customers <patients> availabilities. Care activities can be predefined <coordinated visits>.

B. Parameters and notation

- N, S: number of patients and number of caregivers.
- r_i, d_i: begin/end of the availability of patient #i.
- $A_{is} \in \{0,1\}$: $A_{is} = 1$ if patient #i needs care of caregiver s, and $A_{is} = 0$ otherwise.
- NP_s, NS_i: respectively the number of patients allocated to the caregiver s, and the number of caregivers for patient #i.
- p_{is}: care duration for patient #i by caregiver s, with $p_{is} = 0$ if $A_{is} = 0$.
- $y_{iss'} \in \{0,1\}$: $y_{iss'} = 1$ if caregiver s must realize his care activity for patient #i before caregiver s'.
- td_{ij}: travel time between homes of patients #i to #j.
- M: Large constant,

C. Decision variables

We need the binary variables x_{ijs}, $z_{iss'}$, with $x_{ijs} = 1$ if caregiver s visits patient #i immediately before #j, and $z_{iss'} = 1$ if caregiver s realizes his care activity for the patient #i immediately before caregiver s'. The decision variable t_{is}, is the starting time of the patient's #i visit by caregiver s. We need also the variable u_{is}, which expresses the order of patient #i in the tour of caregiver s.

D. Model formulation

We introduce a dummy patient who represents the HCS

2

(patient #1 in our case) with, $A_{1s} = 1$, $t_{1s} = p_{1s} = r_1 = 0$, $d_1 = H$ (end of the day). The problem can be formulated as the following MILP model. The constraints are:

$$\sum_{j=1}^{N} x_{ijs} = A_{is} \qquad \forall s \in [1,S], \forall i \in [1,N] \qquad (2)$$

$$\sum_{i=1}^{N} x_{ijs} = A_{js} \qquad \forall s \in [1,S], \forall j \in [1,N] \qquad (3)$$

$$\sum_{i=1}^{N}\sum_{j=1}^{N} x_{ijs} = NP_s \qquad \forall s \in [1,S] \qquad (4)$$

$$x_{iis} = 0 \qquad \forall s \in [1,S], \forall i \in [1,N] \qquad (5)$$

Constraints (2) - (5) are modified constraints of classical VRPTW problem [2] [25] [18]. They ensure that each caregiver visits each of his patients once. Constraints (6) are timing constraints of all patients in the tour of a caregiver:

$$t_{is} + p_{is} + td_{ij} - M(1 - x_{ijs}) \le t_{js} \qquad \forall s \in [1,S], \forall i,j \in [1,N] \quad (6)$$

Constraints (7) correspond to precedence constraints of different care visits for a given patient:

$$t_{is} + p_{is} - M(1 - y_{iss'}) \le t_{is'} \qquad \forall s,s' \in [1,S], \forall i \in [1,N], s \ne s' \quad (7)$$

Constraints (8) - (12) ensure that the care activities performed by caregivers for the same patient are not performed at the same time.

$$\sum_{s=1}^{S} z_{iss'} \le A_{is'} \qquad \forall s' \in [1,S], \forall i \in [1,N] \qquad (8)$$

$$\sum_{s'}^{S} z_{iss'} \le A_{is} \qquad \forall s \in [1,S], \forall i \in [1,N] \qquad (9)$$

$$\sum_{s=1}^{S}\sum_{s'} z_{iss'} \quad NS_i - 1 \qquad \forall i \in [1,N] \qquad (10)$$

$$z_{iss} = 0 \qquad \forall s \in [1,S], \forall i \in [1,N] \qquad (11)$$

$$t_{is} + p_{is} - M(1 - z_{iss'}) \le t_{is} \qquad \forall s,s' \in [1,S], \forall i \in [1,N] \quad (12)$$

Constraints (13) - (16) ensure the availability of patients and working time of caregivers:

$$t_{is} + M(1 - A_{is}) \ge r_i \qquad \forall s \in [1,S], \forall i \in [1,N] \qquad (13)$$

$$t_{is} + p_{is} + td_{i1} - M(1 - A_{is}) \le d_1 \qquad \forall s \in [1,S], \forall i \in [1,N] \qquad (14)$$

$$t_{is} + M(1 - A_{is}) \ge r_i \qquad \forall s \in [1,S], \forall i \in [1,N] \qquad (15)$$

$$t_{is} + p_{is} - M(1 - A_{is}) \le d_i \qquad \forall s \in [1,S], \forall i \in [1,N] \qquad (16)$$

The sub-tours of each caregiver are eliminated by constraints (17) - (19) derived from Desrocher and Laport's sub-tour elimination [26], and modified in [18]. The constraints (20) and (21) set u_{is} by 0 while $A_{is} = 0$:

$$u_{is} - u_{js} + (N-1)x_{ijs} + (N-3)x_{jis} \le N-2$$
$$\forall s \in [1,S], \forall i,j \in [2,N] \qquad (17)$$

$$u_{is} + M(1 - A_{is}) \ge \qquad \forall s \in [1,S], \forall i \in [2,N] \qquad (18)$$

$$u_{is} - M(1 - A_{is}) \le NP_s \qquad \forall s \in [1,S], \forall i \in [2,N] \qquad (19)$$

$$u_{is} - MA_{is} \le 0 \qquad \forall s \in [1,S], \forall i \in [2,N] \qquad (20)$$

$$u_{is} + MA_{is} \ge 0 \qquad \forall s \in [1,S], \forall i \in [2,N] \qquad (21)$$

The equations (22) - (23) are binary or non-negativity constraints.

$$t_{is}, u_{is} \ge 0 \quad Wait_{iss'} \ge 0 \qquad \forall s,s' \in [1,S], \forall i \in [1,N] \qquad (22)$$

$$x_{ijs}, z_{iss'} \in \{0,1\} \qquad \forall s,s' \in [1,S], \forall i,j \in [1,N] \qquad (23)$$

The model described is used to define two strategies for planning and scheduling of caregivers. Each strategy is derived with appropriate criterion and additional constraints.

- **First strategy**

In this case, we define an upper bound "α" to limit patients' waiting time between two successive visits. This value will be defined to satisfy patients' preferences. The objective function in this case will minimize the sum of completion care times for all caregivers, which consequently minimizes the travelled and waited durations for caregivers. We have developed for that the objective function (1.a):

$$Min\left(\sum_{i=1}^{N}\sum_{s=1}^{S} C_{is}\right) \qquad (1.a)$$

Such that C_{is} represents the completion time of the visit performed by caregiver s for the patients #i. It will be calculated by the equation (1.a') as follow:

$$t_{is} + p_{is} = C_{is} \qquad \forall s \in [1,S], \forall i \in [1,N] \qquad (1.a')$$

The constraint (13.a) is added to initial model to ensure that the patients' waited time between successive visits is bounded by the upper bound α.

$$t_{is'} \le t_{is} + p_{is} + \alpha + M \times (1 - z_{iss'}) \quad \forall s,s' \in [1,S], \forall i \in [1,N] \quad (13.a)$$

- **Second strategy**

In this case the patients' waited time between two successive visits will be defined as a positive variable, and the objective function will minimize the total sum patients' waited times between successive visits.

$$Min\left(\sum_{i=1}^{N}\sum_{s=1}^{S}\sum_{s'=1}^{S} Wait_{iss'}\right) \qquad (1.b)$$

Constraints (13.b) and (13.b') added to initial model, allow respectively, quantifying patients' waited time between successive visits "$Wait_{iss'}$", and limiting the travelled durations for each caregiver s by the upper bound "$Length_s$".

$$t_{is'} \le t_{is} + p_{is} + Wait_{iss'} + M \times (1 - z_{iss'}) \quad \forall s,s' \in [1,S], \forall i \in [1,N] \quad (13.b)$$

$$\sum_{i=1}^{N}\sum_{j=1}^{N} td_{ij} \times x_{ijs} \le Length_s \qquad \forall s \in [1,S] \qquad (13.b')$$

IV. NUMERICAL RESULTS

For solving the model, we use an academic solver from *LINDO SYSTEMS INC*, namely *LINGO_11.0* solver. In this part, we aim to present results obtained using both strategies based on an example of 4 caregivers and 14 patients (patient #1 is the HCS). The mathematical models were tested using both strategies, such as in the first one, we have varied the maximal patients' waited time (i.e. α), while considering two scenarios, based on patients' location. In the second strategy, we have varied the maximal caregivers' travelled time (i.e. *Length*).

First scenario: all patients live near to each other's and the travelling times are between 15 to 40 minutes

3

Second scenario: two groups of patients, with travelling times between patients of the same group between 15 and 30 minutes, and 40 to 65 minutes between patients from different groups, such as:

- *1st region:* patients {#1(HCS), #2, #3, #4, #5, #6, #7}.
- *2nd region:* patients {#8, #9, #10, #11, #12, #13, #14}.

A. The instances

We have tested the model on an example of 14 patients, and 4 caregivers with shared patients. The assignment of patients to caregivers and visits' order are defined in patients' care protocol, conceived by the care team of the HCS. The patients' availabilities may be the whole day (i.e. [1, 480]); the morning (i.e. [1, 240]) or the afternoon (i.e. [240, 480]). The patients' availabilities in this case are:

- Day: patients {#1(HCS), #2, #3, #8, #9, #10}.
- Morning: patients {#4, #5, #13, #14}.
- Afternoon: patients {#6, #7, #11, #12}.

The patients' allocation to caregivers is as follow:
- Caregiver 1 = {#1, #2, #3, #5, #8, #10, #11, #14}
- Caregiver 2 = {#1, #2, #4, #6, #8, #9, #11, #12, #14}
- Caregiver 3 = {#1, #3, #4, #6, #7, #8, #11, #13}
- Caregiver 1 = {#1, #2, #5, #6, #7, #9, #13, #14}

The patients requiring coordinated (ordered) visits are:
- Patient #2: Caregiver 1 before Caregiver 4.
- Patient #4: Caregiver 3 before Caregiver 2.
- Patient #7: Caregiver 3 before Caregiver 4.
- Patient #8: Caregiver 2 before Caregiver 3.
- Patient #11: Caregiver 2 before Caregiver 1.

TABLE II
CARE DURATIONS (IN MINUTES)

	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14
Caregiver 1	0	20	35	0	15	0	0	30	0	35	20	0	0	25
Caregiver 2	0	30	0	20	0	35	0	20	25	0	25	15	0	25
Caregiver 3	0	0	25	25	0	25	25	35	0	0	35	0	25	0
Caregiver 4	0	30	0	0	25	30	20	0	20	0	0	0	35	30

The travelled times between patients are generated from the literature and varied between "15 minutes" and "40 minutes". The work horizon is the day, 8 hours of work (480 minutes). All caregivers start by patient #1(HCS). The table II contains care durations of each patient. The MILP model was simulated using both strategies. In order to avoid excessive computation time to get the optimal solution, we have studied the evolution of objective function in time, and we have noticed that we get an optimality rate nearly equal to "95.50%", in 20 minutes of calculating time, which presents a satisfactory feasible solution.

B. Results

- *First strategy*

In this strategy, the constraints (2) to (23) are used with those specified to the first strategy, i.e. (1.a'), (13.a) and objective function (1.a). In this tests, we have varied the maximal patients' waited time "α" {10, 20, 40, 50, 60, 90, 120, 240, 480 (day)}. These values were used to calculate the objective function (1.a), which represents the total sum of completion care times for all caregivers. This objective function is considered a criterion to evaluate the tours' quality. The Fig 1 illustrates results in the first strategy and both scenarios. It represents objective function (1.a) behavior, while varying the patients' waited time (α).

In this case, patients' availabilities and coordination between caregivers were respected. In fact, the care dates were generated while taking into account the predefined order between caregivers and also patients' availabilities. The perception of a HCS to the caregivers' tours quality depends on minimal caregivers' waited and travelled times. Nevertheless, the patients' perception to the quality of service depends on minimal waited time between two successive visits. The goal of the tests realized, is to study

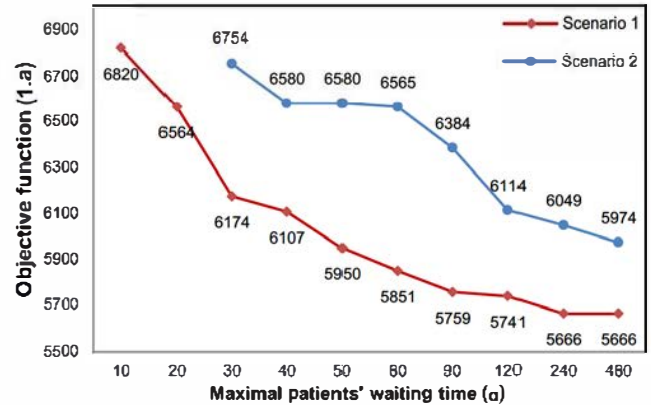and define a method that allows equilibrating satisfactions of all home care actors (patients, HCS).

Fig. 1.Variation of the objective function according to α.

We note from results of the first strategy illustrated on Fig 1, that the total caregivers' worked time decreases while increasing the maximal patients' waited time. This means that the tours' quality is better while increasing the patients' maximal waited time. We remark also that optimal quality was achieved while maximal patients' waited time is equal to 240 and 480 minutes. The best compromise in our example appear, while maximal patients' waited time is equal to $\alpha = 60$ minutes; in this case tours' quality is approximately the same while $\alpha = 480$ minutes (the best tours), i.e. The gap between objective function (1.a) when $\alpha = 60$ min and $\alpha = 480$ min is 55 min (for all caregivers), i.e. an average of 14 minutes for each caregiver. We summarize in table III results obtained in first strategy using both scenarios.

4

TABLE III
RESULTS OF FIRST STRATEGY USING BOTH SCENARIOS (IN MINUTES)

		10	20	40	60	120	480
Scenario N°1	Max caregivers' waited time	[20,50]	[10,50]	[8,20]	[0,40]	[10,34]	[0,14]
	Average caregivers' waited time	[2,9]	[3,18]	= 3	[0,5]	[3,5]	[0,3]
	Average travelled time	187	184	208	192	190	197
Scenario N°2	Max caregivers' waited time	X	X	[0,64]	[0,25]	[0,20]	[5,15]
	Average caregivers' waited time	X	X	[0,10]	[0,7]	[0,3]	[0,3]
	Average travelled time	X	X	209	230	211	208

We remark using the second scenario that there is no solutions when the patients' waited time (α) is lower than or equal to 20 minutes, this is due to excessive travelled and waited times generated because of districting the served region, thus limiting patients' maximal waited time ($\alpha \leq 20$) makes our model infeasible, in another side all solutions proposed using the second scenario ($\alpha \geq 30$) are worse that those obtained when using the first scenario. We note that the tours' generation is also impacted by the districting of deserved region. In fact, the caregivers' tour was generated by scheduling activities for patients from the same district, and taking into account travelled times between different districts. The districting of served region leads to excessive caregivers' waited times like showed in table III (excessive caregivers' waited times in scenario N°2).

- *Second strategy*

In this strategy, the constraints used are (2) to (23), (13.b) and (13.b') while using the objective function (1.b). In this situation we have bounded the travelled time for each caregiver by the upper bound "$Length_s$". The values used for each $Length_s$ are extracted from the first strategy while ($\alpha = 10, \alpha = 50, \alpha = 120, \alpha = 480$).

TABLE IV
CAREGIVERS' LENGTHS (IN MINUTES)

	Test 1	Test 2	Test 3	Test 4
α in first strategy	$\alpha = 10$	$\alpha = 50$	$\alpha = 120$	$\alpha = 480$
$Length_1$	195	230	180	190
$Length_2$	195	180	195	205
$Length_3$	185	160	200	190
$Length_4$	175	205	185	200

The table IV summarizes these values. The Fig 2 illustrates variations of patients' waited time, "$Wait_{iss}$", in different tests. In these tests, patients' availabilities and coordination between caregivers were respected.
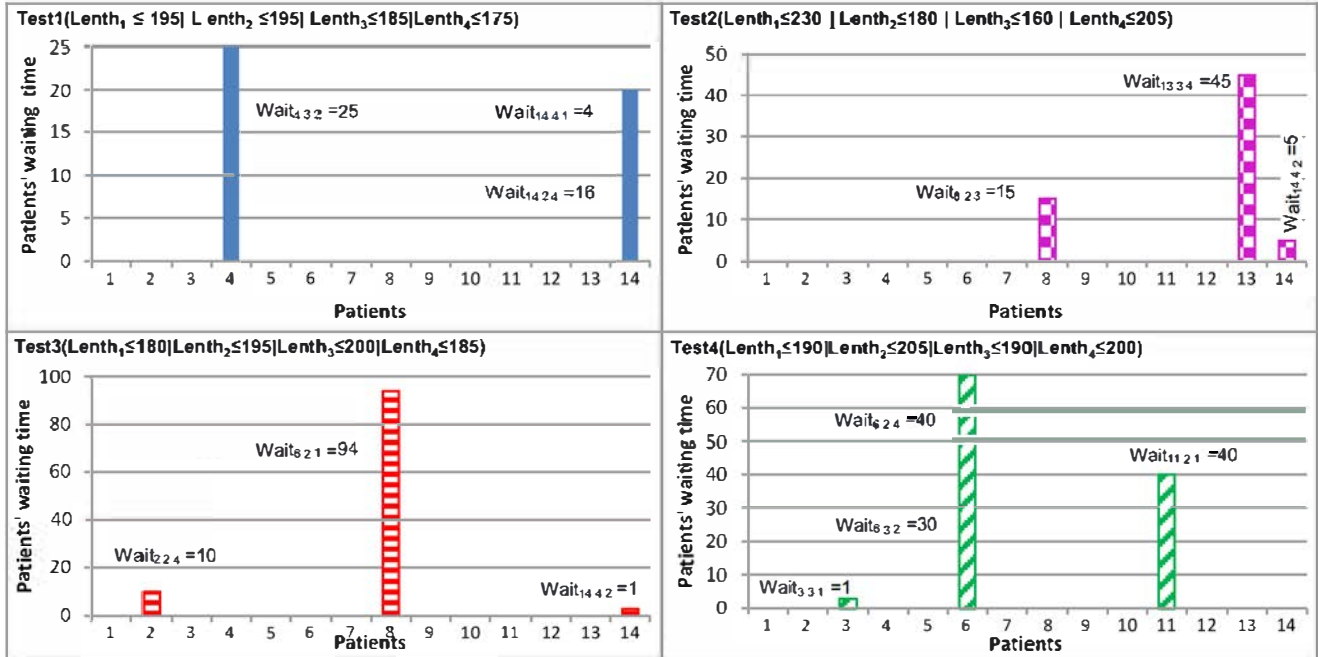

Fig. 2 Variation of patients' waited time according in different tests

We remark from the Fig 2 that using this strategy leads to a minimal patients' waiting times. For example in the first test, 2/13 patients wait, and in tests 2, 3 and 4 the number of waiting patients was 3/13. We noted also that limiting caregivers' travelled duration impacts on the patients' waited time. In fact, the total patients' waited time in test 1 (45 minutes), corresponding to $\alpha = 10$ (strategy N°1), is lower than that in test 2 (65 minutes), corresponding to $\alpha = 50$ (strategy N°1), which is lower than the one in test 3...etc. Thus, conditioning the caregivers' travelled time leads to excessive patients' waited times.

To limit patients waited times and minimizing caregivers' worked durations, we have formalized models presented in both strategies. The idea in the first model is to borne the patients' waited times and studying the impact of this bounds on the tours' quality. In the second model the

developed method allows to fix a maximal travelled time for caregivers' tours and minimizing the total sum of the patients' waited times between successive visits, which allows to study the impact of limiting this maximal traveled time on patients' waited times. Our goal is trying to develop models that lead to define the best accommodation between patients' satisfaction and the tours quality. Both models were efficient to minimizing caregivers' travelled and waited times and patients' waited times, but the model in strategy N°1 was most efficient while balancing waited times between patients while improving caregivers' tours quality.

V. CONCLUSION

In this paper we focused on the caregivers' tours problem, taking into account an important criterion in homecare process, namely coordination between caregivers. Caregivers tours problem is due to costs of waited and travelled times. Minimizing these costs is linked to good planning. We have minimized in the proposed tools both (i) the sum of completion care times for all caregivers, which consequently minimizes the total travelled and waited times for caregivers, while taking into account another important criterion, as a constraint, limiting patients' waited time, and (ii) the sum of patients' waited time between successive care visits, providing that window times of services are not violated. We have tested our model using different contexts linked to patient's availabilities and their geographical locations. We have showed by the first strategy that limiting patients' waited time has an impact on the caregivers' tour quality, and in the second strategy we have noted that limiting caregivers' travelled time impacts the patients' waited time. In another side, we have shown that, the coordination have in impact on generating the tours of caregivers, this is due to the predefined order between visits. We have also shown that the districting of the deserved region have an important impact on caregivers' tours quality.

Besides, this work can be extended to take into account other important constraints in care process, i.e. synchronization (i) between human resources, and/or (ii) between caregiver and material resources, this means planning the arrival of different resources to the patients' home, in the same time. It's clear that the home care process is subject to uncertainties which may be in the caregivers' traveled time, availability of material resources or care durations …etc. so it will be interesting to take into account these environmental constraints.

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