Optimization of the scheduling problem in nursing homes

Inspired by the home care scheduling problem

Abstract

In this paper we consider and test a new model that creates a schedule for caregivers in a nursing home. In a nursing home all the patients needs to be visited by caregivers to help them to perform tasks or to give medicines. The problem can be seen as a Vehicle Routing Problem with Time-Windows and this is known as a NP-hard problem.

The model we made is inspired by a model of Mankowska, which is meant for the scheduling problem in home care. Our focus lies on the patient, which means that a patient should be able to give a time preference for each visit and the number of caregivers by which a patient is treated is minimized. This has led to a department-based model, in which we make use of the different departments in a nursing home and we create a good balance on how to divide the caregivers. Furthermore, we distinct different levels of caregivers and unique durations per visit.

We want to minimize the total tardiness of the visits, the maximum tardiness and the number of visits that a caregiver performs on another department then his/her own department. An important factor was to keep the computational time low, such that a solution of realistic data could be found in reasonable time. We conclude that this model is indeed faster than the original model of Mankowska.

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Preface

This research paper is a compulsory part of the Master's program Business Analytics at the VU University Amsterdam. The aim of this course is to write a research paper about a subject that holds business-related aspects and has a strong link with mathematics or computer science.

In this paper a new model is created to schedule caregivers in nursing homes, such that the visits will be done within a certain time-window, the tardiness is reduced and optionally to let caregivers stay at one department as much as possible.

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Contents

1 Introduction

Home care is an increasingly occurring way to provide care to patients. People have the desire, even when they are not fully self sufficient, to stay in their home as long as possible. With the technology of today it is more often possible to stay home, with new tools like handrails, stair lifts and more. In the organization of home care the patient plays a central role: the care comes to the patient while it used to be the other way around. However, this way of taking care of people at home does not mean that nursing homes will disappear. After all, not in every case home care is possible or desirable.
Both care options have to deal with the planning of carevisits by nurses to patients. This is a difficult problem and for years nursing homes are searching for new ways to make better schedules to reduce costs by using their staff as efficiently as possible. In addition, it is also important to meet the wishes of the patients. Quite often stories come up in the news that patients have not been washed in days due to lack of time, or patients who have waited till eleven or twelve o'clock until they got dressed. These stories confirm that improvement of scheduling activities in nursing homes is necessary.

Since the number of people who get home care is increasing, there is a lot of research done about how the planning of caregivers in home care can be optimized. Since home care and care in nursing homes have similar features, it could be that a solution method that was intended for home care could also be used for nursing homes. Hence, this study looks at how new insights into the theoretical approach to home care may be applicable to schedule activities of nursing homes.

In this paper an overview is given of the situation and theory of planning problems in home care; it will be examined whether and how to turn the theory into the situation of a nursing home. Then an existing model for home care is translated to be applicable in nursing homes and some experiments are carried out to see what kind of results this yields. In this model, the wishes of the patients are discussed and are as far as possible implemented in the new model.

2 Literature

Efficiency in home care becomes more important, since home care is a growing area in health care. In recent years many articles have been written about optimization in home care, in particular about optimizing the schedule and route for caregivers. This section gives an overview of articles that model this problem, they differ since a lot of possible conditions can be considered.
A basic model is given to show what kind of conditions can be taken into account. Then two other articles are discussed that show what an extensive model looks like and what the consequence are when the problem gets more specifications.

Basic model A relative basic form of the home care scheduling problem is given by Redjem [5]. In his setting there are a group of identical patients and a set of identical caregivers, what means that every patient is equally important and that every caregiver is able to perform all visits. A patient needs at least one visit of a caregiver per day. These visits can differ in duration. Also some visits may require the presence of two caregivers. The patients can give their availability according to the following time windows: whole day, morning or afternoon. The locations of the patients are known and traveling times between patients are equal for all caregivers. It is assumed that all patients can be visited in their given time window.
Two objective functions have been studied separately; the first is to minimize the travel distance and the waiting time for the caregivers and the second is to minimize the maximum completion time of the caregivers [5]. A caregiver may need to wait even when he is ready to perform a visit when the patient is not yet available. The completion time is reached when a caregiver has done all visits and is back at a given center, from which he also is assumed to start. To simplify the problem it is assumed that for all caregivers the patients are pre-assigned. Then the remaining problem is only to find the optimal route that minimizes the objective functions described above.
This setting is limited for several reasons; first of all since it assumes pre-assigned patients, and second because it assumes all caregivers to be equal and to give only three options for the time window of the availability of patients.

Extensive model Whereas the setting of Redjem is pretty basic, we can find a more extensive model made by Rasmussen [4]. What remains identical compared to Redjem is that there is a set of patients who all require at least one visit of a caregiver, and that the visits differ in duration. The set of caregivers is extended, since he distinguishes caregivers based on their skill-level. Furthermore, he introduces a preference parameter between a type of caregiver and a type of visit. When this preference parameter is zero it means that the type of caregiver is not allowed to do that type of visit. Since this parameter can be all values between zero and one, he not only distinguish capable from not-capable, but directs which types of visits should be done by which types of caregivers in the most optimal situation [4]. In this way he does not give a hard restriction based on the skill level of the caregiver, but he does increase the efficiency of the caregivers by stimulating the caregivers to do as many visits of their level. Another extension is that he takes into account the method used for traveling. This means that the travel time between two patients may differ for two caregivers when they use different ways for traveling.
The patients give a time window for the start time of the visit, but, different than with Redjem, every time window is possible. However, visits that cannot start in the given time window are left out the schedule and will be given to a manual planner [4]. This means that this method might not be able to create a schedule that includes all visits. To optimize which visits should be left uncovered, a weight is given to every visit that represents the importance of that visit. This gives that the goal is not only to minimize travel time, but also to minimize uncovered visits. Also the combination type of caregiver and type of visit should be maximized based on the preference parameter.
Just like the setting of Redjem, Rasmussen includes visits for which two caregivers are needed at the same time, so called synchronized visits. Furthermore, he adds other types of visits, namely two visits for the same patient that should be done in a certain time window after each other: visits with precedence constraints [4].
This model is more focused on the patient and more realistic than the model of Redjem, since time windows are made more precise and since there is a distinction in the level of caregivers. We also

obtain that this model has more constraints, so the model is more difficult to solve. This model is solved by a branch-and-price algorithm.

VRPTW-problem The scheduling problem in home care, can be obtained as an extension of the Vehicle Routing Problem with Time Windows (VRPTW). This problem is an extension of the Vehicle Routing Problem (VRP) [2], from which the Traveling Salesman Problem is a special case. In a VRP there is a vehicle that needs to visit customers and the goal is to minimize the total distance. In a VRPTW there are additional time windows, what means that customers can only be visited in their time window. An example is the multiple Traveling Salesman Problem with Time Windows (mTSPTW), in which case several salesmen need to visit customers in their time window after which they return to their starting point. The VRPTW is NP-hard [2].

To convert the setting described by Redjem and Rasmussen to a VRPTW, we interpret the caregivers as vehicles and the patients as customers, with their availability as time window. Since a visit has a duration in the home care situation, there must be ensured that the treatment will be finished before the end time of the time window. Since the patients in the model of Redjem are pre-assigned to a caregiver, all caregivers – vehicles – are independent and, hence, we have distinctive problems. However, the model contains visits in which there need to be two caregivers present at the same time and also a patient could get more than one visit from different caregivers which cannot overlap. Hence, we obtain a multiple VRPTW for the model of Redjem, that includes synchronized visits. The model of Rasmussen is more complex and includes precedence constraints. These constraints are the synchronized visits and the temporal dependencies, since vehicles should not only take into account the time window of the customer, but also the visit time of another vehicle at that customer. This problem is comparable to a Vehicle Routing Problem with Time Windows and Temporal dependencies (VRPTWTD). This problem is an extension of the VRPTW and includes temporal dependencies between customers [1]. Note that the model of Redjem can be compared to a VRPTWTD, since it includes synchronized visits. Just as the VRPTW, also the VRPTWTD is NP-hard [1].

Complete Model Finally we discuss the article of Mankowska [3]. This article is less extended than the model of Rasmussen, but has some important features in common. The most important similarities are that they both make a distinction in type of caregiver, there can be a dependency between two visits, synchronization and precedence constraints, and that patients give a time window in which the visit should start. Some extra features treated in the model of Rasmussen are left out, like a preference parameter for the type of patient to a type of visit and the distinction of travel times by travel method. An important difference between the models is that Mankowska schedule visits of patients outside their time window [3]. As a consequence the objective function is to minimize the tardiness, ánd the maximum tardiness, next to the minimization of travel time by the caregivers[3]. Mankowska describes the tardiness of a visit as the time that is needed for a caregiver to perform a visit after the time window.
The problem is solved in different ways. First they tried to solve it with the MILP solver ILOG Cplex 12.3, but for the instances a solution could not be found within 10 hours. Then they tried several local search methods.

In the article this problem is compared with the mTSPTW, but the model is of course also an extension of the VRPTWTD. Again we obtain that there are several vehicles (caregivers) and some customers (patients) that need to be visited more than once. The visits have a duration and also the dependencies between the visits for a customer are taken into account.

Conclusion All three models cover the scheduling problem for home care, but they consider a different setting. Redjem gives a solution for a set patients with visits that can be done by all caregivers and does not contain visits with precedence constraints and self-chosen time windows. Rasmussen creates a much more complicated set with more distinctions, more accurate time windows and dependencies between visits. Mankowska's model is similar to that of Rasmussen, but has left out some extra features but guarantees to give a solution that includes all visits. Although the models differ in complexity, we obtain that all models are NP-hard since they are all extensions of the VRPTWTD.

When the temporal dependencies are left out of the models of Redjem, Rasmussen and Mankowska we notice the models are comparable with the VRPTW.

3 Home care versus nursing homes

Next to home care nursing home is another way to provide care. In a nursing home patients live together or next to each other and during the day caregivers are always nearby. Unfortunately, the small distance between the caregivers and the patients does not make the scheduling problem easier. The distance is namely just one of the many factors that make this problem complex. In this section we describe the situation in a nursing home and compare this to the home care situation.

Situation in a nursing home In a nursing home a large group of patients live together, divided into one or several departments. At every department there are some caregivers. A distinction can be made between the caregivers, based on their skill level: caregivers with the highest level are able to perform all tasks and the ones with the lowest level may only perform some. Since the patients live in the nursing home, in theory a task can be done the whole day. Of course this is not desirable, for example a patient would prefer to have breakfast at 10.00 AM rather than at 4.00 PM. Therefore patients can assign time windows for the tasks that need to be done. Further note that not all tasks are plannable. If a patient falls it needs help, but this task cannot be planned and hence cannot be scheduled in advance. Therefore we only consider plannable tasks in the rest of this research. Another remark is that we assume that synchronized visits and precedence constraints not occur in nursing homes.

Comparison with home care situation Considering the situation described above, it is very similar to the home care situation. A difference is that distances between two patients are less important in optimizing the route of caregivers in a nursing home, since the distances are small. Another difference is that we assume that no time dependent visits occur in a nursing home. Some similarities are the distinction between caregivers and the desire to perform tasks within a certain time window.
However, what the situation in a nursing home really distinguishes from home care, is the fact that there are several departments with patients and one group of caregivers. There are several ways to deal with this. The first option is to divide the caregivers over the departments. Then, for every department we obtain a home care situation since every department has its own patients and its own caregivers. Then the problem is divided in several small problems, which are easier to solve. On the other hand is it possible that the optimal solution for this situation is less than the solution for the second option: to combine all departments. Then we get one group of patients and one group of caregivers. The problem size increases, since the group of patients and caregivers is larger and caregivers are in this case aloud to visit patients on every department. This means the solution for this case is at least as good as in the first option.
When we approach these options with a patient-oriented view, some other aspects have to be taken into account. For example it is for a patient not desirable to have another caregiver at every visit, therefore it would be better to connect a small group of caregivers to every patient. However, a disadvantage is that visits might not be performed in the given time window since in busy periods no extra caregivers are available. Therefore a third option is given, which is described below.

Department-based option In this option the patients are divided over departments and every caregiver is allocated to one department. This department is his base from where he performs his tasks. In principle the caregiver stays on that department, but if it gets very busy on another department the caregiver can go to the other departments for a while. The problem size is equal to option two and is not decreased as in option one, but has important advantages for the patients.
We call this situation department-based and in the next section a model is made using this option.

Table 1: List of variables

Variable	Meaning
C	Set of all departments
S	Set of all visits
V	Set of all caregivers
a_{vs}	Equals 1 iff caregiver $v \in V$ is qualified to provide visit $s \in S$ and 0 otherwise
r_{is}	Equals 1 iff department $i \in C$ requires visit $s \in S$ and 0 otherwise
C^0	Set of all departments and a start/endpoint: $C^0 = C \cup 0$
$[e_s, l_s]$	Time window for visit $s \in S$
d_{ij}	Traveling distance between departments $i \in C^0$ and $j \in C^0$
p_s	Duration of visit $s \in S$
g_{iv}	Equals 0 iff caregiver v belongs to department $i \in C$, 0 otherwise
Decision variables	**Meaning**
x_{ijvs}	Equals 1 iff caregiver $v \in V$ moves from $i \in C^0$ to j for providing visit $s \in S$, 0 otherwise
t_{ivs}	Start time of visit $s \in S$ by staff member $v \in V$ at department $i \in C$
z_s	Tardiness of visit $s \in S$

4 Model

In section 2 different models for the scheduling problem in home care are discussed. In the previous section the differences between home care and nursing homes were explained and some preferences were given for a model to schedule caregivers in nursing homes. To make a new model, we start from a model for home care and transform this such that it is applicable for a nursing home. From the discussed models the model of Mankowska is chosen, because it has several important advantages. It allows, for example, patients to give a self chosen time window for every task - from now visit - what is in line with a patient-oriented approach. Also this model creates a schedule that includes all visits, even when they are planned outside the time window. This is suitable, since all patients stay in the nursing home and besides a time window only gives a preference and does not have to be a restriction. Furthermore, the caregivers are distinguished based on their skill-levels which is current practice in a nursing home.
The model of Mankowska was solved by an LP-solver for several data sets, but it seemed that the model was too complex that even the LP-solver could not find a solution for all data sets within ten hours. If the time dependent visits are left out, the situation is a bit less complicated but still very complex. To reduce the computational time we want to decrease the state space of the model. The department-based situation, as described in the previous section, could help: it might be a good option to set our model over departments instead of over patients as Mankowska did. In this section we describe how the department-based model looks like. The original model of Mankowska can be found in Appendix A, here we show how this department-based model is formulated.

4.1 Outline of the variables

A table with the meaning of the variables for the department-based model is given below, see table 1. Since some meanings of sets and variables are changed, we discuss them first.

The set C is in Mankowska a set of all patients and is now changed into a set of all departments, this leads to a strong decrease in number of elements in the set. The set S is a set for all visits, but where it indicated a service type with Mankowska it now stands for a unique visit. This makes that the set S will strongly increase in number of elements. So Mankowska had a set of visit types which were linked to a patient when he needed a visit of that type and in this model all needed visits are set out separately in the set S and they will be linked to the department where they take place. The set V does not change and stays the set of caregivers.

As a result the meaning of some variables is also changed. For example, r_{is} now shows if visit s must be performed on department i, while it first meant whether patient i needed a visit of type s. Another change is that some variables no longer depend on an element from C, for example p_{is} is changed into p_s. The reason is that the visits are now unique; every visit must be done ones and can only be done on 1 department, namely on the department where the patient is who needs the visit. The duration of a visit does not depend on set C any more, which also decreases the state space.
Finally, one new variable is added: g_{iv}, that links a caregiver to one department; his or her base-department.

4.2 Objective function

The objective function of the problem remains the same as in Mankowska:

$$min \quad Z = \lambda_1 D + \lambda_2 T + \lambda_3 T^{max}. \tag{1}$$

In the model of Mankowska the variable D denotes the distance traveled. For home care it is of main importance that the caregivers should not travel too much. In a nursing home the distances are small - we assume that the walking distance between two departments will just be a few minutes - making this no primary goal anymore. However, something else is more important in this department-based model, namely the times a caregiver leaves his 'base-department'.
We assume that every caregiver belongs to one department, which he can leave for a visit at another department, but then a penalty will be given. By increasing λ_1, this 'base-department penalty' will be more important and hence it becomes less likely a caregiver leaves his department. We introduce parameter g_{iv} that equals 1 if caregiver v does not belong to department i and 0 otherwise. The part D(epartment) of the objective function looks like:

$$D = \sum_{v \in V} \sum_{i \in C^0} \sum_{j \in C^0} \sum_{s \in S} g_{jv} \cdot x_{ijvs}. \tag{2}$$

This equation can be interpreted as the number of visits a caregiver with 'base-department' j performs on a department other than department j.
Since the tardiness of a visit can now be shown as z_s instead of z_{is}, we get the other parts of the objective function to be as follow. Note that equation 4 is also a decision variable.

$$T = \sum_{s \in S} z_s \tag{3}$$

$$T^{max} \geq z_s \quad \forall s \in S. \tag{4}$$

4.3 Constraints

As most constraints are equal to the constraints at Mankowska, we discuss them briefly. The first two constraints guarantee that every caregiver starts and ends the route in the central office (5) and that every caregiver leaves after a visit (6).

$$\sum_{i \in C^0} \sum_{s \in S} x_{0ivs} = \sum_{i \in C^0} \sum_{s \in S} x_{i0vs} = 1 \quad \forall v \in V \tag{5}$$

$$\sum_{i \in C^0} \sum_{s \in S} x_{jivs} = \sum_{i \in C^0} \sum_{s \in S} x_{ijvs} \quad \forall j \in C, v \in V \tag{6}$$

The next constraint (7) states that exactly one qualified caregiver performs a visit when this is needed. Note that this constraint does not hold for visits of department 0. At the end of a service the caregiver is sent to department 0 from a random visit s. Since it will not execute the visit it does not matter which visit is chosen.

$$\sum_{v \in V} \sum_{j \in C^0} a_{vs} \cdot x_{jivs} = r_{is} \quad \forall i \in C, s \in S \tag{7}$$

The start time of a visit should start in the time window and, different than at Mankowska, we state that the end time of a visit should also be within the time window. We think that for a patient it makes more sense to give a time window in which the visit should be performed, then in which it should start since patients might not keep the duration of the visit in mind.
Another change is that we want t_{ivs} to be 0 when task s is not performed by caregiver v. This change will have no effect on the result, but will make the result easier to read. However, since the start times are not minimized in the objective function it can still happen that a start time for a visit is greater than 0 by a caregiver who will not perform that task. The constraints regarding the time window are given in constraints 8 and 9.

$$t_{ivs} \geq e_s \cdot \sum_{j \in C} x_{jivs} \quad \forall i \in C, v \in V, s \in S \tag{8}$$

$$t_{ivs} + p_s \leq l_s + z_s \quad \forall i \in C, v \in V, s \in S \tag{9}$$

We add an extra constraint compared to the model of Mankowska, to make sure that the zero department will be used as a start- and end position. For the routing this is important, hence when a caregiver performs a task it should not be possible to go straight from the start- to the end position:

$$\text{if } t_{i,v,s} > 0 \text{ then } \sum_{k \in S} x_{0,0,v,k} = 0. \tag{10}$$

Finally, some restrictions and non-negativity constraints are given:

$$x_{ijvs} \in \{0, a_{vs} \cdot r_{js}\} \quad \forall i, j \in C^0, v \in V, s \in S \tag{11}$$

$$t_{ivs}, z_s \geq 0 \qquad \forall i \in C^0, v \in V, s \in S. \tag{12}$$

Caregiver start time constraint

There is one constraint that is actually changed in this model and that is the one that is focused on the start times of the visits. This constraint should ensure that a caregiver starts with a new visit when the previous visit is done and the walking time is respected. The original constraint was:

$$t_{ivs_1} + p_{s_1} \cdot min(i,1) + d_{i,j} \leq t_{jvs_2} + M(1 - x_{ijvs_2}) \quad \forall i \in C^0, j \in C, v \in V, s_1, s_2 \in S. \tag{13}$$

With this constraint a caregiver could not perform several visits for the same patient directly after each other, because when $i = j$ the routing becomes unclear and the following two constraint could occur:

$$t_{1,1,1} + p_1 + d_{1,1} \leq t_{1,1,2} + M(1 - x_{1,1,1,2}) \tag{14}$$

$$t_{1,1,2} + p_2 + d_{1,1} \leq t_{1,1,1} + M(1 - x_{1,1,1,1}). \tag{15}$$

Since we have $x_{1,1,1,2} = x_{1,1,1,1} = 1$, equations 14 and 15 can not be satisfied. This is a reasonable restriction when the set C contains many patients, but becomes very hard when the set C contains just a few department. Even more, when there is only one department a solution can not be found. Therefor we made a restriction on the ordering of the visits.

Ordering When an ordering is given the number of options to schedule the visits becomes smaller, because the only thing to be done is to divide the visits over the caregivers. There are several ways to order the visits. It is logical to base the ordering on the time window, how ever this is more difficult when the length of the time window is variable.
When the time windows are equal, the visits can be ordered based on their start or and time, this will not matter. When the time windows are not equal, the ordering is different when it is based on the start time than based on the end time. An ordering based on the start time makes sense, such that a caregiver will not have unnecessary idle time. On the other hand, since we want to minimize the tardiness that is based on the visit time after the time window it might be better to order them on the end time of the time window. Another aspect could be to also take into account the duration

of the visit.

When a right order is chosen we set out the following restriction to the constraint: "If $s_1 < s_2$", in this way a visit with a lower number will start before a visit with a higher number in the ordering. Since we want to minimize the restrictions of the ordering, we saw an option to set the first job free of the ordering in the case when there is only one department. This is possible, since the location before the first job was 0. Therefore we hold no restriction to the ordering when $i <> j$, add "If $i = j$ before the "If $s_1 < s_2$"-part of above and create an extra part to the constraint: "if $i = j$ and $x_{iivs} + x_{iivk} < 2$":

$$t_{ivs} + p_{s_1} \cdot min(1, i) + d_{ij} \leq t_{jvs_2} + M(2 - x_{ijvs_2} - \sum_{h \in C^0} x_{hivs_1} - x_{iivs_1}). \tag{16}$$

When there is more than 1 department, this will not hold because the caregiver will change of departments during the day.
We obtain that the routing disappears and does not help us anymore with determining the start times when we have more than one department. Therefore the variable x is changed into $x_{j,v,s}$: the previous department does not matter anymore. The constraint is than: if $s_1 < s_2$:

$$t_{i,v,s} + p_{s_1} \cdot \min\ (1, i) + d_{i,j} \leq t_{j,v,s_2} + M \cdot (2 - x_{j,v,k} - x_{i,v,s_1}). \tag{17}$$

Actually, the only difference with the situation with 1 department, is that then the first visit could be a higher number. For the rest, all the visits on department 1 which follow a visit that was on department 1, hold the same constraint.

With this MLP-model we can create a schedule for given data sets The complete MLP-model is described in Appendix A (see section A2).

5 Experiments

The model described in the previous chapter is implemented in the AIMMS solver, just as the original model of Mankowska. In this chapter the experiments are described and the outcomes are presented. First a simple problem is solved using both models so that the outcome and the computational time can be compared. An interesting issue is whether the computation time will decrease in the department based model, since that was one of the goals. Furthermore, we explore what happens with the outcome and in computational time when one of the sets (patients, departments or caregivers) is increased. We conclude with the outcome of a realistic situation in which we combine all restrictions.

5.1 Small example

To get a feeling what an outcome looks like, we introduce a small example with 1 department, 2 caregivers and 10 visits over 5 patients. The data set with information about the visits is shown in table 2. We assume a traveling time of 4 minutes between departments 0 and 1 and a traveling time of 1 for two visits on the same department. The 2 caregivers are allowed to perform all visits and belong to department 1. In the objective function we choose all λ's equal to 1.

Table 2: Dataset for a small example

Visits	Department	Start time window	End time window	Duration	Minimal level	Patient
0	0	0	300	0	1	0
1	1	0	30	10	2	1
2	1	0	30	15	3	2
3	1	0	30	10	3	3
4	1	0	30	15	3	4
5	1	0	30	20	2	5
8	1	30	65	20	2	1
9	1	30	70	25	2	2
10	1	30	80	30	2	3
6	1	30	60	5	3	4
7	1	30	60	5	3	5

Mankowska model

The final result of the model of Mankowska was found after 40 seconds, but it took 317 seconds in total to finish the run. The schedule for the two caregivers is shown in table 3. In the model of Mankowska a time-window holds for a patient and hence for all jobs of that patient. For example the time-window for patient 2 is from 0 to 70 and the restriction that the first visit should be done before minute 30 is assumed to cancel. However, the restriction that a first visit should be done before the second visit does hold, see Appendix A.

Table 3: Schedule caregiver 1 and 2 for Mankowska

Caregiver 1

Walking time	Visit (patient)	Start time	End time	Tardiness
4	5 (5)	4	24	0
1	1 (1)	25	35	0
1	2 (2)	36	51	0
1	6 (4)	52	57	0
1	10 (3)	58	88	8

Caregiver 2

Walking time	Visit (patient)	Start time	End time	Tardiness
4	4 (4)	4	19	0
1	3 (3)	20	30	0
1	7 (5)	31	36	0
1	8 (1)	37	57	0
1	9 (2)	58	73	13

Department based model

The department based model gave after 4 seconds the result as shown in table 4 and this was not improved in the remaining computation time that was in total 109 seconds. We see that the total

Table 4: Schedule caregiver 1 and 2 for the department based model

Caregiver 1

Walking time	Visit (patient)	Start time	End time	Tardiness
4	5 (5)	4	24	0
1	2(2)	25	40	10
1	8(3)	41	61	0
1	10 (5)	62	92	12

Caregiver 2

Walking time	Visit (patient)	Start time	End time	Tardiness
4	1(1)	4	14	0
1	3(3)	15	25	0
1	4(4)	26	41	11
1	6(1)	42	47	0
1	7(2)	48	53	0
1	9(4)	54	79	9

tardiness is 42 and the maximum is 12. In this model the time windows are given per visit. Since it is not clear in the model which visits belong to the same patient it is possible that two visits for one patient overlap. In this case this does not happen. Because there are more restrictions regarding the time window than with the previous model, the tardiness is now higher. However, when only the tardiness of the second visit is taking into account, as is done in the first model, we get a total tardiness of 19.

Comparison

Both models give different schemes. A reason for this is that the time-windows are differently used in the models. However, in both models the time the caregivers need to perform their tasks is more or less equal. When the computational times are compared it is notable that the department-based model found the optimal schedule after just a few seconds and that the total computational time is remarkably shorter.

To be able to compare the schedules of Mankowska and the department-based model, we change the setting for Mankowska such that there are 10 patients who all need one job. In this case we have a time-window for every visit and hence the schemes are comparable. When we run the model of Mankowska with this change we obtain almost the same schedule as found with the department based model and the optimal solution is already found in 22 seconds. The only difference between the schemes is that visits 1 and 3 are interchanged. Visits 1 and 3 are identical, hence this is appropriate. We see the model of Mankowska is now fast, and that the algorithm apparently runs much faster when every patient only needs 1 visit.

Real data set

In the next experiments we use a data set from a nursing home with two departments. For three locations in a nursing home we have data that contains all the morning visits for 6 days. Two of the locations have on average 30 visits per department, one location has an average of 70 visits on one department and 60 on the second and this is larger. For the experiments we used the data of day 6 of location 2, see Data set A in Appendix B (section $B1$). The given data set contained only the start time of the time window, but not an end time. Therefore this is chosen as follow: $l_s = e_s{+}\min(90;\max(30; 3 \cdot p_s))$. The time window is always between 30 and 90 minutes and depends on the duration of the visit. The data is ordered based on the end time of the time window, such that a visit with a higher number can be placed later in the schedule. This ordering is very important to get a good result.

In the data set it was not clear to which patient a visit belonged. Therefore a set of 20 patients is taken, 10 on each department. Every patient needs 3 visits except for 2 patients needing 4. By doing this we can implement these requirements easy in the model of Mankowska.

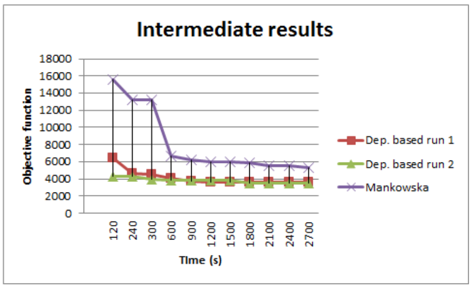
5.2 Enlarge set of patients

We have seen that the department-based model gave a solution after a fraction of time for a small example. However, the new data set contains 30 visits per department and hence has a set of 60 visits. We wonder what the computational time will be when the set of visits is enlarged. The other characteristics stay equal as in the small example, so all visits take place at 1 department and are performed by 2 caregivers who are allowed to perform all visits.
To get an indication of the optimization process, we made an overview of the intermediate results for two runs in figure 1. We see that the first run starts with a higher level of tardiness. The seconds run starts with a lower tardiness but sticks a while at level 3822 before it reaches the final result of 3524. They both find a result after half an hour which does not change any more in the next 15 minutes. The schedule for the two caregivers at run 1 is shown in appendix C (see section $C1$) and table 5 shows a numerical overview of run 1. We see that the visits are nicely divided over the two caregivers; the total duration is about equal while caregiver 2 performs more visits. The tardiness if for both caregivers high, so we remark that it would be better to increase this number of caregivers.

Table 5: Numerical overview for the scheme with 2 caregivers

	Caregiver 1	Caregiver 2
Number visits	28	34
Total duration	360	365
Average duration	12,87	10,74
Total tardiness	1619	1780
Average tardiness	57,82	52,35

Figure 1: Intermediate results with 2 caregivers



The model of Mankowska could not give a result after several hours, so we obtain that the department-based model is significantly faster. However, as we saw in the small example, the model of Mankowska performed better when every patient only needs to have 1 visit. We changed the data into a set of 62 patients who all needs one visit. Then we obtain results, but the value of the objective function is much higher than the results of the department-based model, as can be seen in figure 1.

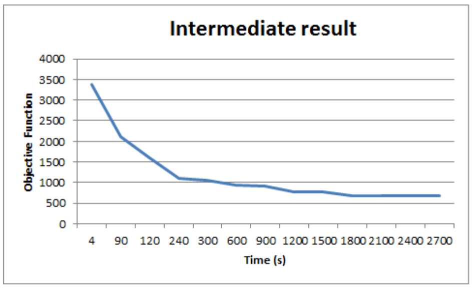
5.3 Enlarge set of caregivers

We saw that the data set used in the previous subsection gave a solution within one hour. We wonder what the influence is on the computational time when we add one caregiver. We obtain that the result that was found after 43 minutes did not change in the next 12 minutes, so after 55 minutes we stopped the run. The results can be found in figure 2. Indeed the running time is longer with 3 caregivers, but still a reasonable result came out in less than an hour. The schedules of the three caregivers can be found in Appendix C (see section $C2$). As we see in table 6, the visits are divided equally over the caregivers based on their total duration. The tardiness is significant higher for caregiver 3 than for caregivers 1 or 2, this is possible since no restrictions are given in order to equally divide the tardiness over the caregivers.

Table 6: Numerical overview for a schedule with 3 caregivers

	Caregiver 1	Caregiver 2	Caregiver 3
Number visits	24	19	19
Total duration	245	240	240
Average duration/visit	10,21	12,63	12,63
Total tardiness	139	145	304
Average tardiness	5,79	7,63	16

Figure 2: Interim results with 3 caregivers



5.4 Enlarge set of departments

When an extra department is added, we have to change the model as was explained in section 4. We also changed the data set a bit, namely we set all time windows equal to 50 minutes. In the previous data set the length of the time window was variable. Because of this change we make sure that a visit with a lower number has an earlier start ánd end time then a visit with a higher number. We also increased the number of patients, such that every patient has less visits. The data set, Data set B, can be found in Appendix B (see section$B2$).
When there are more departments we can test what the consequence is when a penalty is given when a caregiver performs a visit that is not on his base department. First the result is given without a penalty, then with a penalty. Caregivers 1 and 3 belong to department 1 and caregiver 2 belongs to department 2.

5.4.1 Result without base-department penalty

Since we want to compare the optimal results in the situation with and without base-department penalty, we should complete the run to get the optimal solution. However, this took a long time: after 57090 seconds (15 hours, 51 minutes) the run was still not completed. The solution that was found was already known after about 9 hours. That is why we decided to stop the run after 57090 seconds and to not wait till the run was finished. A numerical overview of the result is given in table 7, the schedules are shown in Appendix C(see section $C3$). The total of the objective function was 1311, with a maximum tardiness of 147 and a total tardiness of 1164. Again we notice that the tardiness is not equally divided over the caregivers.

5.4.2 Result with base-department penalty

Now we add the last part of equation 1. The question is how λ_1 should be chosen, if it is too low it will not have any effect but when it is too high no caregiver will leave their department with perhaps a high tardiness as a consequence. First we choose $_1 = 50$, but that has not so much effect so we

Table 7: Numerical overview 3 caregivers without base-department penalty

	Caregiver 1	Caregiver 2	Caregiver 3
Number visit	16	20	26
Total duration	285	240	200
Average duration	17,81	12,00	7,69
Total tardiness	759	233	25
Average tardiness	47,44	11,65	0,96
# Visits department 1	8	6	17
# Visits department 2	8	14	9

increased it to $\lambda_1 = 100$. Of course the calculation time was again very high, this time we stopped the run after 8,5 hours. Now the objective function became 2563, with a maximum tardiness of 82, a total tardiness of 1281 and a penalty of 100 times 12. The numerical overview is shown in table 8 and the schedule of the caregivers can be found in Appendix C (see section $C4$).

Table 8: Numerical overview 3 caregivers with base-department penalty

	Caregiver 1	Caregiver 2	Caregiver 3
Number visit	20	23	19
Total duration	215	290	220
Average duration	10,75	12,61	11,58
Total tardiness	436	549	296
Average tardiness	21,80	23,87	15,58
# Visits department 1	14	2	15
# Visits department 2	6	21	4

When we compare both results we see that indeed caregiver 2 and 3 leave their department less often. Caregiver 1 is the second caregiver that belongs to department 1 and since there are as many visits on department 1 as on department 2 it makes sense that caregiver 1 could not also stay on department 1 for the most part. We also notice that the average tardiness increases as was expected.

5.5 Realistic case

We have seen that the model finds a solution in reasonable time when we enlarge the three sets C, S and V. Now we can include the last element to make the setting realistic: the skill levels of the caregivers. Till now we assumed all caregivers to be able to perform all tasks, while in real-life caregivers differ in skill-level. Based on earlier studies we know that for the used data set (Data set B), we need 7 caregivers: 1 of level 1, 4 of level 2 and 2 of level 3. The caregivers of level 3 are able to perform all tasks, while the caregivers of level 1 may only perform the tasks of level 1. It is not known how many caregivers should belong to which department, but since the number of visits is equal on both departments we should divide them equally. Therefore each department gets 1 caregiver of level 3 and 2 caregivers of level 2. The caregiver of level 1 is assigned to department 1.
We have run this model twice; the first time without the base-department penalty and the second time with the base-department penalty. The results were found after about one hour, in the next 1.5 hours the results did not change so we stopped the run. This is much faster than in the previous sections, a cause can be that the tardiness is 0 for the most visits and hence those visits do not need improvement any more. The intermediate results are presented in figure 3. When the penalty is not included, we obtain that only 2 visits have tardiness of only 2 resp. 8 minutes. When a penalty, with $\lambda_1 = 20$, we notice that the tardiness in increased to a total of 54, divided over 4 visits. We do find that the number of visits performed at the non-base department is decreased from 21 to 5, see tables 9 and 10. The schedules of the caregivers can be found in Appendix C (see section $C5$). We further note that caregiver 1 was not really needed, even though was stated that 7 caregivers was optimal, since caregiver 1 only needs to perform 1 visit. A reason can be that we have chosen a time window

of 50 minutes which apparently is big enough to let almost all visits be performed in time. However, when we decrease the time window to 30 minutes, the tardiness will increase and that it could be very helpful to have 7 caregivers.

Figure 3: Intermediate results

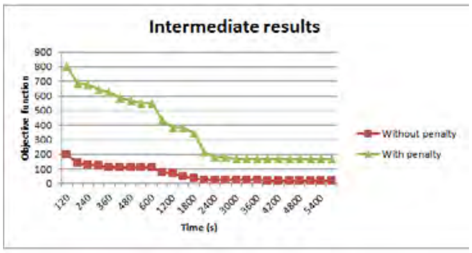


Table 9: Numerical overview without base-department penalty

	Caregiver 1	Caregiver 2	Caregiver 3	Caregiver 4	Caregiver 5	Caregiver 6	Caregiver 7
Number visit	1	8	8	8	9	16	12
Total duration	5	150	105	85	105	150	125
Average duration	5,00	18,75	13,13	10,63	11,67	9,38	10,42
Total Tardiness	0	0	0	0	0	10	0
Average Tardiness	0	0	0	0	0	0,625	0
# visits department 1	1	3	6	2	5	6	8
# visits department 2	0	5	2	6	4	10	4
# visits wrong department	0	3	2	2	4	6	4

Table 10: Numerical overview with base-department penalty

	Caregiver 1	Caregiver 2	Caregiver 3	Caregiver 4	Caregiver 5	Caregiver 6	Caregiver 7
Number visit	1	8	8	7	6	15	15
Total duration	10	125	90	95	80	200	125
Average duration	10,00	15,63	11,25	13,57	13,33	13,33	8,33
Total Tardiness	0	0	0	11	0	14	29
Average Tardiness	0,00	0,00	0,00	1,57	0,00	0,93	1,93
# visits department 1	1	0	8	0	6	3	13
# visits department 2	0	8	2	7	0	12	2
# visits wrong department	0	0	0	0	0	3	2

6 Conclusion

It is a difficult task to make an optimal schedule for a group of caregivers in a nursing home. In this research we were inspired by models for scheduling of caregivers in home care. From this we obtained a routing model that already has some restrictions and features that are present in the scheduling problem for a nursing home: the caregivers have different skills such that not every caregiver should be able perform every task and the patients should give a time window in which they prefer to be visited by a caregiver.
We used the routing model of Mankowska as a starting point and converted it to a model for the nursing home situation. In the new model we obtained that in the situation with 1 department a result was obtained faster than the model of Mankowska, even when the group of patients, visits or caregivers was enlarged. When the data was changed such that every patient needs only one visit, the model of Mankowska improved significantly but still performed less than the department-based model.
In the experiments a real data set was used, making the size of visits and caregivers realistic to what could be seen in regular nursing homes. We noticed that a first result was already obtained within a minute and that within an hour a reasonable result was found. We did not let all the runs finish because that would take a lot of time and because the question was merely to compare the computational time for some reasonable results between the tests than to find the computational time of the optimal result.
We obtained that a reasonable result was found faster in the realistic case with 7 caregivers, than with only 2 or 3 caregivers. A reason can be that there is less tardiness with 7 caregivers so it only needs to improve the tardiness of a few visits instead of for tens of visits.

The department-based model has as advantage that for all the visits a time window can be given, while in the model of Mankowska one time window is given that holds for all visits of one patient. On the other hand, since in the model it is not known which visit belongs to which patient, an overlap of two visits for one patient can not be prevented.
In the department-based model the visits need to be ordered on forehand, because of this the solution could possibly be not the optimal solution. The visits can be ordered based on their start- or end time, this choice has effect on the result.
We introduced a base department penalty in order to stimulate the caregivers to perform as many tasks on one department, because then the patients are more likely to see the same caregivers. As a result the tardiness may increase. An good balance can be found by choosing a good weight for that situation.

7 Discussion

In this research many things were explored, however many more aspects need further research. In this section we give an overview of our assumptions and of the aspects that could be improved by further research.
The model could be adjusted such that more options are possible. First we did not take into account synchronized visits and visits with precedence constraints, while they could occur in nursing homes. A few times in the experiments we obtained that the tardiness was not equally divided over the caregivers, because there was no restriction about this in the model. It might be preferable to have the tardiness equally divided over the caregivers. Also in our model we only allow tardiness after the time window and it was not allowed to start a visit before the time window. The model could be extended such that these options become possible.
We gave as restriction that caregivers should only perform visits when they had the right skill-level, however we could have given a preference within the possible visits as Rasmussen [4] described. Another option is to examine whether it helps to first schedule the caregivers with the lowest level, followed by scheduling the caregivers with a higher level to the visits that are still open and so on. In that case the problem is divided what could decrease the total computation time. On the other hand, it will be more difficult to minimize the base-department penalty.
Even though a reasonable solution was found within several minutes/hours, the optimal solution took a very long time. There was no time, nor a need, to let the runs finish, but it could be investigated how long a run takes and how much the values of the objective function that are found in this paper would further improve.
Since routing was not possible anymore we had to make use of an ordering that was fixed in advance. This is a strong assumption, and can lead to a solution that is far from optimal. It could investigated whether there is another way to find a schedule witch avoids routing.
These aspects show that an optimal way to find a solution to the scheduling problem in nursing homes is not yet found and that further research is needed.

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Appendix A

A1. Model of Mankowska

The model of Mankowska [3] is used as a start for the model used in this paper. The model of Mankowska is presented below.

Table 11: List of variables

Variable	**Meaning**
C	Set of all patients
S	Set of all visits
V	Set of all caregivers
a_{vs}	Equal 1 iff caregiver $v \in V$ is qualified to provide visit $s \in S$
r_{is}	Equal 1 iff patient $i \in C$ requires visit s
C^0	Set of all patients and start/endpoint; $C^0 = C \cup 0$
$[e_i, l_i]$	Time window for patient $i \in C$
d_{ij}	Traveling distance between patient $i \in C^0$ and $j \in C^0$
p_{is}	Duration of visit s at patient i
Decision variables	**Meaning**
x_{ijvs}	Binary, 1 iff caregiver v moves from i to j for providing visit s, 0 otherwise
t_{ivs}	Start time of visit s by staff member v
z_{is}	Tardiness of visit s at patient i.

$$min \quad Z = \lambda_1 D + \lambda_2 T + \lambda_3 T^{max}$$

$$D = \sum_{v=V} \sum_{i \in C^0} \sum_{j \in C^0} \sum_{s \in S} d_{ij} \cdot x_{ijvs}$$

$$T = \sum_{i \in C} \sum_{s \in S} z_{is}$$

$$T^{max} \geq z_{is} \quad \forall i \in C, s \in S$$

$$\sum_{i \in C^0} \sum_{s \in S} x_{0ivs} = \sum_{i \in C^0} \sum_{s \in S} x_{i0vs} = 1 \quad \forall v \in V$$

$$\sum_{i \in C^0} \sum_{s \in S} x_{jivs} = \sum_{i \in C^0} \sum_{s \in S} x_{ijvs} \quad \forall i \in C, v \in V$$

$$\sum_{v \in V} \sum_{j \in C^0} a_{vs} \cdot x_{jivs} = r_{is} \quad \forall i \in C, s \in S$$

$$t_{ivs_1} + p_{is_1} + d_{ij} \leq t_{jvs_2} + M(1 - x_{ijvs_2}) \quad \forall i \in C^0, j \in C, v \in V, s_1, s_2 \in S$$

$$t_{ivs} \geq e_i \quad \forall i \in C, v \in V, s \in S$$

$$t_{ivs} \leq l_i + z_{is} \quad \forall i \in C, v \in V, s \in S$$

The next equation is adjusted to the fact that we assume there are no double services, but we do want that two services for one patient do not overlap.

$$t_{ivk} - t_{iws} \geq p_{is} - M \cdot (2 - \sum_{j \in C^0} x_{jiws} - \sum_{h \in C^0} x_{hivk})$$

$$x_{ijvs} \in \{0, a_{vs} \cdot r_{js}\} \quad \forall i, j \in C^0, v \in V, s \in S$$

$$t_{ivs}, z_{is} \geq 0 \qquad \forall i \in C^0, v \in V, s \in S$$

Table 12: List of variables

Variable	Meaning
C	Set of all departments
S	Set of all visits
V	Set of all caregivers
a_{vs}	Equals 1 iff caregiver $v \in V$ is qualified to provide visit $s \in S$ and 0 otherwise
r_{is}	Equals 1 iff department $i \in C$ requires visit $s \in S$ and 0 otherwise
C^0	Set of all departments and a start/endpoint: $C^0 = C \cup 0$
$[e_s, l_s]$	Time window for visit $s \in S$
d_{ij}	Traveling distance between departments $i \in C^0$ and $j \in C^0$
p_s	Duration of visit $s \in S$
g_{iv}	Equals 0 iff caregiver v belongs to department $i \in C$, 0 otherwise
Decision variables	**Meaning**
x_{ijvs}	Equals 1 iff caregiver $v \in V$ moves from $i \in C^0$ to j for providing visit $s \in S$, 0 otherwise
t_{ivs}	Start time of visit $s \in S$ by staff member $v \in V$ at department $i \in C$
z_s	Tardiness of visit $s \in S$

A2. Department-based model

From the model of Mankowska is created the department-based model. This model is presented below.

$$min \quad Z = \lambda_1 D + \lambda_2 T + \lambda_3 T^{max}$$

$$D = \sum_{v \in V} \sum_{i \in C^0} \sum_{j \in C^0} \sum_{s \in S} g_{jv} \cdot x_{ijvs}$$

$$T = \sum_{s \in S} z_s$$

$$T^{max} >= z_s \quad \forall s \in S$$

$$\sum_{i \in C^0} \sum_{s \in S} x_{0ivs} = \sum_{i \in C^0} \sum_{s \in S} x_{i0vs} = 1 \quad \forall v \in V$$

$$\sum_{i \in C^0} \sum_{s \in S} x_{jivs} = \sum_{i \in C^0} \sum_{s \in S} x_{ijvs} \quad \forall j \in C, v \in V$$

$$\sum_{v \in V} \sum_{j \in C^0} a_{vs} \cdot x_{jivs} = r_{is} \quad \forall i \in C, s \in S$$

$$t_{ivs} \geq e_s \cdot \sum_{j \in C} x_{jivs} \quad \forall i \in C, v \in V, s \in S$$

$$t_{ivs} + p_s \leq l_s + z_s \quad \forall i \in C, v \in V, s \in S$$

$$\text{if } t_{i,v,s} > 0 \text{ then } \sum_{k \in S} x_{0,0,v,k} = 0.$$

$$x_{ijvs} \in \{0, a_{vs} \cdot r_{js}\} \quad \forall i, j \in C^0, v \in V, s \in S$$
$$t_{ivs}, z_s \geq 0 \qquad \forall i \in C^0, v \in V, s \in S.$$

When there is only 1 department we get:
"If $i = j$ and $s_1 < s_2$":

$$t_{ivs_1} + p_{s_1} \cdot min(i, 1) + d_{i,j} \leq t_{jvs_2} + M(1 - x_{ijvs_2}) \quad \forall i \in C^0, j \in C, v \in V, s_1, s_2 \in S.$$

"if $i = j$ and $x_{iivs} + x_{iivk} < 2$":

$$t_{ivs} + p_{s1} \cdot min(1, i) + d_{ij} \leq t_{jvs_2} + M(2 - x_{ijvs_2} - \sum_{h \in C^0} x_{hivs_1} - x_{iivs_1}).$$

"else":

$$t_{ivs_1} + t_{jvs_2} <= M$$

When there are more than 1 department we get:
if $s_1 < s_2$:

$$t_{i,v,s} + p_{s_1} \cdot \min\,(1, i) + d_{i,j} \leq t_{j,v,s_2} + M \cdot (2 - x_{j,v,k} - x_{i,v,s_1}).$$

Appendix B

B1. Dataset A

In table 13 the data set of section 2, day 6 for a morning from 7:10 till 11:00 is shown. In this data set the time windows depend of the duration on the visit: $l_s = e_s$+min(90;max($30; 3 \cdot p_s$)).

Table 13: Dataset A

Visits	Department	Start time window	End time window	Duration	Minimal level	Patients	Visits	Department	Start time window	End time window	Duration	Minimal level	Patients
0	0	0	1000	0	1		32	2	480	555	25	2	15
1	2	430	460	5	3	11	33	1	480	570	35	2	8
2	2	420	465	15	2	12	34	1	480	570	40	3	9
3	2	435	465	5	3	13	35	2	480	570	30	2	16
4	1	450	480	5	2	1	36	2	480	570	35	2	17
5	1	450	480	5	3	2	37	2	510	570	20	2	18
6	1	450	480	5	3	3	38	2	540	570	10	2	19
7	1	450	480	10	3	4	39	1	510	585	25	2	10
8	2	450	480	5	2	14	40	1	555	600	15	2	1
9	2	450	480	5	3	15	41	1	570	600	5	1	2
10	2	435	495	20	2	16	42	2	510	600	50	3	20
11	1	480	510	10	2	5	43	2	570	600	5	2	11
12	1	480	510	10	2	6	44	2	570	600	5	2	12
13	1	480	510	5	3	7	45	2	570	600	5	2	13
14	1	480	510	5	3	8	46	1	600	630	5	2	3
15	2	450	510	20	2	17	47	1	600	630	5	2	4
16	2	480	510	10	2	18	48	1	600	630	5	2	5
17	2	480	510	5	3	19	49	1	600	630	10	2	6
18	2	480	510	5	3	20	50	1	600	630	10	2	7
19	2	480	510	5	3	11	51	2	600	630	5	1	14
20	2	480	510	10	3	12	52	2	600	630	5	1	15
21	1	495	525	10	2	9	53	2	600	630	5	1	16
22	1	495	525	5	3	10	54	2	600	630	10	1	17
23	1	495	525	5	3	1	55	1	615	645	10	2	8
24	1	510	540	10	2	2	56	1	620	650	5	2	9
25	1	510	540	10	2	3	57	2	640	670	10	2	18
26	1	510	540	10	3	4	58	1	660	690	10	1	10
27	2	510	540	5	2	13	59	1	660	690	10	2	1
28	2	510	540	10	2	14	60	2	600	690	45	2	19
29	1	525	555	5	3	5	61	2	660	690	10	1	20
30	1	525	555	5	3	6	62	2	660	705	15	1	11
31	1	525	555	5	3	7							

B2. Dataset B

In table 14 the data set of section 2, day 6 for a morning from 7:10 till 11:00 is shown. In this data set the time windows are equalto 50 minutes independent of the duration of the visit.

Table 14: Dataset B

Visits	Department	Start time window	End time window	Duration	Minimal level	Patients	Visits	Department	Start time window	End time window	Duration	Minimal level	Patients
0	0	0	1000				32	2	510	560	5	2	15
1	2	420	470	15	2	14	33	2	510	560	10	2	16
2	2	430	480	5	3	15	34	2	510	560	20	2	17
3	2	435	485	5	3	16	35	1	510	560	25	2	4
4	2	435	485	20	2	17	36	2	510	560	50	3	18
5	1	450	500	5	2	1	37	1	525	575	5	3	5
6	1	450	500	5	3	2	38	1	525	575	5	3	6
7	1	450	500	5	3	3	39	1	525	575	5	3	7
8	1	450	500	10	3	4	40	2	540	590	10	2	19
9	2	450	500	5	2	18	41	1	555	605	15	2	8
10	2	450	500	5	3	19	42	1	570	620	5	1	9
11	2	450	500	20	2	20	43	2	570	620	5	2	20
12	1	480	530	10	2	5	44	2	570	620	5	2	21
13	1	480	530	10	2	6	45	2	570	620	5	2	22
14	1	480	530	5	3	7	46	1	600	650	5	2	10
15	1	480	530	5	3	8	47	1	600	650	5	2	11
16	2	480	530	10	2	21	48	1	600	650	5	2	12
17	2	480	530	5	3	22	49	1	600	650	10	2	13
18	2	480	530	5	3	23	50	1	600	650	10	2	1
19	2	480	530	5	3	24	51	2	600	650	5	1	23
20	2	480	530	10	3	25	52	2	600	650	5	1	24
21	2	480	530	25	2	26	53	2	600	650	5	1	25
22	1	480	530	35	2	9	54	2	600	650	10	1	26
23	1	480	530	40	3	10	55	2	600	650	45	2	27
24	2	480	530	30	2	27	56	1	615	665	10	2	2
25	2	480	530	35	2	14	57	1	620	670	5	2	3
26	1	495	545	10	2	11	58	2	640	690	10	2	14
27	1	495	545	5	3	12	59	1	660	710	10	1	4
28	1	495	545	5	3	13	60	1	660	710	10	2	5
29	1	510	560	10	2	1	61	2	660	710	10	1	15
30	1	510	560	10	2	2	62	2	660	710	15	1	16
31	1	510	560	10	3	3							

Appendix C

C1. Schedule for 2 caregivers on 1 department

The schedule of two caregivers for the situation described in Appendix B, in which all visits take place on department 1 and in which both the caregivers are able to perform all visits, is presented in table 15

Table 15: Schedule caregivers with all visits on 1 department

Caregiver 1					Caregiver 2				
Distance	Patient	Starttime	Endtime	Tardiness	Distance	Patient	Starttime	Endtime	Tardiness
4	10 (16)	435	455	0	4	2 (12)	420	435	0
1	4 (1)	456	461	0	1	1 (11)	436	441	0
1	5 (2)	462	467	0	1	3 (13)	442	447	0
1	7 (4)	468	478	0	1	6 (3)	450	455	0
1	12 (6)	480	490	0	1	8 (14)	456	461	0
1	18 (20)	491	496	0	1	9 (15)	462	467	0
1	19 (11)	497	502	0	1	11 (5)	480	490	0
1	20 (12)	503	513	3	1	13 (7)	491	496	0
1	21 (9)	514	524	0	1	14 (8)	497	502	0
1	23 (1)	525	530	5	1	15 (17)	503	523	13
1	24 (2)	531	541	1	1	16 (18)	524	534	24
1	26 (4)	542	552	12	1	17 (19)	535	540	30
1	29 (5)	553	558	3	1	22 (10)	541	546	21
1	30 (6)	559	564	9	1	25 (3)	547	557	17
1	31 (7)	565	570	15	1	27 (13)	558	563	23
1	32 (15)	571	596	41	1	28 (14)	564	574	34
1	33 (8)	597	632	62	1	35 (16)	575	605	35
1	34 (9)	633	673	103	1	36 (17)	606	641	71
1	37 (18)	674	694	124	1	38 (19)	642	652	82
1	40 (1)	695	710	110	1	39 (10)	653	678	93
1	41 (2)	711	716	116	1	43 (11)	679	684	84
1	42 (20)	717	767	167	1	44 (12)	685	690	90
1	48 (5)	768	773	143	1	45 (13)	691	696	96
1	51 (14)	774	779	149	1	46 (3)	697	702	72
1	53 (16)	780	785	155	1	47 (4)	703	708	78
1	54 (17)	786	796	166	1	49 (6)	709	719	89
1	61 (20)	797	807	117	1	50 (7)	720	730	100
1	62 (11)	808	823	118	1	52 (15)	731	736	106
					1	55 (8)	737	747	102
					1	56 (9)	748	753	103
					1	57 (18)	754	764	94
					1	58 (10)	765	775	85
					1	59 (1)	776	786	96
					1	60 (19)	787	832	142

C2. Schedule for 3 caregivers on 1 department

When there are 3 caregivers to perform all visits, we get the results shown in table 16.

Table 16: Schedule for 3 caregivers

		Caregiver 1					Caregiver 2					Caregiver 3		
Distance	Patient	Starttime	Endtime	Tardiness	Distance	Patient	Starttime	Endtime	Tardiness	Distance	Patient	Starttime	Endtime	Tardiness
4	10 (16)	435	455	0	4	4 (1)	450	455	0	4	3 (13)	435	440	0
1	8 (14)	456	461	0	1	5 (2)	456	461	0	1	1 (11)	441	446	0
1	15 (17)	462	482	0	1	6 (3)	462	467	0	1	2 (12)	447	462	0
1	16 (18)	483	493	0	1	13 (7)	480	485	0	1	7 (4)	463	473	0
1	19 (11)	494	499	0	1	14 (8)	486	491	0	1	9 (15)	474	479	0
1	21 (9)	500	510	0	1	18 (20)	492	497	0	1	11 (5)	480	490	0
1	22 (10)	511	516	0	1	20 (12)	498	508	0	1	12 (6)	491	501	0
1	25 (3)	517	527	0	1	26 (4)	510	520	0	1	17 (19)	502	507	0
1	29 (5)	528	533	0	1	32 (15)	521	546	0	1	23 (1)	508	513	0
1	31 (7)	534	539	0	1	33 (8)	547	582	12	1	24 (2)	514	524	0
1	35 (16)	540	570	0	1	39 (10)	583	608	23	1	27 (13)	525	530	0
1	37 (18)	571	591	21	1	40 (1)	609	624	24	1	28 (14)	531	541	1
1	38 (19)	592	602	32	1	47 (4)	625	630	0	1	30 (6)	542	547	0
1	43 (11)	603	608	8	1	50 (7)	631	641	11	1	34 (9)	548	588	18
1	44 (12)	609	614	14	1	52 (15)	642	647	17	1	36 (17)	589	624	54
1	45 (13)	615	620	20	1	55 (8)	648	658	13	1	41 (2)	625	630	30
1	46 (3)	621	626	0	1	56 (9)	659	664	14	1	42 (20)	631	681	81
1	49 (6)	627	637	7	1	58 (10)	665	675	0	1	48 (5)	682	687	57
1	53 (16)	638	643	13	1	60 (19)	676	721	31	1	51 (14)	688	693	63
1	54 (17)	644	654	24										
1	57 (18)	655	665	0										
1	59 (1)	666	676	0										
1	61 (20)	677	687	0										
1	62 (11)	688	703	0										

C3. Schedule for 3 caregivers on 2 departments without penalty

Now there are 2 departments. Caregiver 1 and 3 belong to department 1 and caregiver 2 to department 2. However, the penalty D in the objective function is 0 since λ_1 is chosen 0. We get the following schedules, see in table 17.

Table 17: Schedule 3 caregivers without penalty

		Caregiver 1					Caregiver 2					Caregiver 3		
Department	Number	Start time	End time	Tardiness	Department	Number	Start time	End time	Tardiness	Department	Number	Start time	End time	Tardiness
2	3	447	452	0	2	2	436	441	0	1	5	450	455	0
2	4	468	488	3	2	3	442	447	0	1	26	506	516	0
1	7	477	482	0	2	4	448	468	0	1	27	517	522	0
1	13	490	500	0	1	7	472	477	0	1	28	523	528	0
1	14	496	501	0	1	13	480	490	0	1	31	529	539	0
2	16	510	520	0	1	14	491	496	0	1	37	563	568	0
2	19	516	521	0	2	16	500	510	0	1	38	569	574	0
1	23	560	600	70	2	19	511	516	0	1	39	575	580	5
1	30	571	581	21	1	23	520	560	30	1	41	581	596	0
2	36	625	675	115	1	30	561	571	11	1	42	597	602	0
2	40	636	646	56	2	36	575	625	65	1	47	621	626	0
2	43	642	647	27	2	40	626	636	46	1	49	627	637	0
1	46	651	656	6	2	43	637	642	22	1	50	638	648	0
2	51	660	665	15	1	46	646	651	1	1	56	661	671	6
2	52	666	671	21	2	51	655	660	10	1	57	672	677	7
2	54	677	687	37	2	52	661	666	16	1	59	683	693	0
					2	54	667	677	27	1	60	694	704	0
					2	58	678	688	0	2	9	459	464	0
					2	61	689	699	0	2	11	465	485	0
					2	62	700	715	5	2	18	486	491	0
										2	20	492	502	0
										2	32	543	548	0
										2	33	549	559	0
										2	44	606	611	0
										2	45	612	617	0
										2	53	652	657	7

C4. Schedule for 3 caregivers on 2 departments with penalty

In this case λ_1 is 100 and hence there is a penalty given when caregivers perform a visit on another department, the schedules are presented in table 18.

Table 18: Schedule 3 caregivers with penalty

Caregiver 1					Caregiver 2					Caregiver 3				
Department	Number	Starttime	Endtime	Tardiness	Department	Number	Starttime	Endtime	Tardiness	Department	Number	Starttime	Endtime	Tardiness
0	0	0	0	0	2	1	420	435	0	1	5	450	455	0
2	1	435	450	0	2	2	436	441	0	1	6	456	461	0
2	2	441	446	0	2	3	442	447	0	1	8	462	472	0
2	3	447	452	0	2	10	450	455	0	1	12	480	490	0
2	10	455	460	0	2	11	456	476	0	1	23	508	548	18
2	11	476	496	0	2	16	480	490	0	1	26	549	559	14
2	16	490	500	0	2	17	491	496	0	1	27	560	565	20
2	17	496	501	0	2	19	497	502	0	1	29	566	576	16
2	19	502	507	0	2	21	503	528	0	1	31	577	587	27
2	21	528	553	23	2	25	529	564	34	1	37	605	610	35
2	25	564	599	69	2	32	565	570	10	1	41	611	626	21
2	32	570	575	15	2	34	571	591	31	1	46	639	644	0
2	34	591	611	51	2	36	592	642	82	1	47	645	650	0
2	36	642	692	132	1	39	646	651	76	1	48	651	656	6
1	39	651	656	81	2	40	655	665	75	1	50	657	667	17
2	40	665	675	85	2	44	666	671	51	2	20	494	504	0
2	44	671	676	56	2	51	672	677	27	2	33	591	601	41
2	51	677	682	32	2	53	678	683	33	2	45	630	635	15
2	53	683	688	38	2	54	684	694	44	2	55	671	716	66
2	54	694	704	54	2	58	695	705	15					
					1	59	709	719	9					
					2	61	723	733	23					
					2	62	734	749	39					

C5. Realistic case

In this situation we observe 7 caregivers (see table 19). In the first table, table 20, is shown the result without the base-department penalty, in the second table, table 21, with the penalty by a λ_1.

Table 19: Base department caregivers

Caregiver	Level	Department
1	1	1
2	2	2
3	2	1
4	2	2
5	2	1
6	3	2
7	3	1

Table 20: Schedule without base-department penalty

Caregiver 1

Department	Visit	Start time	End time	Tardiness
1	42	570	575	0

Caregiver 2

Department	Visit	Start time	End time	Tardiness
2	9	450	455	0
2	11	456	476	0
2	25	480	515	0
1	29	519	529	0
1	35	530	555	0
1	38	556	561	0
2	44	570	575	0
2	55	600	645	0

Caregiver 3

Department	Visit	Start time	End time	Tardiness
1	12	480	490	0
1	22	491	526	0
2	32	530	535	0
2	34	536	556	0
1	48	600	605	0
1	49	606	616	0
1	50	617	627	0
1	56	628	638	0

Caregiver 4

Department	Visit	Start time	End time	Tardiness
1	5	450	455	0
2	16	480	490	0
2	24	491	521	0
2	40	543	553	0
2	45	570	575	0
1	46	600	605	0
2	54	609	619	0
2	61	660	670	0

Caregiver 5

Department	Visit	Start time	End time	Tardiness
2	4	435	455	0
1	6	459	464	0
1	13	480	490	0
2	21	494	519	0
1	26	523	533	0
1	30	534	544	0
2	33	548	558	0
2	52	600	605	0
1	59	660	670	0

Caregiver 6

Department	Visit	Start time	End time	Tardiness
2	2	430	435	0
2	3	436	441	0
1	7	450	455	0
1	8	456	466	0
2	10	470	475	0
1	15	480	485	0
2	17	489	494	0
2	18	495	500	0
2	19	501	506	0
2	20	507	517	0
2	36	518	568	8
1	37	572	577	2
2	51	600	605	0
1	57	620	625	0
1	60	660	670	0
2	62	674	689	0

Caregiver 7

Department	Visit	Start time	End time	Tardiness
1	14	480	485	0
1	23	486	526	0
1	27	527	532	0
1	28	533	538	0
1	31	539	549	0
1	39	568	573	0
1	41	574	589	0
1	47	602	607	0
2	1	420	435	0
2	43	593	598	0
2	53	611	616	0
2	58	640	650	0

Table 21: Schedule with a base-department penalty

Caregiver 1

Department	Visit	Start time	End time	Tardiness
1	59	660	670	0

Caregiver 2

Department	Visit	Start time	End time	Tardiness
2	4	435	455	0
2	9	456	461	0
2	16	480	490	0
2	24	491	521	0
2	33	522	532	0
2	34	533	553	0
2	40	554	564	0
2	44	570	575	0
2	53	606	611	0
2	54	612	622	0

Caregiver 3

Department	Visit	Start time	End time	Tardiness
1	5	450	455	0
1	12	480	490	0
1	29	510	520	0
1	35	522	547	0
1	41	555	570	0
1	50	600	610	0
1	57	620	625	0
1	60	683	693	0

Caregiver 4

Department	Visit	Start time	End time	Tardiness
2	1	420	435	0
2	21	480	505	0
2	25	506	541	11
2	32	542	547	0
2	43	570	575	0
2	51	600	605	0
2	52	606	611	0

Caregiver 5

Department	Visit	Start time	End time	Tardiness
1	13	480	490	0
1	22	491	526	0
1	26	527	537	0
1	30	538	548	0
1	46	600	605	0
1	56	615	625	0

Caregiver 6

Department	Visit	Start time	End time	Tardiness
2	2	430	435	0
2	3	436	441	0
2	10	450	455	0
2	11	456	476	0
1	14	480	485	0
2	17	489	494	0
2	18	495	500	0
1	28	504	509	0
1	31	510	520	0
2	36	524	574	14
2	45	575	580	0
2	55	600	645	0
2	58	646	656	0
2	61	660	670	0
2	62	671	686	0

Caregiver 7

Department	Visit	Start time	End time	Tardiness
1	6	450	455	0
1	7	456	461	0
1	8	462	472	0
1	15	480	485	0
2	19	489	494	0
2	20	495	505	0
1	23	509	549	19
1	27	550	555	10
1	37	556	561	0
1	38	562	567	0
1	39	568	573	0
1	42	574	579	0
1	47	600	605	0
1	48	606	611	0
1	49	612	622	0