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Improving the routing and scheduling process in a home healthcare environment. A case analysis at TWB.

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THUISZORG MET AANDACHT

Preface

This thesis marks the end of my period as an Industrial Engineering and Management student at the University of Twente. I started this master in September 2020 in the middle of the COVID-19 pandemic. This meant that I have only had a hand full of on-campus lectures. Therefore, I would like to thank my fellow students that still allowed me to have a good time during my studies even though we primarily met online.

Additionally, I would like to thank my supervisors Dr.ir. Eduardo Lalla-Ruiz, Dr.ir. Gréanne Leeftink and Yelte Kikke MSc. I have enjoyed our meetings together even though we have never met each other in real life. I have always valued your feedback and it has definitely improved the quality of this report.

I would like to thank TWB for allowing me to perform my master graduation assignment at their company. I have met many different employees during my time at TWB and all have been willing to help throughout the duration of my graduation assignment. I would like to thank my external supervisor Gabriëlle Jehee in particular. I have always enjoyed our meetings and you always gave me the indication that my input was valued. This has motivated me to further improve the quality of this report.

Finally, I would like to thank my family for their continuous support throughout my time as a student.

I hope you enjoy reading this report!

Tim Nijhuis

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Management summary

Thuiszorg West Brabant (TWB) is a home healthcare company in the region West Brabant in the Netherlands. In this work, we focus on the routing and scheduling of TWB's nurses. TWB aims to improve their current planning and scheduling approach to be more cost efficient but also improve their employee satisfaction level to reduce the outflow of employees. TWB is divided into 11 different clusters that operate independently from each other. We primarily focus on determining the effect of combining multiple clusters in the routing and scheduling process of TWB. We consider the clusters Kroeven-Tolberg, Wouw, Centrum-Westrand and Heilig Hart in this research. We analyze the effect of combining multiple clusters by creating an algorithm that is capable of creating high quality routing and scheduling solutions. Furthermore, we investigate the benefit of the routing and scheduling algorithm for individual clusters, the benefit of improving the composition of TWB's workforce and the effect of reducing the number of visits after 22:00.

Context analysis & scientific literature

We start this research with gaining insight in TWB's current planning and scheduling approach. The planning and scheduling solutions are currently created manually by planners of TWB. By analyzing the results of these original solutions, we can conclude that the current manual planning and scheduling approach is sub-optimal. We identified this by two separate indicators, the percentage skill linking and the amount of required overtime. The percentage skill linking shows what percentage of visits are performed by a nurse that has the identical skill level required to perform that visit. The percentage skill linking is an indicator of both the total costs and the employee satisfaction level. The performance of the manually created solutions is sub-optimal because a relatively low percentage skill linking is observed and individual nurses have worked more overtime than necessary. Finally, the context analysis shows that the in-route salary costs (salary paid to nurses during their shift, excluding travel time from and to the nurse's home location) is the main cost component.

We investigate scientific literature to develop an algorithm that can create a cost-effective routing and scheduling solution. Furthermore, we can identify that TWB's routing and scheduling problem can be described as a home healthcare routing and scheduling problem (HHCRSP). The results of the literature search showed that TWB's instances are considerably larger than the instances investigated in literature. Therefore, a solution approach that uses a heuristic is deemed more promising. The Greedy Randomized Adaptive Search Procedure (GRASP) heuristic and variable neighborhood search (VNS) heuristic are two heuristics that are used in studies that consider cases similar to TWB's case.

Solution approach & validation

In this work, we develop a solution approach that decomposes the HHCRSP in separate routing and scheduling problems. The decomposition of the routing and scheduling problem results into multiple independent single day routing problems. Solving these routing problems creates the required routes for each individual day. The scheduling problem is solved to assign nurses to the created routes. A flowchart of the solution approach can be seen in Figure M1.

The solution approach is as follows. We start by selecting a full week instance that needs to be solved. Then, we select the individual day for which we solve the routing problem. The routing problem is solved by a multi-stage GRASP algorithm followed by an adaptive variable neighborhood search. The goal is to minimize the in-route salary costs in the routing problem. A routing solution is created by first creating a set of initial solutions (GRASP stage 1). This is followed by two local searches to ensure that a promising subset of GRASP stage 1 solutions results in feasible overall HHCRSP solutions (GRASP stage 2). A promising subset of GRASP stage 2 solutions is improved using a local search (GRASP stage 3) after which the best obtained GRASP stage 3 solution is improved by the AVNS algorithm. If a routing solution for each day is created, then routes are turned into shifts (scheduling stage 1) with the goal of minimizing the total number of nurses on a single day. In scheduling stage 2, nurses are assigned to shifts in a cost-effective method that aims to minimize nurse overtime.

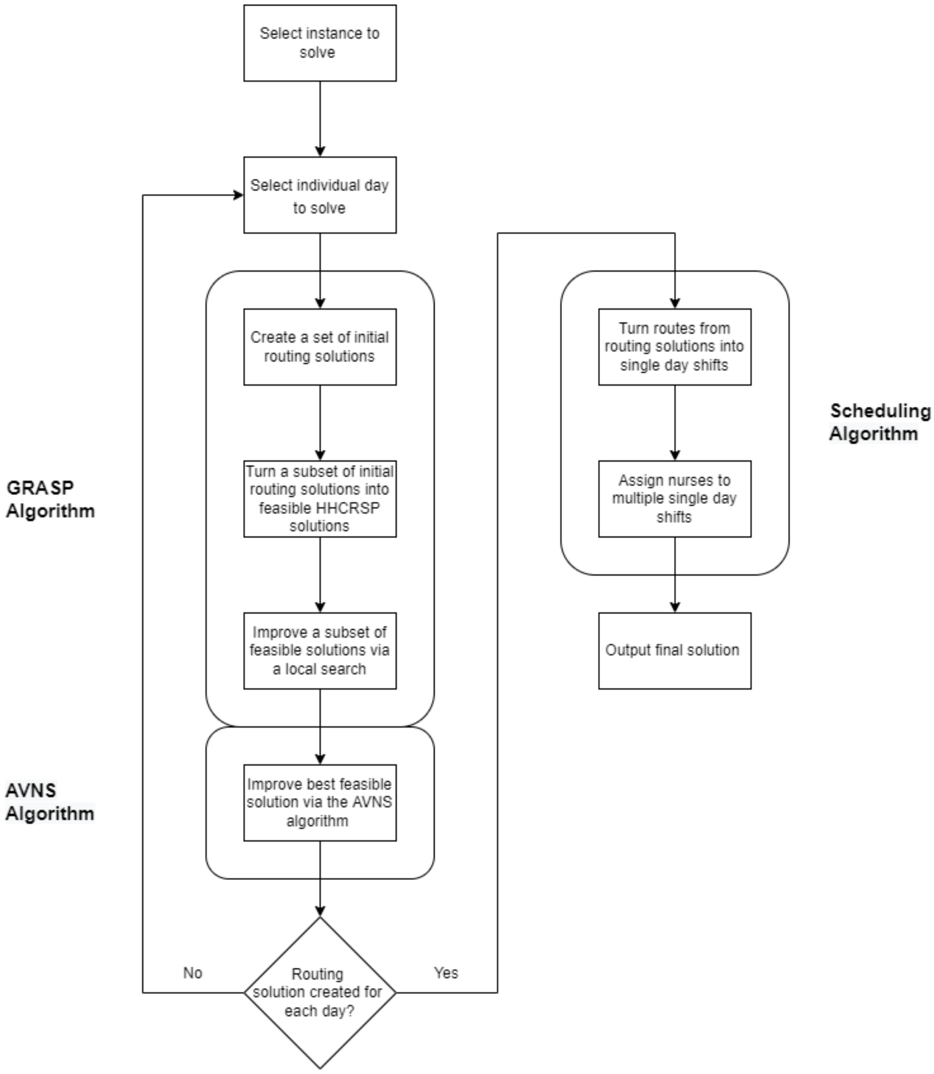

Figure M1: Flowchart of the proposed solution approach.

We analyze the performance of the routes resulting from the GRASP-AVNS algorithm. The results show that the algorithm is capable of creating efficient routes with respect to costs and overall required working time. Furthermore, the results show that the created routing solutions do not contain any constraint violations. This means that the created routing solutions are fully feasible.

Individual clusters

We use the proposed solution approach to generate a routing and scheduling solution for each individual cluster. We compare the results from the algorithmic solution to the results from the original solution created by the planners of TWB. The results indicate an increase in the percentage skill linking, a decrease in 3-IG nurse working time and a decrease in the amount of required overtime. Furthermore, the results indicate that an average weekly in-route salary cost reduction of 250.15 ± 61.25 Euro (95% confidence interval) per cluster is expected by the implementation of the proposed routing and scheduling algorithm. Extrapolating these results gives us an expected annual in-route salary cost reduction of 143085.80 ± 35035 Euro (95% confidence interval). This cost saving amounts into an expected total cost reduction of 1.42 ± 0.35 percent (95% confidence interval). However, the majority of these total costs are fixed and cannot be optimized. Therefore, a cost saving potential is calculated. The cost saving potential indicates a maximum cost reduction compared to the original solution created by the planners of TWB. The results show that the algorithm is able to obtain 14.75 ± 3.02 percent of this entire cost saving potential. However, the proposed algorithm also results in 44 more double/broken shifts (+39%) and a reduction in the continuity of care of 0.095. Which indicates that, on average, a client is visited by 0.95 more nurses compared to the original solution created by the planners of TWB, if the client has ten different visits in the selected instance.

Combining clusters

We perform multiple experiments where we combine the clients and nurses of clusters Kroeven-Tolberg, Wouw, Centrum-Westrand and Heilig Hart. The results of the combined clusters are compared to the results from the individual clusters that are discussed in the previous section. The results indicate that combining both the routing and scheduling approach is not promising because the algorithm produces lower quality routes which results in a total cost increase. However, we show that it is beneficial to combine only the scheduling procedure of nurses. This results in a decrease of overtime but also results in an increase in the number of double/broken shifts which results in a weekly expected cost increase of 127.34 Euro combined over the four clusters. However, the combined weekly costs are expected to decrease with 49.85 Euro when nurses are allowed to work the same fraction of overtime as in the solution of the individual clusters. In all cases, an additional continuity of care reduction of at least 0.15 is observed.

Workforce composition

The results from the individual cluster experiments show that only a small percentage of the entire cost saving potential is achieved by the implementation of an algorithm. A larger part of this cost saving potential can be obtained by improving the workforce of TWB. The results from the individual clusters indicate that TWB has an excess of high skill level personnel (level 3 and 3-IG) and a shortage of low skill level personnel (ADL and level 2). The effect of this skill discrepancy is investigated by changing the skill level of nurses to the ADL skill level in cluster Kroeven-Tolberg. Although, it has to be noted that the ADL skill level is currently only assigned to trainees. The results from changing the skill level of nurses show that TWB indeed has an excess of high level personnel and a shortage of low level personnel. Extrapolating the results from Kroeven-Tolberg results in a maximum annual expected cost saving of 583245.52 Euro that can be obtained by hiring more ADL employees. The same experiment is performed where the skill of nurses is downgraded to level 2. In that case, a maximum annual cost saving of 220889.24 Euro is expected. In both cases, also other performance indicators such as the percentage skill linking and continuity of care increase compared to the algorithmic individual cluster results.

Reducing late evening visits

We performed experiments where the time windows of visits are adjusted in such a fashion that no time windows of visits end after 22:00. The results indicate that no cost saving is expected when the working time after 22:00 is reduced. However, the results indicate that this results into more double/broken shifts. So, whether the visits after 22:00 should be reduced can be judged best by the nurses of TWB since it is not expected to have a major cost influence.

Contribution to literature

The contribution of this work to literature is two fold. We developed a HHCRSP algorithm that decomposes the HHCRSP in a separate routing and scheduling problem. The resulting daily routing problems are independent and this allows for a decomposition of the routing problem into individual days. This allows the algorithm to find solutions for HHCRSPs containing a large number of visits. The second contribution is that the proposed algorithm shows whether or not there is a discrepancy between the workforce of the home healthcare organization and the requirements of its clients. The results show that this discrepancy has a substantial influence on total costs. To our understanding, the influence of this discrepancy is an untouched topic in literature.

Conclusion

Our work indicates that creating the routes and schedules via an algorithm has substantial advantages for TWB. We expect an annual cost saving of 143085.80 ± 35035 Euro (95% confidence interval). Furthermore, the created solution does not violate any constraints and produces valid results. However, the current solution approach does result in a substantial continuity of care reduction of 0.095. Based on the results in our work, TWB could combine the scheduling procedure of multiple clusters because this is expected to result in a reduction of individual nurse overtime. However, no substantial cost reduction is observed. The biggest contribution of this work is that it shows that TWB has an overqualified workforce and TWB should consider the ADL skill level as an actual skill level and hire ADL skilled employees. This is expected to substantially reduce the total costs while also improving other performance indicators related to the nurse and client satisfaction level.

Recommendation for future research

Several topics suitable for future research are identified. The first topic suitable for further research is an improved scheduling approach. The results in our work show that a substantial decrease in continuity of care is expected by using the proposed solution approach. However, it is expected that this can be attributed to the scheduling approach. Therefore, further research in the scheduling procedure with the focus on the trade off between continuity of care and costs is recommended. Furthermore, this new scheduling research could take additional details into account such as the fixed day off from a nurse and reducing the number of morning shifts after an evening shift. Both of these are not considered in this work.

The second topic suitable for further research is the day that certain visits take place. For instance, TWB indicates that it is also performing visits on Sundays that could be performed on other days. Sundays are the most expensive days. So, performing these visits on a different day is expected to be more cost-effective.

The third topic that could be interesting for future research is a different approach to breaks and double/broken shifts. The current algorithm creates results that contain substantially more double/broken shifts than the original solutions created by the planners of TWB. However, changing the approach to breaks and double/broken shifts may result in a different routing algorithm which means a new algorithm has to be developed.

Recommendation for practical implementation

The proposed algorithm cannot be used in practice in its current state. This is because TWB indicates that shared visits (two nurses at the same time, at the same client) do occur in practice, but these are not included in the algorithm. However, it has to be noted that TWB does not store which visits are shared visits. So, future versions of the proposed algorithm should also consider shared visits to allow for a practical implementation of the algorithm.

Contents

1 Introduction

Thuiszorg West Brabant (TWB) is a home healthcare company in the Netherlands. The company focuses on the region West Brabant. In this region, the cities of Roosendaal, Bergen op Zoom and Etten Leur are located. As well as smaller towns such as Wouw and Nisten. TWB serves thousands of clients each day and has around 2000 employees. TWB provides different types of care to clients. These can be putting together a client's diet or helping with their daily tasks such as cleaning. The main task of TWB employees is providing regular care for a client like helping with their medicine and putting on socks. TWB employees also perform more difficult tasks such as wound treatment. In general, the employees provide care for their clients to allow them to live at their current homes instead of moving to elderly homes or extending their hospital stay.

This research is focused on the Verpleging & Verzorging (nursing & caring) department of TWB. This department is responsible for providing the home healthcare services. Each client has different needs and consequently requires different services from various nurses. Therefore, standard routes have to be created that ensure that a qualified nurse visits the correct clients. This is done by a planner. The routes and schedules within the home care environment are very prone to change. For instance, a nurse can get sick and a different nurse has to perform that route. Another example is that a client has to travel to the hospital on a certain day and therefore requires care earlier during the day. These adjustments mean that the originally created routes and schedules have to be updated by the planner. Furthermore, the planner is also responsible for determining which nurse drives which route on a given day. So, the planner has three tasks. The first task is creating standard routes. The second task is determining which nurse does which route and the final task is updating this planning if changes occur.

TWB consists of 11 clusters. A cluster can be described as a group of clients that are grouped because of their geographical location. Each cluster has one planner that is employed full time. Furthermore, the clusters are divided into multiple teams. These teams are based on the geographical location of the clients within a cluster. A cluster can cover multiple districts and contain multiple independent teams. Each cluster also has their own nurses. Furthermore, each nurse has their own skill level. These levels are: Level 2 ADL, Level 2, Level 3, Level 3-IG, Level 4 and Level 5 district nurses.

The planner is responsible for routing and scheduling all nurses and clients from ADL level to 3-IG level within their own cluster. This is different for level 4 nurses. Level 4 clients from multiple clusters are combined and the level 4 nurses determine their own routes to visit these customers. So, clusters are already combined for level 4 nurses. The scheduling of level 5 nurses is again done in a different fashion. This is because a level 5 nurse has more tasks than providing care for clients. Aside from providing care, a key task from level 5 nurses is monitoring the care level of clients. So, these level 5 nurses indicate to a planner which clients they would like to visit such that these clients can be monitored. This automatically means that the schedule of level 5 nurses is more flexible.

The previously mentioned nurse types perform the regular healthcare tasks. However, TWB also has more specialized teams that are used for specific tasks. These are the following teams:

- A night care team that provides care during the nights.
- An emergency team that helps clients in case of emergencies.
- A hospice team that provides palliative care.
- A top clinical team that performs complex tasks such as kidney dialysis.

1.1 Problem context

TWB faces multiple problems that will be discussed in this section. The first problem is that different clusters have different shortages and excesses in their workforce. For instance, one cluster can have a shortage of 3-IG personnel which means that new clients might have to be rejected because of personnel shortages. A solution to still provide care is that these tasks are performed by a higher level nurse, which is more expensive. However, it is possible that there is an excess of 3-IG personnel in the neighboring cluster. In this case, the 3-IG nurse in the second cluster might perform tasks that could be performed by a lower qualified nurse, or does not work at all. Which is again sub-optimal. It would seem very logical to combine the workforce of the two clusters in this example to ensure that these imbalances are cancelled out. However, this is not done in practice because the clusters do not share information and personnel amongst each other.

A second problem is that the current alteration and creation of routes and schedules is done manually by the planners. This is time consuming for the planners. Furthermore, each planner makes different decisions when creating and altering their routes. Rick Uylen [40] has developed a planning tool for TWB that automatically updates the routes when a change in the schedule is required. At this point TWB does not have a planning tool that helps planners create standard routes and schedule personnel.

Another problem is the satisfaction of employees. TWB indicates that they notice a large outflow of employees. TWB thinks that one reason for this low satisfaction level is the different shifts employees make during the week. For instance it is not preferable for employees to work the morning shift (starting at 7:00) after doing an evening shift (ending at max 23:00). A second reason for the low employee satisfaction level is that nurses have to perform visits that are below the nurse's skill level.

The final problem is that TWB indicates that the workforce of TWB is expected to decline in the coming years. A lot of employees are close to their retirement age. So, in a few years time there will be fewer employees. However, the people within the Netherlands are still getting older. It is expected that in 2050 the number of people the age of 80 will be twice as large as it currently is [25]. This means that the workforce is getting smaller whereas the number of clients requiring care increases in the coming period. This is a problem because TWB is already almost fully utilizing their nurses.

1.2 Core problem & Scope

The problems introduced in Section 1.1 can be mitigated by a more efficient planning and scheduling approach. The planning and scheduling tasks can be divided into two parts. A standard schedule that stays constant for multiple weeks and adaptations of this standard schedule to end up with the final route that is worked by nurses. Rick Uylen [40] has already created a program that can perform the required adaptations to existing routes and schedules. So, in this research the focus will be on creating standard routes and schedules. Furthermore, TWB is specifically interested in the effect of combining clusters. This leads to the following main research question:

What is the effect of combining multiple clusters in the routing and scheduling process on the employee satisfaction level and costs for TWB?

The main research question defined in this section will be answered by performing a case analysis. For this analysis, four clusters that are in/close to Roosendaal are investigated. These clusters are Kroeven-Tolberg, Wouw, Centrum-Westrand and Heilig Hart. Around 530 individual clients are visited on a daily basis within these four clusters. Also, nurses of level 4 and 5 are excluded from this research. Level 4 nurses are already scheduled as if multiple clusters are combined. Level 5 nurses are excluded because creating a long term standard schedule with level 5 nurses makes no sense because they have to monitor many different clients and therefore visit different clients each week.

1.3 Research questions

The first step in answering the main research question is understanding the current routing and scheduling approach and determining its the performance. This leads to the following research question with several sub research questions:

1. How does the current routing and scheduling process work and how does it perform?

- How are the standard routes and schedules currently created?
- How are different stakeholders involved in the routing and scheduling?
- Which characteristics determine whether or not a route and schedule are feasible?
- What performance indicators can be used to determine the performance of a routing and scheduling solution?

- What is the performance of the manually created routing and scheduling process?

A literature search is conducted after understanding TWB's current routing and scheduling process. The goal of this literature search is identifying how routes and schedules for nurses are created in other scientific studies. Here, a two step approach is followed. The first is identifying the different components of the home healthcare routing and scheduling problem. The second step is discovering how the home healthcare routing and scheduling problem is tackled in literature.

2. How is the home care routing and scheduling problem solved in scientific literature?

- What are the different components of the home care routing and scheduling problem?
- What has been researched with respect to the home care routing and scheduling problem?
- What are the differences between TWB's problem and the problems tackled in literature?
- Which solution approaches are used in problems similar to TWB's case?

The first research question gives insight in TWB's problem and the second research question gives insight in which similar problems are solved in practice. The answers to these two questions allow for a development of the solution approach to solve TWB's problem. This solution approach is developed by answering research question 3.

3. How should the solution approach for the home healthcare routing and scheduling problem be generated?

- What is the problem that needs to be solved?
- What are the assumptions of the model?
- How can the assumptions and feasibility characteristics be included in the solution?
- How can the performance of a solution be judged?
- Which solution strategy is promising?

The proposed solution approach should be tested to determine whether or not it generates usable solutions. This is divided into multiple steps to test the different components of the solution approach.

4. How can the solution approach generate feasible and high quality solutions?

- Can the solution approach generate feasible solutions?
- Which settings of the algorithm lead to high quality solutions?
- How should nurses be allocated to routes?

By answering research question 4, a solution approach is generated that can now be used to perform experiments. These experiments aim to provide more insight into the performance of different planning and scheduling approaches.

5. What is the influence of different instances on the performance of the planning and scheduling approach?

- What is the performance of using an algorithm to create a routing and scheduling solution in the current clusters?
- What is the effect of the time window of visits?
- What is the effect of combining multiple clusters in Roosendaal?

The final step is drawing conclusions and determining recommendations based on the outcome of the experiments.

6. What are the conclusions and recommendations for TWB resulting from the experiments?

1.4 Research design

This research is divided into different stages. Each stage is used to answer a specific research question. The answer to the main research question defined in Chapter 1 will be determined by answering the research questions in each stage. In Chapter 1, the problem has been introduced and the steps to solve the problem are displayed. In the next stage, the problem is investigated in detail. This is done by answering sub-research questions 1 and 2. The context analysis of the problem (sub-research question 1) is covered in Chapter 2. The literature review off the problem (sub-research question 2) is covered in Chapter 3. After Chapter 2 and 3, several promising solution approaches can be distinguished. Selecting a solution approach corresponds to the third sub-research question and this is covered in Chapter 4 in this report. Different experiments to tune the solution approach will be performed once a solution approach has been selected. This corresponds to sub-research question 4 and is covered in Chapter 5. Then, experiments are performed to provide more insight into experimental parameters of TWB's planning and scheduling approach in Chapter 6. Finally, conclusions and recommendations can be formulated from these experiments. This answers sub-research question 6 and is covered in Chapter 7. The different steps of this research are also displayed in Figure 1.

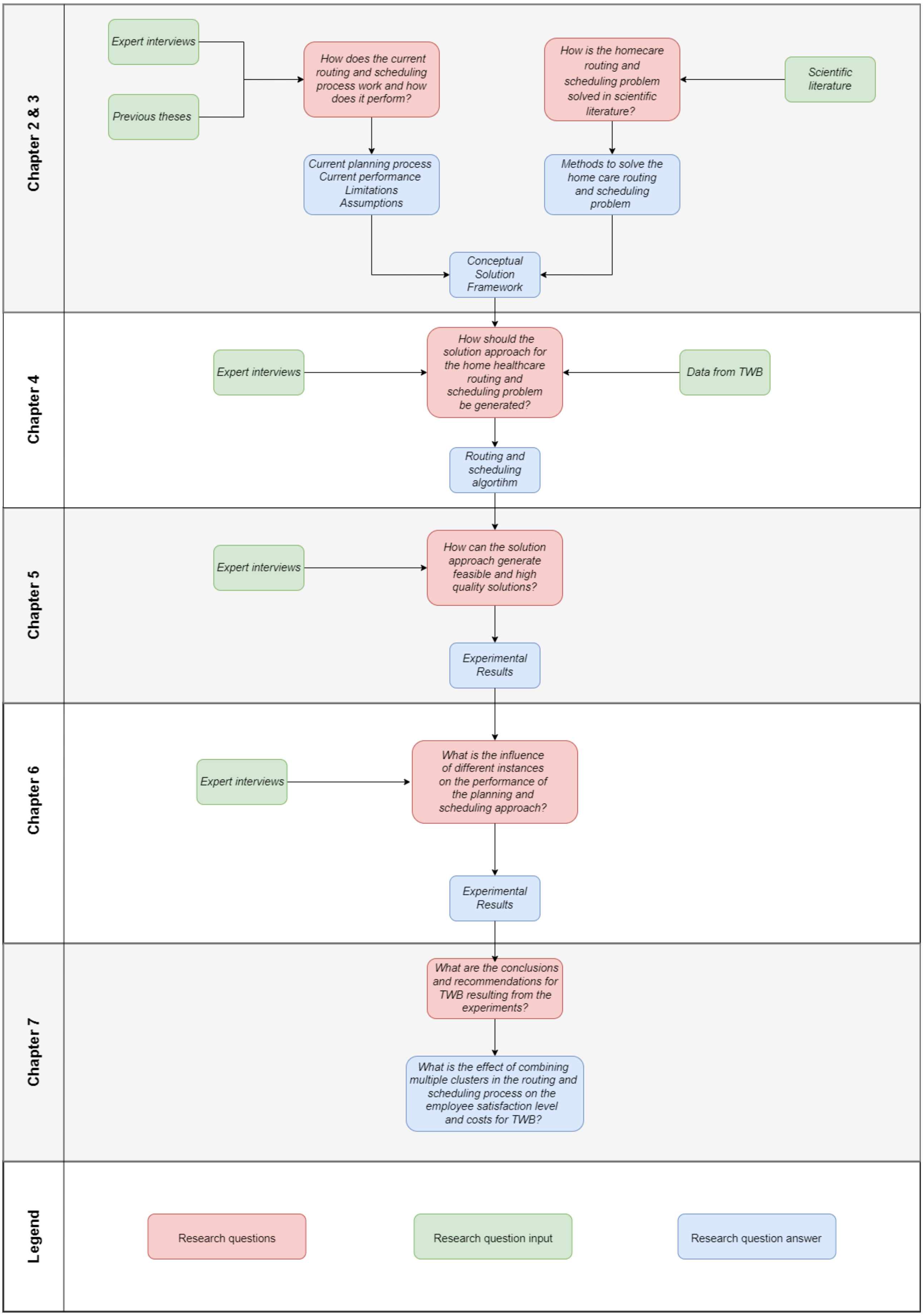

Figure 1: Research Design. This figure shows which research question is covered in which chapter of this report.

2 Context analysis

In this chapter, we answer the research question: *How does the current routing and scheduling process work and how does it perform?*. We do this by analyzing the current routing and scheduling process. First, Section 2.1 covers all components of the current planning system. Next, a stakeholder analysis is performed to identify the goals of the different stakeholders involved in the planning process in Section 2.2. Constraints for a feasible schedule are investigated in Section 2.3. Section 2.4 gives insight into the data retrieved from TWB's current planning and scheduling procedure. In Section 2.5 the performance indicators are defined. In Section 2.6, the performance of the current planning and scheduling process is analyzed. We finalize this chapter with a conclusion in Section 2.7.

2.1 Current planning & scheduling system

This section explains the current planning and scheduling process. First, the clients are introduced in Section 2.1.1. Next, the different level of nurses are introduced. In Section 2.1.3, the additions and adaption of care of clients are covered. The tasks of the planner are covered in Section 2.1.4. Finally, the concept of clusters is explained in Section 2.1.5.

2.1.1 Clients

Clients are the persons that receive the care from employees from TWB. These can be elderly people that require care at their home but it can also be someone that has recently been released from a hospital that still requires some care. A client can have multiple appointments on a single day. For instance, a client that requires insulin shots needs multiple shots on a single day. Furthermore, these insulin shots need to be given at very specific times during the day (for instance right before dinner). So, TWB uses time windows when scheduling their visits to clients to ensure that the right care is given at the right time. Clients can have preferences with respect to the employees that help them. For instance, some clients only want to be helped by a female employee. These preferences are not taken into account by TWB when assigning personnel. Another example is that some clients require more than one employee at the same time. A reason for this shared visit might be that the client is overweight and therefore requires more than one nurse. The final topic is that each client requires a different level of care. A client that needs help with washing requires a lower level of care than a client that needs an insulin shot. These levels of care are the same as the level of nurses and are introduced in the following section.

2.1.2 Nurses

The employees of TWB are nurses. The nurses can have different skill levels. A list of the skill levels, along with the tasks and salary of each level, can be seen in the list below.

- Level 2 ADL nurses. This is the lowest level of nurses. This skill level is primarily associated with trainees. ADL nurses are only allowed to do basic tasks at a client's home. These tasks range from washing and clothing clients to helping a client with their lunch. An ADL level nurse is not allowed to perform any medical tasks. A level 2 ADL nurses costs TWB 17.48 Euro per hour.

- Level 2 nurses. The level 2 nurses are the second lowest level of nurses. Level 2 nurses are allowed to perform the same tasks as ADL nurses but are allowed to perform slightly more tasks such as putting on compression stockings and giving clients non medical eye drops. Level 2 nurses cost TWB 21.19 Euro per hour.

- Level 3 nurses. Level 3 nurses are allowed to perform the same tasks as level 2 nurses but are also allowed to perform some medical tasks. Such as helping with medicine and giving clients medical eye drops. Level 3 nurses cost TWB 24.52 Euro per hour

- Level 3-IG nurses. The 3-IG level nurse is allowed to do the same tasks as the level 3 nurse. But 3-IG nurses are also allowed to perform more difficult tasks such as taking care of wounds and injections. Level 3-IG nurses cost TWB 27.23 Euro per hour.

- Level 4 nurses. Level 4 nurses are the second highest nurse qualification. Nurses of this level are allowed to perform all regular tasks within TWB. Level 4 nurses cost TWB 30.43 Euro per hour.

- Level 5 district nurses. These are the highest qualifications of nurses. District nurses are allowed to perform all regular tasks that occur at TWB. Level 5 nurses can have additional specializations such as wound treatment or diabetes. These, high level, specializations are nurse specific. Furthermore, a key task of the district nurse is determining the level of care that is required for clients. Level 5 nurses cost TWB 33.44 Euro per hour.

The level 5 district nurse determines, along with the client, the care plan for the client. During this intake process the level of required care and the number of visits per week is determined. Furthermore, the care levels are hierarchical. So, a client that requires level 3 level of care is allowed to be helped by nurses of level 3, 3-IG, 4 and 5.

Looking at the tasks of each level of nurse then a clear trend is visible. The low level nurses perform mainly non medical tasks. Whereas the higher level nurses mainly perform medical tasks. The salaries of each nurse group also differs with the level 5 nurses receiving the highest salary.

2.1.3 Client arrival & monitoring

As indicated in the previous section, level 5 nurses have an intake meeting with the client during which the level of care and number of visits per week is determined. However, the required level of care and visits per week of a client can change over time. That is why the status of the clients need to be monitored. TWB uses their own Project Integral Care (project integrale zorg in Dutch) philosophy. Here, different employees of TWB visit the same client on purpose. These can be higher level nurses. But, these can also be employees working at different departments of TWB (dietitians for instance). The logic behind this philosophy is that different employees notice different things at a client. These things could be that a client needs more care or that the level of care of a client can be lowered. In both cases, it is important that this is noticed by TWB such that the client receives the right amount and level of care. This monitoring over time is not just done by level 5 nurses. This can also be done by level 4 and 3-IG nurses for clients below their care level.

2.1.4 Creating a schedule

Up to this point, all of the nurses, clients as well as how the required care of a client is determined is covered. The next step is the creation of a route and schedule that ensures that all clients are visited. In general, this is done by a planner. However, routes for level 4 and 5 nurses are not (fully) planned by a planner. In this section, first the tasks of a planner are explained and then the creation of routes for level 4 and 5 nurses is discussed.

Long-term weekly schedule

The first task of the planner is determining the long-term weekly schedule. The long-term schedule is a schedule that is updated over time when new changes are required. These changes are introduced in Section 2.1.3. For instance, a client needs an additional care appointment then the planner has to update the existing long-term schedule such that this new appointment is covered by a nurse in the future. Another example is that a client requires a higher skill level at an already existing appointment. In that case, the planner most likely has to move this appointment out of the route of the current nurse and into the route of a higher level nurse. The long-term schedule is the direct result of these long-term changes over time. No cost optimization is performed to create a better long-term schedule.

Short-term schedule

The second task of the planner is determining the short-term schedule of a nurse. The short-term schedule contains the final routes that the nurses have to drive to visit their clients. The short-term schedule uses the long-term schedule as starting point. The short-term schedule is created by applying one time changes to the long-term schedule. For instance, a client needs to travel to the hospital on a certain day and therefore requires care earlier on that day. Another example is that a nurse becomes sick and the clients of the sick nurse have to be distributed amongst the other nurses. In these cases, the planner updates the short-term schedule to incorporate these changes.

Assigning personnel

The third task of the planner is assigning nurses to shifts, while respecting assignment rules. Nurses have one fixed day off in a week. The nurses determine which day of the week this is. Furthermore, nurses also determine the weekends that they do not want to work (nurses have to work 50% of the weekends). Then, the planner determines which days and which shifts the nurses have to work. There are three different shifts. A morning shift (starting at 7:00 until roughly 11:30). An afternoon shift (starting at 12:00 until 15:00) and an evening shift (starting at 16:00 until roughly 23:00). The times indicate the earliest start time of a shift and the latest end time. For instance, it is possible that a nurse works a full morning and afternoon shift and is free for the remainder of the day (from 7:00 until 15:00). But it is also possible that a nurse works from 8:00 until 11:00 in the morning shift and has a route from 19:00 until 22:00 in the evening. The planner also takes the working hours per week of a nurse into account according to their contract. Assigning of personnel happens in two stages. First, employees are assigned to shifts based on the long-term schedule for a period of four weeks. Then, nurses are swapped in case a nurse cannot work a specific shift. This for instance occurs if a nurse becomes sick for a longer time period.

Routing of level 4 & 5 nurses

The routing of high level nurses is done differently. First, the routing of level 4 nurses is explained. During the day level 4 nurses provide care to clients from their own cluster. However, during the weekends and evenings, the clients from multiple clusters are combined into three larger clusters. These clusters are: Roosendaal, Halderberge & Rucphen and Brabantse wal. During the day the planner from the nurse's cluster determines which level 4 nurse visits which client. The nurse then determines in which order the clients are served. In the evenings and weekends, one planner is responsible for assigning clients from all clusters to the level 4 nurses. The nurses still determine themselves in which order the clients are visited.

The routing of level 5 nurses differs per cluster within TWB. However, the routes are created in collaboration with the planner of the nurse's cluster in all cases. For instance, a level 5 nurse indicates to their cluster's planner that they want to visit a certain client. In that case, the planner assigns the level 5 nurse to the route containing that client. A level 5 nurse can also have an 'intake' route. In this type of route the nurse mainly visits clients for an initial intake meeting. Finally, level 4 & 5 nurses sometimes work routes of a lower level in cases of employee shortages. But this is undesirable. Level 4 and 5 nurses are excluded from this research because of these different routing and scheduling procedures.

Nedap Ons

The routes and schedules are created in a software tool called Nedap Ons. The routes created via Nedap Ons are automatically shared with nurses, ensuring that nurses always have the latest version of their routes. Aside from that, Nedap simplifies administrative tasks such as salary registration of personnel. Finally, Nedap also stores data of the routes.

2.1.5 Clusters

The most time consuming tasks of the planner is updating the long and short-term schedules. This takes so much time that this is impossible to do for one planner. That is why TWB has divided their workforce (nurses) and clients into clusters. Here, each planner is responsible for one cluster. The clusters are created based on the location of clients. The clusters are usually a couple of districts within the larger cities (for instance Kroeven-Tolberg in Roosendaal) but these can also be smaller municipalities (such as the cluster Wouw). Dividing clients into multiple clusters has the downside that routes do not cross boarders of clusters even though this may be more cost efficient. Additionally, regular nurses are not shared between clusters. TWB also employs flex workers. These flex workers can work in multiple clusters. However, flex workers are a very small portion of TWB's workforce. The upside of using clusters is that one planner is responsible for one cluster and therefore no information is lost between planners working on the same routes. In total, TWB has 11 different clusters with 11 different full time planners. These clusters are: Bergen op Zoom Centrum-Zuid, Bergen op Zoom Noord-Oost, Bergen op Zoom Halsteren, Steenbergen, Woensdrecht, Rucphen, Halderberge-Etten Leur, Roosendaal Centrum-Westrand, Roosendaal Heilig Hart, Roosendaal Kroeven-Tolberg and Wouw.

2.2 Stakeholder Analysis

The first stakeholder that is covered is the management of TWB. They are responsible for ensuring that all clients receive their care. TWB receives compensation from serving their clients and has to pay their employees for their service. These employees are paid based on the amount of hours and which hours they have worked. Furthermore, TWB wants to keep their personnel and clients satisfied such that they stick with the company.

TWB prefers a cost efficient solution while still keeping their clients and employees satisfied.

The second stakeholder are the nurses of TWB. These are the employees of TWB that provide the service to the clients. These employees also have their preferences with respect to the planning and scheduling system. These preferences relate to the amount of working hours on a day, at what times they work and how many tasks they perform at their skill level. For instance, short working days (less than three hours) are not preferred, but very long days (longer than eight hours) are not preferred either. Finally, employees do not prefer to have an early morning shift after performing a late evening shift. The employees of TWB prefer a solution with convenient working times and where nurses primarily perform visits at their actual skill level.

The final stakeholder that can be identified are the clients of TWB. TWB's clients select the time window of their appointment in consultation with employees of TWB. The preferences of clients are that they are helped within these time windows. Furthermore, the clients prefer to see the same set of nurses because of social reasons. This is also preferred from TWB's side since this enables a nurse to quicker identify changes with regard to a client's health. The clients prefer a planning and scheduling approach where their appointment time windows are not violated and where the same nurse visits the client over time.

2.3 Route restrictions

Not every set of created routes and schedules leads to a valid solution to the problem. The restrictions of a feasible route and schedule are covered in this section. In Section 2.3.1 the requirement to serve all clients is covered. The necessity to respect the client's appointment time window is explained in Section 2.3.2. Nurse's working time regulations are described in Section 2.3.3. Finally, a minimum shift length from TWB is covered in Section 2.3.4

2.3.1 Servicing all clients

If TWB accepts a client then a term of the contract is that these clients receive the appropriate level of care. TWB has to ensure that this is also realized in practice. So, in general TWB has to serve all clients on their own. However, it is possible for TWB to hire self employed professionals (ZZP'er in Dutch) to take care of their clients if this is necessary. This is not preferred by TWB since these self employed professionals are more expensive than their own employees. So, it does not make sense to include these self employed professionals when creating TWB's long-term schedule. Therefore, the option of hiring additional self employed professional is excluded from this research. Clients can only be served by nurses with a sufficient skill level. This skill level is also taken into account when creating a schedule.

2.3.2 Time windows

The next restriction is that all appointments of clients must be served within their time window. Initially, TWB has agreed with the client to these time windows and it is very inconvenient for the clients if these time windows are violated. We can identify four different types of time windows.

1. Medical essential service has to be applied within this time window. Deviation of this time window is not allowed under any circumstance.
2. Customer care has to be provided before the end of the time window. For instance, the client has a fixed daytime activity that starts at that time. It is not preferred that service starts before the start of the time window but this is possible if necessary.
3. Customer care has to be provided after the start of the time window. For instance a client returns home from their fixed daily activity after a specified time. Then it is impossible to start service before the start of the time window. It is not preferred that service starts after the end of the time window but this is possible if necessary.
4. This type of time window is the most flexible one. This time window is based purely on the preference of the client. It is possible that a client is helped both before the start time and after the end time of the time window. But this is not preferred.

In practice, TWB uses only one type of time window even though these four different types can be identified. Only time window type 1 is used when scheduling clients. Data about which service has which type of time window is also unavailable within the data set of TWB. So, in this research all time windows are of type 1 and thus none of them can be violated.

2.3.3 Collective labor requirements

The created routes have to be in line with the collective labor agreement (CAO in Dutch) [14]. This collective labor agreement is agreed upon between employers and the employee's union. A workday longer than ten hours, working more than 5,5 hours without a break and overtime of more than ten percent in a period of four months is not allowed. If a workday becomes longer than ten hours for a nurse then another nurse has to perform parts of this route to ensure that this maximum number of working hours is not violated. Nurses are compensated for their overtime via a 'time for time' principle. This means that nurses receive additional time off for working overtime. This amount of additional time off is equal to the worked overtime. Furthermore, if too much overtime is required then the only option is to hire more personnel. Finally, breaks are mandatory and these breaks are not paid by TWB.

2.3.4 Minimum Shift Length

The final restriction on a feasible schedule is that it does not include shifts that are too short. TWB aims for a minimum shift length of three hours, even though the minimum shift length according to the collective labor agreement is two hours. TWB does not prefer shifts shorter than three hours because this decreases the satisfaction of employees. If a shift shorter than three hours occurs then the planner tries to distribute the clients of this shift over the other shifts on that day. Another solution is that clients from other shifts are placed into this route to increase the length. If both of these solution do not solve the problem then the shift is left in its original state but this is very undesirable.

2.4 Data analysis

In this section, the data from TWB is analyzed. First, the process of preparing the data is discussed. Then, the characteristics of the clusters Centrum-Westrand, Heilig Hart, Kroeven-Tolberg and Wouw are discussed in Section 2.4.2. Finally, the distribution of visits throughout the day and throughout the week is discussed in Section 2.4.3.

2.4.1 Data Preparation

The data related to TWB's visits is retrieved from a database from Nedap Ons. This database contains all information related to visits. There are four main problems and two smaller issues with the data in the database. The first problem is related to time windows. Time windows are stored as notes (without a clear structures) in the database. This means all time windows need to be manually added to the data sets. Additionally, not all visits have time window notes stored in the database. As a result, a substantial amount of time windows (30-50%) need to be estimated. These time windows are estimated such that they are similar to previous, and subsequent visits within the route that do have a time window note. It can occur, that many sequential visits do not have a time window note. In such a situation, the time windows of the sequential visits are estimated based on the service time of the visits. The second problem is that cancelled appointments still remain in the database. There is no way to distinguish these cancelled visits from performed visits. So, these visits remain in the data sets used in this work. The third problem is that each task is registered separately. In practice, a single visit to a client can consist of two tasks. A frequent occurring combination of two tasks is putting on an insulin bandage (one minute service time) along with a regular task (around 20 minutes). In the database, these are registered as two separate visits. However, it may also occur that a client requires two different visits with a time window very close to each other. In such a situation, the visits should actually be registered as two separate visits. There is no possibility to distinguish these two situations from another. So, all registrations are identified as visits. The final problem is that flex nurses have no fixed amount of contract hours. Furthermore, the database does not store the actual amount a flex nurse has worked. Therefore, the contract hours of a flex worker is set equal to the actual number of hours a flex worker has worked throughout the week.

The two smaller issues are related with specific clusters. The data set from the cluster Centrum-Westrand contains two clients live in the center of another cluster. These clients have been removed from the Centrum-Westrand data set. A similar case occurred in the Wouw data set. However, in this case the clients were at the border of a neighboring cluster. So, these clients have not been removed from the data set of Wouw. The second small issue is that the data set from the cluster Heilig Hart does not contain any breaks (even though breaks occurred in practice). This further complicates the addition of time windows since it may be the case that a visit is later because of a break in between previous visits.

2.4.2 Cluster Analysis

In this section, the clusters Centrum-Westrand, Heilig Hart, Kroeven-Tolberg and Wouw are discussed. These clusters are first discussed individually before combining them together.

Centrum-Westrand

The cluster Centrum-Westrand is the second largest cluster in Roosendaal. The cluster consists of two different urban districts. These are the city center and the district Westrand (west of the city center). The data shows that there have been 1775 visits to clients over a time period of a week in this cluster. This data only accounts for visits performed by a level 3-IG nurse or lower (since higher level nurses are not taken into account in this work). In total, 175 different routes have been worked by nurses to perform these visits. These 175 different routes have been worked by 44 different nurses. The workforce of Centrum-Westrand consists of 7 ADL nurses, 11 level 2 nurses, 14 level 3 nurses and 12 level 3-IG nurses. Two of these nurses are flex workers. One flex worker has a skill level of 3-IG (worked 7 routes) and the other has a level 3 skill level (worked two routes). Finally, The cluster Centrum-Westrand has the tightest time windows of all clusters with an average time window width of 1.39 hours.

Heilig Hart

Heilig Hart is the largest cluster in the city of Roosendaal. The cluster is a combination of three different districts. The district 'Kalsdonk/buitengebied' is located north-east of the city center and has both urban and suburban characteristics. The 'Fatima Burgerhout' district is an urban district located east of the city center. Finally, the district 'Duiken Langdonk' is another urban district located south-east of the city center. In total 2503 visits occurred over a time period of a week by nurses with skill level 3-IG or lower. These 2503 visits are placed in 209 different routes. In total 44 different nurses have been employed to work these shifts. The workforce consists of 3 ADL nurses, 13 level 2 nurses, 13 level 3 nurses and 15 level 3-IG nurses. 7 of these nurses are flex workers. 1 level 2 nurse (working 1 route), 4 level 3 nurses (working 12 routes) and two 3-IG nurses working (4 routes). The cluster Heilig Hart has an average time window width of 1.48 hours.

Kroeven-Tolberg

Kroeven-Tolberg is the second smallest cluster of Roosendaal. This cluster consists of two different districts (Kroeven and Tolberg). The district Kroeven is located south of the city center and is best described as an urban district. The district Tolberg is located south-west of the city center and has both urban and suburban characteristics. 1532 visits have been performed by nurses of 3-IG level and below in a time period of a week. 133 routes have been performed to fulfill these visits. These 133 routes have been performed by 31 different nurses. The cluster has 1 ADL nurse, 12 level 2 nurses, 10 level 3 nurses and 8 3-IG nurses. 4 routes have been performed by 4 different flex workers. These flex workers have a skill level of level 2 (once) level 3 (once) and level 3-IG (twice). All flex nurses only worked one route. Finally, the cluster Kroeven-Tolberg has the largest average time window width of 1.64 hours.

Wouw

Wouw is the smallest cluster that is taken into account in this research. It is best described as a rural cluster that is located further west of the clusters Centrum-Westrand and Kroeven-Tolberg. In total 1005 visits of nurses with a skill level of 3-IG or lower occurred in a time span of a week. 89 routes were required to schedule all visits. These 89 different routes were done by 22 different nurses. This workforce consists of 2 ADL nurses, 2 level 2 nurses, 6 level 3 nurses and 12 3-IG nurses. 5 3-IG flex workers have worked 12 routes in the cluster Wouw during the selected week. The average time window width in the cluster Wouw is 1.61 hours.

All Roosendaal clusters

In this section the four clusters are combined to give an overview of all data that is used in this work. This section starts with an overview of the geographical location of all clients.

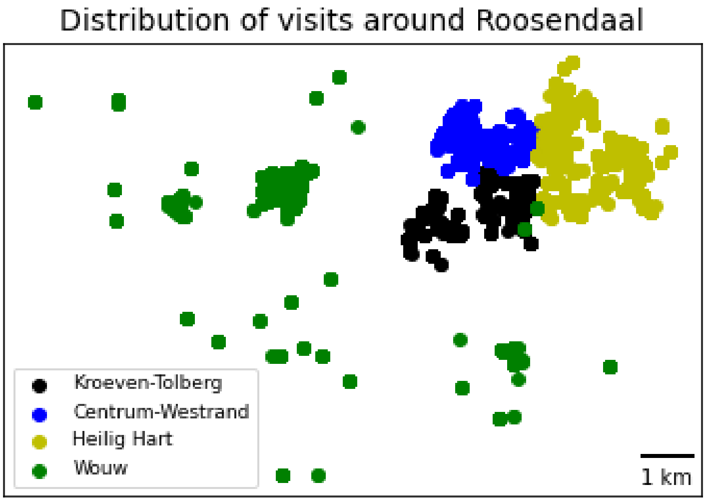

Figure 2: Location of all visits in the Roosendaal area included in this work.

Figure 2 shows the location of all visits that are investigated in this work. Here, a clear difference is visible between the cluster Wouw and the other clusters. The distances between clients in cluster Wouw are much larger compared to the other clusters. This confirms that Wouw is better described as a rural cluster whereas the other clusters are better described as urban clusters. The downside of Figure 2 is that the location of many urban visits overlap. This makes it difficult to see where most visits occur in Roosendaal. Therefore, Figure 3 is created to show the density of visits in the urban clusters.

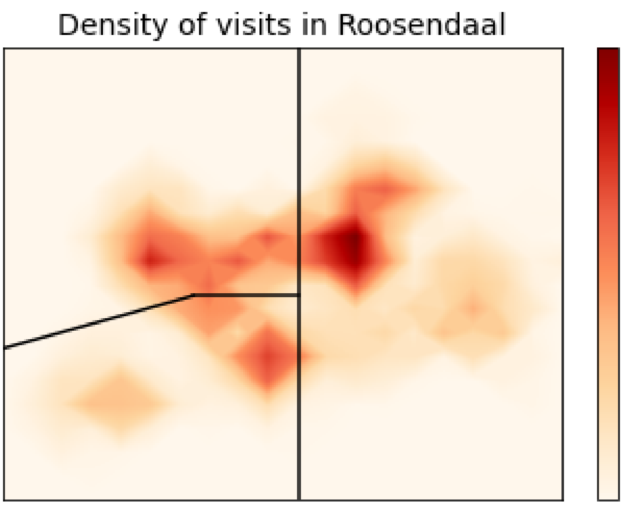

Figure 3: Visit density of Roosendaal. Right: Heilig Hart, Bottom left: Kroeven-Tolberg, Top left: Centrum-Westrand. Wouw is not included within the figure.

Here, Heilig Hart is on the right half of the figure, Kroeven-Tolberg is in the bottom left and Centrum-Westrand is in the top left corner. From Figure 3, it becomes clear that most of the visits from the three clusters occur close to the city center. Furthermore, both Figure 2 & 3 indicate that the geographical distance between the three urban clusters is small. In total, 6815 visits occurred in the four clusters during a time period of a week. These visits are placed into 606 different routes. These 606 routes are performed by 138 different nurses. This number is lower than the total amount of nurses per cluster (141). This is the because some flex workers have worked in multiple clusters.

2.4.3 Visit analysis

The final part of the data analysis is focused on the distribution of visits during the day and over multiple days. The distribution of the time windows on a single day can be seen in Figure 4.

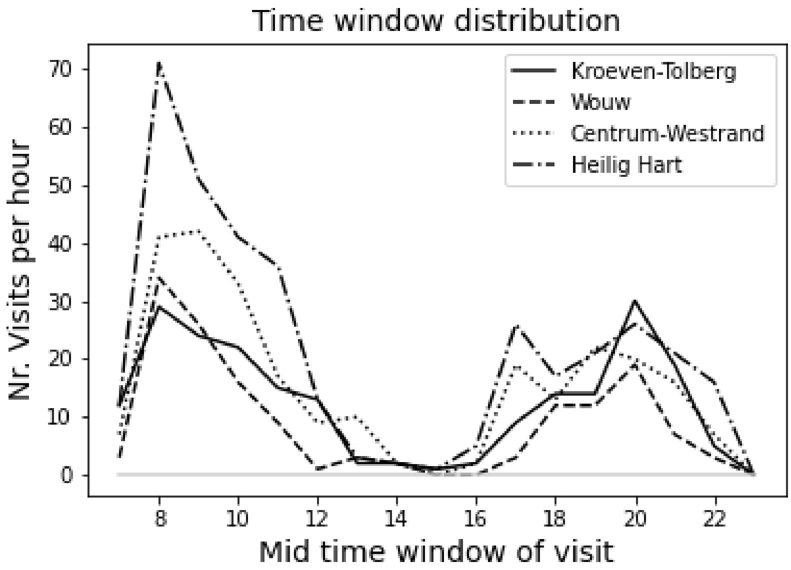

Figure 4: Distribution of visits during the day. Selected day is Monday.

The figure shows that most visits occur in the morning in each cluster. This is followed by an afternoon shift (between 13:00 and 16:00) that does not have many visits in all cases. Finally, this afternoon is followed by an evening that has substantially more visits. Figure 4 shows that there is not a clear separation between morning and evening shifts. For instance, a visit with a time window of 14:00 until 16:00 can be placed at the end of a morning shift at 14:00 but also at the start of an evening shift at 16:00. This means that the morning and evening routes are still connected via the afternoon even though there are hardly any visits in the afternoon.

A second distribution related to visits is the distribution of visits per day. The distribution of visits per day can be seen in Figure 5.

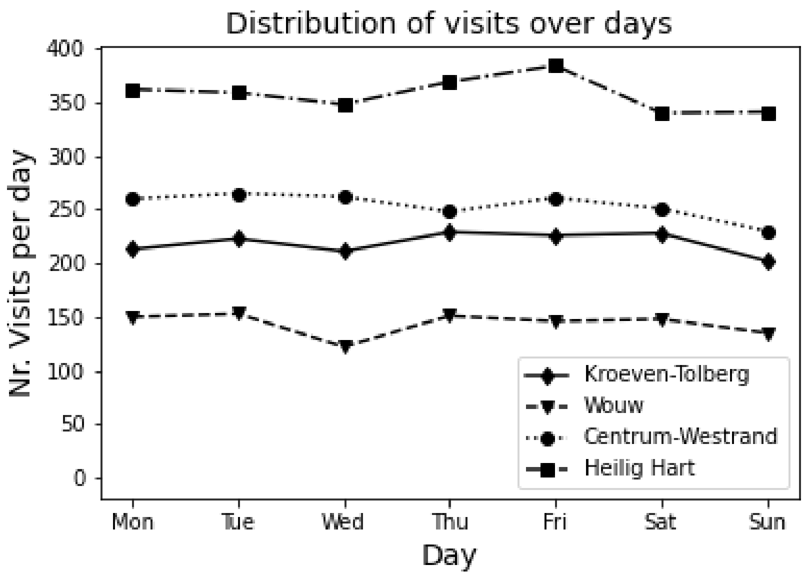

Figure 5: Distribution of visits during the week.

The figure shows a relatively flat distribution of visits throughout the week in all clusters. The exception is the Sunday. All clusters have slightly fewer visits on Sunday compared to other days. However, in general, the difference between different days with regard to number of visits is small.

2.5 Performance indicators

The limits of a feasible route are explained in Section 2.3. In this section, the performance indicators are explained. These performance indicators enable the comparison between multiple feasible routes and schedules. These performance indicators can be divided into different categories: Performance indicators related to costs, indicators related to employee satisfaction level and indicators related to client satisfaction level. No performance indicator related to profit is used. This is because the income is fixed. TWB receives a fixed fee based on the prescribed service time of a service at a client. Also, TWB has to serve all of their clients. So, the total income is the same in all feasible schedules. Therefore, only the costs are evaluated. The amount of used personnel is also included as separate performance indicator. At the end of this section key performance indicators are selected that will be used in this research.

2.5.1 Determination of costs

At this point TWB has no direct performance indicator related to costs. However, TWB does judge a route based on the link between the skill level of the nurse and required level of care of the client. This performance indicator is expressed as a percentage of visits that are performed by a nurse with the skill that is the same as the minimum skill required to perform the visit. A higher percentage indicates a better schedule. However, a higher skill matching percentage does not always lead to the most cost efficient solution. Consider the following example: A high level nurse just finished service at a client. Another client at the correct skill level can be reached by this high level nurse. However, this client is far away. Travelling times are also paid by TWB. So, it can be cheaper to send this high level nurse to a lower level client that is closer and have another high level nurse perform the job that is far away. Saving costs while slightly lowering the percentage of skill linking between clients and nurses.

The scenario described in the previous paragraph can be avoided when the costs are used as performance indicators instead of the percentage of skill linking. The costs consists of two different components. A component related to travelled distance on a route and a component of the nurse's salary.

The first cost component that is covered are the kilometer compensation costs. Kilometer compensation is paid at the moment the nurse leaves their home and is paid until the nurse returns home. Furthermore, this kilometer compensation is not included within the salary. So, it is an additional cost factor. The amount that has to be paid depends on the used transportation type. However, TWB does not determine which vehicle type is used by their personnel. Therefore, the assumption is made that all nurses use a car as sole transportation type. The kilometer compensation costs per nurse can be calculated in the following fashion. For the first ten kilometers, a compensation of 0.15 Euro per kilometer is paid. All additional kilometers cost 0.27 Euro per kilometer. The amount of driven kilometers on a single day for each nurse is calculated by Equation 1. Here $X_{i,j,n}$ is 1 if nurse n travels from location i to j. The locations i and j are the locations of all clients (H_c) and the home location of the nurse (H_n). $Distance_{i,j}$ is the distance between location i and j in kilometers.

$$DD_k = \sum_{i,j} X_{i,j,n} * Distance_{i,j} \qquad \forall i,j \in \{H_c + H_n\} \tag{1}$$

The next step is to calculate the costs for each of the individual nurses. Here, two different cases can be distinguished. A case where the driven distance is below ten kilometers and a case where kilometers are above ten kilometers.

1. If the driven distance of a nurse is below ten kilometers then the driving costs are the driving distance times 0.15 Euro.
2. If the driven distance of a nurse is above ten kilometers then the driving costs are the driving distance times 0.27 minus 1.2 Euro.

In the final step the driving costs of all nurses from all days are added together to end up with the total driving costs.

The second component is the salary component. The calculation of salary is not as straightforward as it seems. Salary is paid from the moment a nurse starts service at their first client until it is done with the service at their last client. However, this is not true when a nurse works a double/broken shift. A shift is a double/broken shift if there is a break of more than two hours between clients. In that case, it is assumed that a nurse travels to their own home in between these two shifts. In those cases, salary is paid from the last client to the nurse home and from the nurses home to the first client of the second shift. The time that the nurse stays at home is unpaid. Furthermore, the breaks within a nurses schedule are unpaid too. Another scenario that may occur is that a nurse arrives at a client before the time window of the appointment. In that case, the nurse should wait before the service starts. This waiting time is paid. Nurses also make irregular working hours. Nurses receive additional compensation for working at these hours. The additional compensation is fixed by the collective labor agreement (CAO) [14]. These additional compensations can be seen in the list below.

- 22% additional income on Monday until Friday between 20:00 and 22:00
- 44% additional income on Monday until Friday between 22:00 and 24:00
- 38% additional income on Saturday from 7:00 until 8:00 and 12:00 until 22:00
- 49% additional income on Saturday from 22:00 until 24:00
- 60% additional income on Sunday. Irrelevant of the working hours

The salary cost of each nurse can be calculated using the following equation:

$$Cost_k = (\sum_{i,j} X_{i,j,n} * TT_{i,j} + \sum_{i} X_{i,j,n} * ST_i) * (1 + Z_t) * Y_k \qquad \forall i,j \in \{H_c + H_n\} \tag{2}$$

Here, $TT_{i,j}$ is the travel time from location i to j. ST_i is the service time at client i. This service time is zero at nurses home location. Z_t accounts for the percentage additional income based on the time, t, of the route. Finally, the total cost of a nurse is calculated by multiplying the total time with the hourly cost Y of each nurse. With this information salary of individual nurses can be calculated. The salaries of these individual nurses are combined to end up with the total salary costs of that day.

2.5.2 Employee satisfaction indicators

The satisfaction level of employees is subjective. Each employee has different preferences. However, some key characteristics that are not preferred by employees can be identified.

Even though it is sometimes inevitable, employees do not like to work an evening shift on a certain day and then work a morning shift on the following day. So, one performance indicator to estimate the employee satisfaction level is how often a morning shift has to be performed after an evening shift.

A second performance indicator would be the total amount of time employees need to work after 22:00. In general, these late evening shifts are not preferred. Although it has to be noted that some nurses also prefer working after 22:00 because they receive more salary. But we still expect that reducing the working time after 22:00 will increase the employee satisfaction level.

Nurses prefer to not work any shifts shorter than four hours. So, decreasing the number of shifts shorter than four hours should improve the employee satisfaction level.

The skill linking between clients and nurses is also an indication of the employee satisfaction level. Nurses do not prefer to perform tasks lower than their skill level since these are not challenging. Leading to a lower employee satisfaction level over time.

Nurses prefer to not work any overtime. So, reducing the overtime of nurses is expected to increase the employee satisfaction level.

The final performance indicator related to the employee satisfaction level is the number of double/broken shifts. Employees prefer to not have double/broken shifts. So, a higher amount of double/broken shifts reduces the employee satisfaction level.

2.5.3 Client satisfaction indicators

For the client satisfaction level, two different indicators are applicable. The first performance indicator is the percentage of times a client's service is started within their time window. Violations of these time windows are inconvenient for clients and therefore not preferred. The second performance indicator is related to the number of different nurses visiting a client, also known as the continuity of care. In general, a client prefers to visit as few nurses as possible. Multiple different techniques are possible to express the continuity of care. The continuity of care equation used in this work relates the number of different nurses arriving at a client with the total number of visits at that client. The continuity of care for each client can be calculated in the following fashion:

$$COC = 1 - \frac{Number\,of\,nurses\ - 1}{Number\,of\,visits\,per\,week} \tag{3}$$

Equation 3 returns a 1 under full continuity of care and numbers below 1 if a client is visited by multiple nurses over a time period of a week. For instance, if a client has ten visits in a week and is visited by one nurse then the equation returns a value of 1, full continuity of care. If three nurses are used then the equation returns a value of 0.8. Furthermore, if a client has five different visits, performed by three different nurses then a continuity of care of 0.6 is observed.

The continuity of care of the entire schedule is calculated by taking the weighted average of the continuity of care over all of the clients. The weights are determined by how many times a client has been visited in a time period of a week.

2.5.4 Number of nurses

The final performance indicator that is covered is the number of different nurses that are used to serve all clients on a given day. Initially, this performance indicator seems very promising, but it is not as straightforward as other performance indicators. In practice, the number of used nurses and created routes are fixed by the planner. The order and number of clients within these routes usually change, but the number of routes stay the same. On the other hand, a different planner might generate a different long-term schedule that requires either more or less nurses. The effect of using a different amount of nurses is included in the other performance indicators (for instance more nurses may make it more expensive). Therefore, on its own, the number of used nurses is not a valid performance indicator but it does give some more insight in the performance of the schedule and therefore it is included as a performance indicator.

2.5.5 Main performance indicator

In this section, a selection is made of previously introduced performance indicators. TWB aims to improve the efficiency of their created routes while still keeping employees and clients satisfied. So, the total costs here is the main performance indicator. Multiple employee satisfaction indicators also have a direct effect on costs. For instance, reducing the amount of service remaining after 22:00. Employing nurses after 22:00 means their additional compensation increases. So, it is expected that minimizing costs also increases the employee satisfaction level. A similar logic is true with respect to the number of double/broken shifts on one day. In case of a broken shift, the time a trip takes from and to the nurses home is included in the salary. So, reducing the amount of double/broken shifts also decreases the total costs. The amount of overtime is included as second performance indicator. Finally, the number of nurses is selected as the third performance indicator. TWB expects to have employee shortages in the future. Therefore, if two schedules are similar in costs and overtime then the schedule that uses fewer nurses is preferred.

2.6 Performance of current system

The performance of the current planning and scheduling system is analyzed in this section. First, the travelling distance and time equation required to determine the performance is introduced in Section 2.6.1. How the start time of a route is selected is discussed in Section 2.6.2. The performance of a one day schedule in the cluster Kroeven-Tolberg is discussed in Section 2.6.3. Finally, the performance of the planning and scheduling system of a full week is discussed in Section 2.6.4.

2.6.1 Travel distance & travel time

An equation to determine the distance and travel time between two clients is necessary to determine the costs of the routing and scheduling solution. The routes and schedules are created in Nedap Ons and this software tool has its own build in equation to determine the travel distance and times. The exact equation is unknown in this work. However, it can be approximated based on the information provided by Nedap Ons and TWB. The equation determines the distance between two clients based on the Euclidean distance. This Euclidean distance is used as actual distance between two clients. Furthermore, these distances are converted to travel time by dividing them by a standard travel speed. Finally, a minimum travel time between two clients is set. The minimum travel time is used to ensure there is still a travel time between two clients live in the same apartment building for example. The Euclidean distance method, standard travel speed and minimum travel time between clients are not shown in this work since these are from the Nedap Ons software and Nedap is not involved in this research.

2.6.2 Appointment start time & route start time

In this section, the selection of start times of an appointment and start times of an entire route is discussed. The appointment start time is straightforward in practice. According to TWB, nurses do not wait in front of a client's home if they arrive there before the client's time window. So, if a nurse arrives at a client's home at 8:00 but the time window of that client's appointment starts at 8:15 then the nurse will start the service at 8:00 and violate the appointment time window. This also means that there is no waiting time in the routes of nurses.

The start time of a route also has an influence on time windows and costs. In Nedap, a route can start every minute. However, the data provided by TWB does not (always) indicate this exact starting time of a route. So, the start time of a route has to be determined with the use of data. Here, the first possible start time of a route is the start of the time window of the first client in the route. With this start time, a total number of time window violations in the route can be calculated. The start time of a route is then postponed by one minute (starts at 7:01 instead of 7:00) and the number of time window violations is calculated again. This procedure is continued until the start time of a route is two hours after the start of the appointment time window of the first client. The best start time of the route is the start time that leads to the lowest amount of time window violations. If multiple start times result in the same minimum number of time window violations then the earliest start time resulting in a minimum number of time window violations is selected. Fixing the start time of an entire route automatically fixes the start time of all appointments because of the assumptions that nurses do not wait at a client if they arrive before the client's time window.

2.6.3 Kroeven-Tolberg, single day performance

In this section, the performance of the current planning and scheduling approach of one day of the cluster Kroeven-Tolberg is discussed. At this day 67 ADL, 59 level 2, 43 level 3 and 44 3-IG visits are performed. This leads to a total of 213 visits. The performance of the current system is discussed based on the route restrictions discussed in Section 2.3 and the performance indicators discussed in Section 2.5. Two additional performance indicators are used, the in-route driven distance and the in-route salary cost. These two metrics exclude the driven distance and salary in case of a double/broken shift between a nurse's home and a client. This gives better insight into the actual performance of the routing and scheduling procedure since a planner cannot determine the home location of a nurse. The results of the current planning & scheduling approach for one day can be seen in Table 1.

Characteristic	Performance
Nr. of nurses	12
Nr. of level 3-IG nurses	3
Nr. of level 3 nurses	3
Nr. of level 2 nurses	5
Nr. of ADL nurses	1
Nr. of routes	19
Nr. of 3-IG routes	6
Nr. of level 3 routes	5
Nr. of level 2 routes	6
Nr. of ADL routes	2
Nr. of broken shifts	6
Nr. of breaks between shifts	1
Nr. of shifts shorter than 4 hour	7
Nr. of shifts shorter than 3 hour	0
Nr. of illegitimate assignments	8

Characteristic	Performance
Total visits	213
Total costs	2153.33 Euro
Total salary costs	2090.02 Euro
Total kilometer compensation	63.29 Euro
Total driven distance	283.65 km
In-route salary costs	2058.67 Euro
In-route driven distance	106.48 km
Hours worked after 22:00	3.01 hour
Total in-route working time	83.87 hour
3-IG in-route working time	25.44 hour
Level 3 in-route working time	25.09 hour
Level 2 in-route working time	24.76 hour
ADL in-route working time	8.57 hour
Nr. of time window violations	34
Percentage skill linking	59.6%

Table 1: 1 Day performance of current routing and scheduling approach in cluster Kroeven-Tolberg.

In total 12 different nurses are used to perform all of the visits. These 12 nurses work 19 different routes throughout the day. Most of these shifts are double/broken shifts. In the double/broken shifts, a nurse works a morning route and then either a late afternoon or an evening route. Only two routes are connected via a break. These are two 3-IG routes. Here, the morning route is connected to an early afternoon route with a roughly 35 minute break in between. The current routing and scheduling approach has illegitimate assignments of nurses to clients. The current approach results in two routes performed by an ADL nurse. However, both of these routes have at least one level 2 visit. So, these routes have a visit that is above the skill level of the assigned nurse. In total, eight of these illegitimate assignments occurred.

In the current routing and scheduling approach, 34 time windows are violated. However, as stated in Section 2.2, 30-50 % of the time windows are estimated. So, this is not a very reliable performance indicator. When looking at the results it can be seen that more than 97% of the costs consist of salary costs. Only 3% of the cost are kilometer compensation costs. Furthermore, the in-route driven distance is substantially lower than the total driven distance. So, it can be concluded that the salaries are the main cost factor. Around 95% of the total cost are actually in-route salary costs. In this performance metric, the trips from and to a nurse's home are excluded. A skill linking percentage of only 59.6 % is observed. This is relatively low and gives an indication that improvements are possible in the routing and scheduling approach.

2.6.4 Full week performance Kroeven-Tolberg

The performance of an entire week is calculated by combining the performance of individual days. The performance of the individual days Kroeven-Tolberg, as well as the other clusters can be seen in Appendix A. Furthermore, the entire week performance also provides a better insight in the scheduling of nurses. For instance, it allows to determine the continuity of care and the amount of overtime required to perform all shifts. The performance of an entire week in Kroeven-Tolberg can be seen in Table 2.

Characteristic	Performance
Total visits	1532
Nr. 3-IG visits	241
Nr. level 3 visits	345
Nr. level 2 visits	505
Nr. level 3-IG nurses	8
Nr. level 3 nurses	10
Nr. level 2 nurses	12
Nr. level ADL nurses	1
Nr. routes	133
Total costs (Euro)	16074.90
Total salary costs (Euro)	15730.71
Total in-route salary costs (Euro)	15584.53
Total kilometer compensation (Euro)	344.19
Total in-route driven distance (km)	683.24
Hours worked after 22:00	12.37
Percentage skill linking	49.3
Continuity of care	0.524
Total working time (Hour)	587.96
Total in-route working time (Hour)	581.88
Total working hours available	669.31
Total overtime hours	56.93

Table 2: Performance of the current routing and scheduling process of a week in Kroeven-Tolberg

The performance of an entire week shows a comparable cost distribution as on a single day. Almost 98% of the total costs are salary costs and almost 97% of the cost are in-route salary costs. The results indicate a total working time of almost 588 hours throughout the week. The employee workforce of that week has a combined contract hour duration of 669.31 hours. This indicates that there are enough nurses to fill all shifts. However, not all nurses have worked their set amount of contract hours, resulting in overtime. An overtime of 56.63 hours is calculated. The overtime is nurse specific and can occur because of multiple reasons. For instance, a nurse becomes sick and another nurse has to fill that shift. In that case, one nurse may make additional overtime whereas the other works fewer hours. Another example is that a nurse works more in this week but works fewer shifts in the following week. Resulting in no overtime over a longer time period. Whether or not these situations occur is unknown since this data is not available in the retrieved data sets. The full week performance highlights the inefficiencies in both the routing and scheduling approach. Inefficiencies in the routing approach are highlighted by the low percentage skill linking. A higher percentage skill linking is expected to result in lower in-route salary costs and therefore lower total costs. Furthermore, having nurses with overtime even though the data indicates that there are enough working hours available indicates that the current scheduling approach is sub-optimal.

2.6.5 Full week performance

In this section, the performance of all four clusters is analyzed. Furthermore, the combination of all clusters is also included to give an overall performance of the city of Roosendaal. The results can be seen in Table 3.

Cluster	K-T	Wouw	C-W	HH	RSD
Total visits	1532	1005	1775	2503	6815
Nr. 3-IG visits	241	237	335	521	1334
Nr. level 3 visits	345	246	457	604	1652
Nr. level 2 visits	441	186	338	565	1530
Nr. ADL visits	505	336	645	813	2299
Nr. nurses	31	22	44	44	138
Nr. level 3-IG nurses	8	12	12	15	45
Nr. level 3 nurses	10	6	14	13	44
Nr. level 2 nurses	12	2	11	13	36
Nr. level ADL nurses	1	2	7	3	13
Nr. routes	133	89	175	209	606
Total costs (Euro)	16074.90	12214.83	19124.07	26398.60	73812.40
Total salary costs (Euro)	15730.71	11623.74	18482.41	25555.61	71394.47
Total in-route salary costs (Euro)	15584.53	11470.36	18383.73	24953.79	70392.41
Total kilometer compensation (Euro)	344.19	591.08	541.67	842.99	2319.93
Total in-route driven distance (km)	683.24	1141.38	652.14	1199.72	3676.48
Hours worked after 22:00	12.37	7.00	7.96	20.48	47.82
Percentage skill linking	49.3	47.7	63.8	54.6	54.8
Continuity of care	0.524	0.454	0.533	0.497	0.506
Total working time (Hour)	587.96	416.20	717.50	937.81	2659.47
Total in-route working time (Hour)	581.88	405.05	701.09	917.37	2605.39
Total working hours available	669.31	438.84	855.72	927.00	2890.87
Total overtime hours	56.93	40.17	53.33	119.40	269.53

Table 3: Performance of the current routing and scheduling process of a week in all clusters. K-T is Kroeven-Tolberg, C-W is Centrum-Westrand, HH is Heilig Hart and RSD is all 4 clusters combined.

Table 3 indicates that there are both similarities and differences between the clusters. The main similarity is the build-up of the total costs. In all clusters, the in-route salary cost is the main cost component resulting in more than 90% of the total costs in all cases. This is more than 95% of the total costs if all clusters are combined. A second similarity is that each cluster has a large number of ADL visits but only a relatively low number of ADL nurses. Here, cluster Centrum-Westrand has the highest percentage skill linking. This higher percentage skill linking can be explained because cluster Centrum-Westrand has the most ADL level nurses.

The first difference between clusters is that cluster Wouw has a large in-route driven distance even though it does not have many visits. This confirms that cluster Wouw has more rural characteristics compared to the other clusters. A second difference is visible in the total working time and overtime. All clusters have overtime, but cluster Heilig Hart has the most overtime. Cluster Heilig Hart has a total working time that is longer than the available working time of the employees. Therefore, it is logical that overtime is required to ensure all visits are performed. This amount of overtime could possibly be reduced when all clusters are combined since in that case, the total available working hours are larger than the total working time. Furthermore, Figure 3 indicates that the visits of the urban clusters are close to each other. This gives a second indication that it could be better to combine the four clusters in Roosendaal.

2.7 Conclusion

In this chapter we answer the research question: *How does the current routing and scheduling process work and how does it perform?*. First, we explain the different employees from TWB as well as their clients. The employees from TWB are divided into nurses and planners. Nurses are responsible for performing the visits and planners are responsible for the scheduling and routing of these visits. This is followed by the different rules and performance indicators of the routing and scheduling procedure. The rules of a feasible schedule are that all clients receive care by nurses, within their time window, without violating the collective labor agreement. Finally, the chapter ends with a performance analysis. The performance analysis indicates that the primary cost term are the in-route salary costs. Furthermore, the results indicate that the performance of the manually created solutions is sub-optimal because a relatively low percentage skill linking is observed and individual nurses have worked more overtime than necessary. The results show that it may be beneficial to combine multiple clusters within the city of Roosendaal. In the next chapter, we investigate scientific literature to develop a solution approach that can be used to determine whether or not it is beneficial to combine multiple clusters in Roosendaal.

3 Literature review

In this chapter, we aim to answer the second research question: *How is the home healthcare routing and scheduling problem (HHCRSP) solved in scientific literature?* The HHCRSP can be described as the following problem: A set of clients distributed over a geographical area require visits at their home location. These visits have to be done by qualified nurses that provide care to the clients. The core components of the HHCRSP are covered in Section 3.1. Then, the different variants of the HHCRSP covered in literature are investigated in Section 3.2. The differences and similarities between TWB's case and cases in literature are covered in Section 3.3. Finally, we end this chapter with a conclusion in Section 3.4.

3.1 Components of the HHCRSP

The HHCRSP is a problem in literature that is a combination of two separate problems. These problems are the vehicle routing problem (VRP) and the nurse rostering problem (NRP) [31]. The nurse rostering problem is also called the nurse scheduling problem (NSP) in literature. The goal in a VRP is to route a fleet of vehicles to meet customer demand in the most efficient way. The goal in the NRP is to assign nurses to shifts such that all shifts are filled. However, results from the NRP are required for the VRP. For instance, the total amount of nurses scheduled on a single day is an important input parameter of the VRP. If only 10 nurses are scheduled then a VRP solution with 11 nurses is not valid. The VRP and NRP problems are covered in detail in the next two sections.

3.1.1 Vehicle routing problem

The problem in a VRP is finding an optimal set of routes such that the demand of all clients is covered. Dantzig et al. [15] were the first authors to introduce the VRP in 1959. Examples of the VRP in practice are the collection of waste throughout a city, delivering parcels to customers at their homes, or routing nurses to visit clients in a home healthcare environment. Over the years different variants of the VRP have been investigated. Here, 4 VRP variations and the routing part of the HHCRSP are covered.

Vehicle routing problem with time windows

A frequent variation of the vehicle routing problem is the vehicle routing problem with time windows (VRPTW). In this scenario, customers need to be visited within a predefined time window [26]. Solomon [36] introduced VRPTW test cases that have been used as benchmark cases for testing VRPTW algorithms. Furthermore, Solomon analyzed different solution approaches to create solutions from scratch for the VRPTW in his work. A healthcare VRPTW variation is the routing of nurses such that they visit their clients within their predefined time window. Another example is delivering parcels within the predefined times at customers.

Vehicle routing problem with multiple depots

Another variation of the vehicle routing problem is the vehicle routing problem with multiple depots (MD-VRP)[24]. A depot is a location where a vehicle can start and end their route. In the regular VRP all vehicles leave from, and return to, a single depot. However, different vehicles can leave from multiple depots in a multi-depot VRP. For example, a parcel delivery company has multiple warehouses where trucks depart from. A second example is waste collection throughout a city where garbage trucks are stored at different locations in the city. A home healthcare example is the routing of nurses. Here, each home location of a nurse can be seen as a depot.

Heterogeneous & site dependent vehicle routing problem

In this section, two closely related vehicle routing problems are discussed. First, the Heterogeneous VRP is explained. In the heterogeneous VRP, there are different classes of vehicles [2]. An example is that a vehicle has more capacity at the cost of a slower travelling time compared to another vehicle. In that case, the vehicle type is also an optimization parameter. The site-dependent VRP is closely related to the heterogeneous VRP. In the site-dependent VRP (SD-VRP) there is a compatibility relation between vehicles and customers [2]. So, customers can only be visited by a limited number of vehicle types. An example is that a client can only be helped by nurses of a certain skill level in a home healthcare case.

Home healthcare routing

In most cases, the home healthcare routing can be described as a combination of the VRP variations mentioned in the previous paragraphs [21]. The clients have a time window during which they need to be served by nurses. Nurses start and end their routes at their own home, not from a central depot, and the visits are site-dependent (not all nurses can help all clients). Therefore, the home healthcare routing problem can be described as a site-dependent multi-depot vehicle routing problem with time windows (SD-MDVRPTW).

3.1.2 Nurse rostering problem

The second part of the HHCRSP is the nurse rostering problem. The problem in an NRP is finding an optimal nurse schedule ensuring that all required shifts are filled. The NRP is a personnel scheduling problem where the personnel are nurses [41]. Different related problems are the airplane crew scheduling problem, the bus/truck driver scheduling problem and call center scheduling problem. Possible goals of the scheduling of personnel could be the maximization of preferences of employees, minimizing costs, balancing the workload of employees or using a minimum number of employees.

3.2 HHCRSP variants

In this section, the different HHCRSPs in literature are discussed. First, the early literature on the HHCRSP is covered in Section 3.2.1. Next different HHCRSP variants are covered. This is divided into three parts. Section 3.2.2 covers which and how constraints are taken into account. The different scenarios of a HHCRSP are covered in Section 3.2.3. Finally, the different objective functions are covered in Section 3.2.4. For more information, the reviews of Fikar and Hirsch [21] and Cisse et al. [12] are recommended.

3.2.1 Early HHCRSP literature

The first authors to specifically discuss the routing of nurses in a home care environment were Begur et al. in 1997 [5]. They developed software that is used as a decision support system. This software is capable of creating routes for a weekly period. The authors took several constraints such as the time window of appointments, the skill linking between client and nurses and the working time regulations of nurses into account. The goal of their decision tool is to minimize the total travel time of nurses. The authors solve a case including 7 nurses and 40 clients. They create a solution by adapting the Clarke and Wright savings heuristic [13]. The solution is then improved using a K-opt operator [28]. From their results they estimate a cost saving potential of over $20000 per year.

Cheng et al. [11] investigated the HHCRSP in 1998. In their research, they focus on real life data provided by a home care provider. They propose two Mixed Integer Linear Program (MILP) models to solve their HHCRSP. Furthermore, the authors propose a problem specific heuristic for larger instances. Cases up to 900 clients and 294 nurses are solved using this heuristic. In their approach, they only consider full time and part time nurses. The goal is minimize the number of part time nurses being used. The authors include a skill linking constraint but these are determined randomly, not based on the level of required care and skill of the care giver. The authors also take time windows, contract hours and mandatory breaks of nurses into account.

In 2006 Eveborn et al. [18] introduced the decision support system *Laps Care*. *Laps Care* is based on a set partitioning problem that is solved using a repeated matching algorithm. They solve cases up to 123 visits per day. The goal of the algorithm is to minimize the total costs. The authors take time windows, skill linking, breaks, working time regulations, client & nurse preferences and multiple vehicle types into account. In 2009 Eveborn et al. [19] published a follow up article discussing the benefits of *Laps Care*. At that time, Laps care was used in 200 different home care units and created routes for 4000 employees. *Laps Care* increased the operational efficiency with 10 to 15 %. The annual saving of using *Laps Care* was estimated to be between 20 and 30 million Euros per year. From 2008 onward *Laps Care* is used in the city of Stockholm. Which resulted in 15000 additional employees that are being routed by *Laps Care*.

In 2006 Bertes and Fahle [6] published an article about the optimization of routes in the *parpap* project in Germany. In the *parpap* project home healthcare companies, universities and software companies are working together to create a optimization tool for the HHCRSP. The goal of the optimization tool is to minimize the total costs. The authors compare multiple solution approaches. They consider constraint programming, Tabu search and simulated annealing. The conclusion of the authors is that a combination of constraint programming and tabu search leads to the best results. The authors take time windows, breaks, skill levels, preferences and working time regulations into account. The authors solve cases up to 600 visits with 50 nurses within 900 seconds.

Akjiratikarl et al. [1] solved a HHCRSP by using a particle swarm optimization heuristic in their work. The goal in their work is to minimize the travel distance. Time windows and working time regulations are taken into account in their research. They solve cases with over 100 visits carried out by 12 nurses in around 3.5 minutes. The authors show that the driven distance is reduced by 11-31 percent.

3.2.2 HHCRSP constraints

In this section, the constraints and how they are taken into account in different models in literature is covered. Not all articles in literature take all of the constraints mentioned below into account. However, all of the constraints below occur in realistic HHCRSP cases.

Skill linking & client preferences

Skill linking is one of the most frequently occurring constraints in the HHCRSP. The skill linking constraint ensures that a subset of clients can only be served by a subset of nurses that can provide the correct level of care. This is modelled as a hard constraint, a client can only be served by a nurse with a sufficient skill level. If this is not the case, then the solution is infeasible. Examples can be found in for instance [31], [34] and [22].

Including client preferences is very similar to skill linking. For instance, a client only wants to be helped by a nurse that speaks Dutch or by a female nurse. In those cases, these constraints can be modelled as hard constraints in the same way as the skill linking constraint. For instance, only a subset of nurses is female so only that subset can help that client. These preferences are sometimes taken into account as soft constraints as well. For instance, a client prefers to helped by a female nurse. This means that these can be violated but with a penalty. This penalty is accounted for in the objective function.

Time windows

The next topic that is considered are appointment time windows. In literature two different types of appointment time windows can be used, hard and soft time windows. With hard time windows, service has to start after the start of the time window and before the end of the time window. The soft time windows are allowed to be violated but increase a penalty cost [6]. A combination of both time windows (a soft time window within a hard time window) is also possible. Examples of this can be seen in the works of Bertels and Fahle [6] and Trautsamwieser and Hirsch [39].

Working time regulations

Working time regulations are a very common constraint in the HHCRSP. The working time regulations indicate the maximum amount of hours a nurse is allowed to work on a day. The working time regulations can also be interpreted as a hard nurse time window. A nurse is only available to work within the start and end of their nurse time window. The start of the time window is the starting time of the shift. The end of the time window is then calculated by adding the maximum amount of working hours to the start of the nurse time window. Examples of this can be found in Trautsamwieser and Hirsch [39] and Decerle et al. [16]. Grenouilleau et al. [22] follow a different approach. They observe a weekly schedule and add hard constraints to the maximum and minimum amount of working hours over this week. They also add a soft maximum and minimum amount of working hours constraint for each day.

Breaks

Breaks can be interpreted as a special type of working time regulations. A break has to be placed within the shift of a nurse, if a nurse is otherwise working for a too long time period. However, breaks are not frequently included in literature studies and there is no standard way to take breaks into account. Therefore, three different approaches are covered in this section. The first approach that is covered is the approach by Bard et al. [3]. In their approach they consider therapists visiting clients. These therapists only have a day shift (from 8:00 until 17:00). A therapist requires a break if their working time is longer than 6 hours. In that case a break is scheduled between 11:00 and 13:00. A similar approach is followed by Cheng et al. [11]

The second approach that is covered is the approach of Nickel et al. [31]. In their approach a nurse has to take a break if their shift is longer than 6 hours. They fix the maximum shift length to 6 hours. Ensuring that no breaks need to be scheduled within shifts. A nurse is allowed to work multiple shifts. But a nurse is only allowed to work multiple shifts if there is at least a 30 min break between shifts if the combined working time exceeds 6 hours.

The final approach that is covered takes a more flexible approach. Xiao et al. [43] make use of a flexible break time window. This works in the following fashion: If a nurse works both before and after the 'lunch' time window then a break must be scheduled within the 'lunch' time window. This approach allows for working with multiple different 'lunch' breaks during the day. The downside is that in their research they use an MILP on a very small scale. The largest scenario uses 15 nurses with a total of 23 visits. A similar approach to breaks has been used in the works of Trautsamwieser and Hirsch [39] & Trautsamwieser et al. [37].

Shared visits

The final topic that is covered within this section is the topic of shared visits. A shared visit can for instance occur in practice if a client is overweight and therefore requires two nurses to perform a single task. The difficulty arising from shared visits is that two routes are connected with each other. This is a crucial and difficult problem according to Di Mascolo et al. [17]. Both Bredström and Rönqvist [8] and Xiao et al. [43] also investigate the concept of shared visits. Bredström and Rönqvist looked at the concept of shared visits on the largest scale of these authors but in their research the size is still limited to 80 visits and 16 nurses.

3.2.3 HHCRSP scenarios

There exist many different HHCRSP variants in practice. In the previous section the constraints are introduced. In this section the different scopes of HHCRSPs in literature is covered.

Assigning clients

The first variation of HHCRSP models is whether or not all clients have to be assigned to nurses to ensure a feasible solution. An example of a model where not all clients need to be assigned to nurses can be seen in the article by Nickel et al. [31]. Here, clients can be assigned to dummy nurses that can always serve all clients, but this increases the objective function. These situation can also arise in real life where a home care company can outsource some clients to private contractors.

Heterogeneous fleet

The second variation of HHCRSP is with respect to the transportation type of nurses. In most models, a single transportation type for all nurses is assumed (for instance a car). However, other scenarios have also been covered in literature. For instance, Rest and Hirsch [32] look at a combination of walking and using public transport for nurses in Vienna. In their model, they also include time dependent travel times (e.g. a bus could travel slower in rush hour because of heavier traffic). The article of Hiermann et al. [23] considers two transportation types (car and public transport) in the city of Vienna but mainly focuses on comparing different algorithms. Fikar and Hirsch [20] investigate a HHCRSP where a small bus fleet is used instead of individual cars for each nurse. In their research, they use designated bus drivers. Multiple nurses can travel with the same bus and walk to their individual clients. They show that this substantially reduces the number of vehicles and also reduces the pressure on nurses since they do not have to drive themselves.

Model time span

A key element in a HHCRSP is the time span for which the model has to create routes and schedules. In literature, both single and multi-day cases are analyzed. Single-day cases usually focus on creating a schedule that could be used on that day. So, run time is usually limited as in Bertels and Fahle [6]. In a multi-day model, not all clients are served on a the same day. This leads to additional constraints such as the number of hours a single nurse is allowed to work per week. Furthermore, this also allows for the creation of longer term schedules that could be used for multiple weeks.

Use of patterns

Cappanera and Scutella [9] consider the care plan of a client in their research. A care plan describes how often and at which level of service a client requires care. From this care plan they derive multiple patterns. A pattern indicates at which days the patient requires care. For instance, a patient requires care three times a week according to their care plan. Then, two possible patterns could be service on Monday, Wednesday and Friday or on Tuesday, Thursday and Friday. The model then determines on which days the client is helped.

Cappanera and Scutella consider an exact MILP method. The works of Shao et al. [34] and Bard et al. [3] also consider the use of patterns in the same fashion. They solve cases with up to 20 therapists and 600 clients using a GRASP heuristic.

Uncertainty

The topic of uncertainty in a HHCRSP is not taken into account frequently in literature. However, some authors have investigated the effect of uncertainty with respect to some parameters. The first article that is covered is the article of Hiermann et al [23]. In their research they use stochastic travel times based on data from the Viennese public transport system and historical data.

Shi et al. [35] focus on creating a robust schedule. Taking both stochastic travel and service times into account. The authors state that taking stochastic travel and service times into account increases the robustness of their planning schedule.

Cappanera et al. [10] focus on the stochastic demand of patients. In their model, they consider a cancellation of a request from a client but also consider additional appointments from existing clients or the arrival of new clients. The objective in their model is to share the workload amongst nurses. The authors show that this is improved when taking demand uncertainty into account.

3.2.4 HHCRSP objective functions

In this section, the different objective functions in a HHCRSP are covered. Many different objective functions are used by authors in literature. Therefore, the objective functions are placed in four different groups in this section. The objective functions are: costs, workload balancing & preferences, continuity of care and mixed objective functions.

Costs

The first objective function that is covered are the costs. Many articles use an objective function related to costs. These can be travel time, travel distance, travel costs, wait time and overtime [21]. In this work, all of these objectives are grouped as cost objectives. Since minimizing each of these components should lead to an overall reduction in costs. The objective functions related to costs are used in both single and multi-day literature.

Preferences & workload balancing

The second type of frequently occurring objective functions are preferences and workload balancing. These objective values give an indication on the nurses satisfaction level and in some cases also on the clients satisfaction level. An example of nurses' preferences are that nurses do not have to work on their preferred day off. An example of a client preference is that service is conducted within the predetermined time windows. These preferences are commonly modelled as soft constraints. Maximizing these preferences is achieved when the soft constraint violations are minimized. The preferences are used in both single and multi-day models. Another similar objective function is the workload balancing. With this objective function the workload is balanced over multiple nurses such that a fair allocation of working time is achieved. This objective function is also used in both single and multi-day scenarios.

Continuity of care

The continuity of care is an indicator of client preferences and has received special attention in literature. A high continuity of care indicates that a only a few nurses visit a client over a period of longer time. The work of Wirnitzer et al. [42] introduces multiple performance indicators to measure the continuity of care. The benefit of having a high continuity of care is that no information is lost amongst nurses and therefore clients perceive a higher quality of care [10]. The continuity of care is primarily taken into account in multi-day literature.

Mixed objective functions

In literature, a combination of multiple objective functions is frequently used. This can be done in two different ways. The first option is constructing a weighted objective function. This approach is followed by Nickel et al. [31]. They use a mixed objective function of continuity of care, number of tasks assigned to dummy nurse, total travelled distance and the amount of overtime of nurses. Trautsamwieser and Hirsch [39] follow a similar approach. In their research, they use mixed objective functions consisting of seven different terms.

The considered objectives are: Total travelling time, overtime, unfulfilled preferences, soft client time window violations, soft nurse working time violations, services done by nurses of a higher skill level than required and the unpaid driving times of nurses. In these cases, one objective function is used that is a combination of multiple objective functions.

A different approach is followed by Braekers et al. [7]. Here, the authors solve a bi-objective HHCRSP by selecting one objective as objective function and adding the other as a constraint. In their research they use costs and client inconvenience as objective functions.

3.3 Current case comparison with literature

In this section, the case considered in this report is compared to cases investigated in literature. First, the case considered in this report is classified based on the characteristics introduced in Section 3.1 and Section 3.2. An overview comparing TWB's case with cases in literature is shown in Section 3.3.2. Articles that tackle a similar HHCRSP as TWB are discussed in Section 3.3.3.

3.3.1 Classification of TWB's case

In this section, TWB's routing and scheduling case will be classified using the characteristics introduced in Section 3.2.

Constraints

In this work, the skill linking between clients and nurses, appointment time windows, working time regulations and breaks are taken into account as hard constraints. A minimum shift length of a nurse's shift is taken into account as a nurse preference (hard constraint). Assignment preferences between nurses and clients are not taken into account. So, all clients can be helped by all nurses as long as the skill of the nurse sufficient. Finally, shared visits occur in practice but these will not be considered in this work.

Scenario

All clients need to be assigned to care operators from the home care company in this work. TWB can outsource clients to third parties but this is deemed too expensive. Furthermore, this case analysis is based on already performed routes. So, it should be possible to create a schedule with TWB's workforce without the need of outsourcing clients. TWB's nurses can choose their transportation type. For instance, in a city center all clients may be close to each other. In that case, the nurse can chooses to travel by bicycle or by car. However, this is not a decision made by TWB. So, in this work a homogeneous fleet is used. In other words, all nurses travel by car in the model. Currently, TWB uses a weekly schedule that is used for multiple weeks. Therefore, a multi-day period is considered in this work. Using different patterns is a possibility in multi-day models. However, determining the patterns is not a task done by the planner at TWB . The level 5 nurses determine at which days the client receives which care. So, the care moments are fixed from a planner's perspective and therefore using different patterns is not considered in this work. Finally, uncertainty also influences TWB in practice. However, uncertainty in demand, service time and travel time are not taken into account in this research.

Objective function

The final classification is the objective function that is being considered in this report. The objective is to create a cost effective long-term solution. This cost function consists of two terms (see Section 2.5.1). These terms are the salary costs of employees and the kilometer compensation costs. Other objectives are also important, such as nurse preferences and continuity of care but the primary objective function are the costs.

3.3.2 Overview of TWB's case and literature

In this section, all relevant HHCRSP literature obtained during the literature search is classified based on the characteristics introduced in Section 3.2. The size (number of visits and nurses) are included as additional selection criteria as well. If a client requires a visit on five days a week, then this is counted as five visits in the table in a multi-day model. Finally, the works of Lanzarone et al. and Wirnitzer et al. are included even though they are not considering the routing part of a HHCRSP. In both works, only the assignment of nurses to already created routes is considered. This why the number of visits is not applicable in these two works, since these are already fixed. The results of the literature analysis can be seen in Table 4.

	Considers		Used constraints						Considered scenario					Objective function				Size	
Article	Routing	Rostering	SL	Pr	TW	WT	Bk	Sv	Own	H	M	Pa	Uc	Cost	Pr & WB	COC	Mix	#V	#N
This work	•	•	•		•	•	•		•		•			•				6815	138
Begur [5]	•	•	•		•				•		•			•				40	7
Cheng [11]	•	•			•	•	•							•				900	294
Bertels [6]	•	•	•		•	•			•					•	•		•	600	50
Eveborn [18]	•	•	•		•	•	•	•	•	•				•	•		•	123	21
Akjiratikarl [1]	•	•			•	•			•					•				100	12
Bredstrom [8]	•	•	•	•	•	•		•	•					•	•		•	80	16
Trautsamwieser [39]	•	•	•	•	•	•	•		•					•	•		•	523	75
Trautsamwieser [37]	•	•	•		•	•	•		•					•	•		•	523	75
Lanzarone [27]		•		•		•					•		•	•		•	•	NA	22
Nickel 1 [31]	•	•	•		•	•					•	•		•		•	•	361	12
Nickel 2 [31]	•	•	•		•	•	•				•	•		•		•	•	361	12
Shao [34]	•	•	•		•	•	•		•		•	•		•				215	16
Bard [3]	•	•	•		•	•	•		•		•	•		•				160	16
Bard [4]	•	•	•		•	•	•		•		•			•				650	18
Di Mascolo [17]	•	•			•	•		•	•					•				40	40
Mankowska [29]	•	•	•		•	•		•	•					•	•		•	400	40
Trautsamwieser [38]	•	•	•	•	•	•	•		•		•			•				203	45
Cappanera [9]	•	•	•		•	•			•		•	•			•	•	•	162	11
Fikar [20]	•	•	•		•	•	•	•	•	•				•				125	20
Hiermann [23]	•	•	•	•	•	•				•			•	•	•		•	717	500
Braekers [7]	•	•	•	•	•	•			•					•	•		•	300	90
Decerle [16]	•	•	•		•	•		•	•				•	•				60	Unkown
Rest [32]	•	•	•	•	•	•	•		•	•				•				173	35
Wirnitzer [42]		•	•	•		•					•					•		NA	37
Yalcindag [44]	•	•	•						•		•	•		•	•	•	•	514	16
Cappanera [10]	•	•	•			•			•		•	•	•		•			60	3
Xiao [43]	•	•	•	•	•	•	•	•						•				23	15
Grenouilleau [22]	•	•	•		•	•					•			•		•	•	430	20
Shi [35]	•		•		•				•				•	•				100	8

Table 4: Literature overview. SL = skill linking, Pr = preferences, TW = time windows, Bk = breaks, Sv = shared visits. Own indicates that all clients need to be served by nurses from the organisation, H indicates the use of heterogeneous vehicles, M indicates a multi-day model, Pa indicates the use of patterns and Uc indicates the inclusion of uncertainty. Pr & WB = preferences and workload balancing, COC = continuity of care. Mix indicates a mixed objective is used in the model. The other objective functions still get a mark if they are considered in the mixed objective.#V and #N indicate the amount of visits and nurses considered in the work. NA indicates that this measurement is not applicable in this work. Only the surname of the first author is used to save space.

3.3.3 Similar studies and their solution approaches

A selection of relevant articles can be made based on Table 4. The first study that is selected is Bard et al. (2014) [4]. This work scores exactly the same on all characteristics as TWB's case. Trautsamwieser and Hirsch (2014) [38] and Bard et al. (2014) ([3]) are included because a very similar HHCRSP is considered. Trautsamwieser and Hirsch and Trautsamwieser et al. from 2011 ([39] & [37]) and Hiermann et al. (2015) [23] are included because they investigate large size problems and consider similar constraints. Finally, Nickel et al. (2012) [31] is included because of their implementation of breaks. The articles are discussed in chronological order of appearance.

Trautsamwieser and Hirsch & Trautsamwiser et al. 2011 ([39] & [37])

The authors published two articles in 2011. In their first article [39], the authors consider a single day HHCRSP. The authors take skill linking, preferences, appointment time windows, working time regulations and breaks into account. In their work, a nurse is allowed to work a maximum of ten hours on a single day (consisting of multiple shifts). If a nurse is working longer than six hours then a break has to be scheduled between four and six hours of working time. They also include both soft and hard appointment time windows for clients. For instance, a client can be served between 7:00 and 11:00 but prefers to be served between 8:00 and 10:00. In that case 7-11 is the hard time window and 8-10 the soft time window. These soft time windows also exist for nurse time windows and breaks. In their work, a mixed objective function is used to minimize the total travelling time, overtime, unfulfilled preferences, soft client time window violations, soft nurse working time violations, services done by nurses of a higher skill level than required and the unpaid driving times of nurses. The largest instance that the authors investigate consists of 512 visits and 75 nurses. The authors propose a problem specific initial solution approach with a variable neighborhood search (VNS) improvement heuristic to solve their single-day HHCRSP. In their VNS, the authors use four move operators and eight swap operators in their shaking procedure and a best improvement 3-opt operator in their local search. The authors follow up on their initial work in Trautsamwieser et al. [37]. In this work, the authors specifically focus on providing home care in case of disasters. The only difference with their previous work is that they only minimize the total travel time in case of disaster instead of a mixed objective function to ensure all care is still provided. In this work, the authors also reflect on using the best improvement 3-opt local search. The authors state that this is the most time consuming part of their model and that it might be better to move to a first improvement 3-opt local search or even a 2-opt local search.

The difference between both studies and this work is the use of soft time windows for clients and nurses and the objective function. The soft time window violations are minimized in their objective function. So, in most cases the clients are visited within their soft time windows. This simplifies the break scheduling. Because, if a nurse requires a break, then it can be done by just violating soft time windows and still respecting hard time windows. In our work, there are only hard time windows which means this break scheduling procedure is not viable.

Nickel et al. 2012 ([31])

Nickel et al. consider two different problems (which is why it is included twice in Table 4). For both problems, instances up to 361 visits with 12 nurses are investigated. In the first problem, the authors cover the situation where a new solution is created from scratch for every week. The authors take skill linking, appointment time windows and some working time regulations constraints into account. The only working time regulation that is taken into account is that a nurse has a maximum number of working hours in a week. Breaks and daily working time regulations are not considered. Furthermore, it is allowed that some clients remain unscheduled. The authors include multiple patterns (visiting days) for their clients as well. The objective function aims to minimize the number of unscheduled clients, nurse overtime costs, the travelled distance and maximize the continuity of care. The nurse overtime cost is based on the qualification since higher skilled nurses receive a higher salary. The authors propose a constraint programming constructive heuristic together with an adaptive large neighborhood search (ALNS) improvement heuristic to solve a multi-day HHCRSP. In their ALNS, the authors use multiple removal and insertion heuristics. However, not all used removal and insertion heuristics are discussed in their work.

In the second part of their work, the authors consider a long-term (master) and short-term (operational) schedule. The difference with the previous problem is that the short-term schedule for a week is not started from scratch. But uses a long-term standard schedule as initial solution. This long-term schedule takes into account some additional constraints compared to the previous problem. The authors take breaks into account by setting a maximum shift length. A break has to be inserted if a nurse works more than six hours. So, the authors fix the shift length to six hours. The goal of the long-term schedule is creating a solution that requires the lowest number of nurses. The authors only use a constraint programming heuristic, the ALNS is not used in their solution procedure. The authors also mention a procedure on how to turn the long-term schedule into an usable short-term schedule. But this is out of the scope of this work and will not be covered.

The main difference between TWB's case and the cases included in the work of Nickel et al. is the goal of the model. The goal in TWB's case is to create a long-term schedule that can be used for multiple weeks and adapted over time. In the first problem from Nickel et al. they start from scratch for each week and do not include breaks. Whereas in the second problem they create a long-term schedule which is no longer updated. A second difference is that there is a very large difference in the number visits and nurses. However, the approach to including breaks in the authors long-term schedule could work very well for TWB's case.

Bard et al. (2014) ([4])

Bard et al. considered a weekly travelling therapist routing and scheduling problem that is similar to the HHCRSP considered in this work. The authors take skill linking, appointment time windows, working time regulations and breaks into account. Their work considers therapists that work from Monday until Friday from 8:00 until 17:00 with a break between 11:00 and 13:00 if the therapist works more than six hours. Their objective function consists of three terms. The first term minimizes the travel costs between clients and the assignment costs for client-therapist pairs. The second term aims to minimize the kilometer compensation and the final term minimizes the overtime costs. In their work, they propose a branch, price and cut (BPC) model for small instances and a rolling horizon heuristic for the larger instances. Instances up to 650 visits with 18 therapists are solved using this heuristic whereas the BPC algorithm is not used for scenarios containing more than 162 visits. Therefore, the heuristic method is considered the more applicable solution approach. Their heuristic solution method consists of a two stage approach. In stage one, a parallel route building algorithm (multiple routes are built simultaneously) is used. In their algorithm, each day is decomposed into multiple sections. The routes are then build section by section. The authors also improve their initial solution using an exact model in stage two. The problem is decomposed into individual days and optimized one day at a time during this optimization. However, the authors state that these improvements only reduce the objective function by less than a percent on average while increasing the run time of the algorithm by a factor five for larger data sets.

The work from Bard et al. shows many similarities with TWB's case. The authors use a similar set of constraints and scenario. However, there are two differences. The case from TWB considers substantially more nurses and visits. A second difference is with respect to working times of employees. The therapists work between 8:00 and 17:00 whereas TWB's nurses work between 7:00 and 23:00. This leads to problems with the scheduling of breaks. In the work from Bard et al. a break is placed between 11:00 and 13:00. This ensures that a therapist never works longer than six hours as long as a break is placed between 11:00 and 13:00. The nurses from TWB have longer working days. Therefore, scheduling a break within a fixed time period does not ensure that the constraints with respect to breaks are met. This means the break scheduling approach used by Bard et al. cannot be used directly in this work.

Bard et al. (2014) ([3])

Bard et al. published a second article in 2014. In this work, the authors take skill linking, appointment time windows, working time regulations and breaks into account. Their work considers therapists that work from Monday until Friday from 8:00 until 17:00 with a break between 11:00 and 13:00 if the therapist works more than six hours. The primary difference with their previously discussed article is that the authors consider multiple patterns resulting from the client's care plan. In this work, the authors consider an objective function that aims to minimizes the travelling and service costs of nurses. The authors propose a sequential GRASP algorithm that consists of two stages. In the first stage, the authors focus on creating a feasible solution using a five step procedure. In the second stage, a local search is performed to improve a subset of stage 1 solutions. The authors consider instances consisting of 160 visits and 16 therapists. The authors indicate that a cost reduction of 18.09% is possible. Furthermore, the authors indicate that a sequential GRASP algorithm outperforms a parallel GRASP algorithm. The authors state that this is especially true for larger instances.

The work from Bard et al. shows many similarities with TWB's case. The authors use a similar set of constraints and scenario but also consider the use of multiple patterns resulting from the client's care plan. The GRASP algorithm from the article cannot be used in TWB's case because no patters are considered. However, the work from Bard et al. does indicate that a sequential GRASP algorithm shows promising results, especially for larger instances.

Trautsamwieser and Hirsch (2014) ([38])

In the work from Trautsamwieser and Hirsch, a weekly HHCRSP is considered. The authors take skill linking, client-nurse preferences, appointment time windows, working time regulations and breaks into account. The goal of their model is to minimize the total working time of nurses. This total working time consists of the travel time and the waiting time before an appointment time window. The authors propose a branch, price and cut (BPC) model for instances with up to 9 nurses and 203 visits throughout a week. In their work, they also use a variable neighborhood search (VNS) to generate upper bounds for the BPC model. The authors investigate two different cases. In case one, the BPC algorithm starts from scratch. In the second case, an initial solution is generated by a VNS algorithm. In both cases, the computation time of the algorithm is set to one hour. The authors state that using the VNS as initial solution helps the BPC model find feasible solutions. The authors state that the BPC algorithm can be used to determine lower bounds for larger instances in short computation times as well. Allowing to judge the performance of heuristic approaches. A downside is that the exact characteristics of this VNS are not discussed in the article.

The work from Trautsamwieser and Hirsch considers a very similar HHCRSP as in this work. The main problem is the size difference. 9 nurses and 203 visits in a week is much smaller than the scenario in TWB's case. Therefore, the proposed BPC algorithm is most likely not usable, because it cannot solve TWB's problem in reasonable time. The VNS algorithm is more promising. However, authors do not discuss the exact characteristics of their VNS.

Hiermann et al. (2015) ([23])

Hiermann et al. considered a single-day, heterogeneous fleet HHCRSP. The authors take skill linking, client-nurse preferences, appointment time windows and working time regulations into account. Breaks are not considered. The objective function first minimizes the infeasible assignments in a schedule and then considers a mixed objective of travel distance, soft time window violations, soft assignment preference violations, overtime and travel time. The focus of the authors is on comparing multiple metaheuristics. Variable neighborhood search, simulated annealing, the memetic algorithm and scatter search are discussed in their work. Instances with up to 717 visits and 500 nurses are investigated. However, the maximum number of nurses used in any solution is only 252. The authors state that the memetic algorithm clearly shows the best performance and the VNS algorithm shows second best performance. For the characteristics of the memetic algorithm, the reader is referred to the article of Hiermann et al. [23] since many different parameters are involved in tuning the algorithm. Here, only the local search part of memetic algorithm is covered. The local search uses three different operators. The outer-route move operator (move a client from route A to B), the in-route move operator (move a client's position within the current route) and the swap nurses operator (nurse from route A is moved to route B and vice versa). A cyclic neighborhood search is used. In a cyclic neighborhood search, one operator is used until no further improvements can be obtained or a time limit is reached. Then, the next neighborhood is searched until all neighborhoods are searched. The VNS in their work uses the outer-route move operator during the shaking procedure. The same three operators are used in the improvement stage. The difference in the improvement stage is that a next neighborhood is only investigated when the current neighborhood is fully investigated.

The work of Hiermann et al. shows that it is possible to find solutions for large size single-day instances. They show that the VNS is not the best solution method but still works rather well. The main downside in their work is that mandatory nurse breaks are not considered. This limits the applicability of their algorithms with respect to TWB's case.

3.4 Conclusion

In this chapter, we answer the research question: *How is the home healthcare routing and scheduling problem solved in scientific literature?*. First, the HHCRSP is identified as a combination of two optimization problems. These are the site-dependent multi-depot vehicle routing problem with time windows (SD-MDVRPTW) and the nurse rostering problem. Since 1997, many authors have investigated the HHCRSP. This has led to many different variants and solution approaches for the HHCRSP in literature. Works similar to TWB's case have been identified. The primary difference between TWB's case and cases in literature is that TWB's case contains substantially more visits that need to be scheduled. In all of the discussed articles, a two stage solution approach is used. The goal of the first stage is to create a feasible solution from scratch. Problem specific solution approaches as well as constraint programming and GRASP are used to create initial solutions. The goal of the second stage is to improve the solution obtained in stage one. Common stage two algorithms are variable neighborhood search, large neighborhood search and local search. We selected a sequential GRASP procedure followed by a variable neighborhood search in this work. A sequential GRASP algorithm is selected because the sequential GRASP algorithm from Bard et al. [3] shows a large cost reduction. Furthermore, the variable neighborhood search algorithm is selected because Trautsamwieser et al. [39] & [37] show that the variable neighborhood search works well for instances containing a large number of visits. It has to be noted that the other mentioned algorithms can also lead to promising solutions and could be promising for additional research. In the next chapter, we develop the solution approach in detail to solve the HHCRSP arising at TWB.

4 Solution approach

In this chapter, we answer the third research question: *How should the solution approach for the home healthcare routing and scheduling problem be generated?*. First, a problem description is given in Section 4.1. Assumptions are discussed in Section 4.2. The general solution approach is described in Section 4.3. The individual parts of the solution approach are described in Sections 4.4, 4.5, 4.6 and 4.7. Finally, we conclude this chapter in Section 4.8.

4.1 Problem description

The decision in the home healthcare routing and scheduling problem is the assignment of each visit ($v \in V$) of each client ($c \in C$) to a nurse ($n \in N$). In this work, the visits have to be planned over a time period ($t \in T$) of a week. Visits of multiple clients are combined into a route (r). Nurses are assigned to shifts (Sh). The difference between routes and shifts is that a shift can consist of multiple routes that are connected via a break. But, if a route is not connected to another route via a break then that route is a shift. Finally, all nurses start their shifts from their home location (H_n).

Constraints

The constraints can be divided into three different categories. These categories are individual visit constraints, route & shift constraints and individual nurse constraints. All constraints are hard constraints (cannot be violated) unless specifically stated otherwise.

Individual visit constraints

- Skill linking constraint: A nurse is only allowed to treat a client if the nurse's skill (SN_n) level is equal to, or higher than the required care level of the scheduled visit (SV_v).
- Visit time window constraint (TW_v): Each visit has their own time window and service time (ST_v). The time window indicates when service to a client is allowed to start. Service to a client is not allowed to start outside of the visit's time window.
- Performing all visits constraint: All visits need to be performed by nurses. Not visiting a client is not allowed.

Route & shift constraints

- Maximum route length (MRL): A route is not allowed to be longer than the maximum route length.
- Minimum break length constraint (MIB): If a break is shorter than the minimum break length then the break is invalid. In that case, the two routes are not allowed to be combined into a single shift.
- Maximum break length constraint (MAB): If a break is longer than the maximum break length then the break is invalid. In these situations, the two routes cannot be combined into a single shift. The two routes become a double/broken shift.
- Minimum shift length constraint ($MISh$): A shift is not allowed to be shorter than the minimum shift length.
- Double/broken shift constraint: Nurses are expected return to their home location in case of a double/broken shift. Then, a trip from the last client in the first shift to the home location of the nurse as well as a trip from the home location of the nurse to the first client in the second shift is included as paid working time.

Individual nurse constraints

- Fixed day off constraint ($NA_{n,t}$): Nurses have a fixed rest day in the week. At this day a nurse is unavailable for work.
- Contract hour constraint (C_n): Each nurse has a contract indicating how many hours they are available for work each week. This constraint is a soft constraint. The constraint may be violated to ensure that all visits are performed if there are not enough nurses available.

- Maximum work hours on a day ($MAWH$): A nurse is allowed to work multiple shifts on a single day. However, the combined working time in these shifts must be below the maximum work hours on a day.

Objective function

The duration of a shift (DR_{Sh}) is the sum of all service times in the route, all travel time ($TravelTime_{i,j}$) between visits and waiting time before a visit. Waiting time (WT_v) can occur if a nurse arrives at a visit before the start time. The travel time between a nurse's home location and the first/last visit in a shift is also included as travel time in case of a double/broken shift.

The break duration within a shift in unpaid. The regular salary cost of a shift (RSC_{Sh}) is calculated by multiplying the shift duration with the salary cost. The salary cost is dependent on the nurse's skill level (Y_{SN_n}). Nurses may receive a percentage additional salary compensation for a shift (Z_{Sh}) based on the day and time of day of the shift. The actual salary compensation is calculated by adding the additional salary compensation to the regular salary compensation. Nurses also receive kilometer compensation (Kc_n). The kilometer compensation is the same for all nurses and is a direct result from the travelled distance ($Distance_{i,j}$) between all visits and the home location of a nurse on a day. The total costs of a solution is a combination of the kilometer compensation and the actual salary compensation.

The quality of a feasible routing and scheduling solution is measured by the amount of necessary overtime, total costs and the number of required nurses.

4.2 Assumptions

1. Nurses can work a maximum of six days per week. In practice, nurses have a fixed day off in a week. However, this fixed day off cannot be retrieved from the data set and is unknown. Therefore, the assumption is made that nurses have no preference on which day of the week they are off.

2. Nurses have no preference between working two single shifts on two days or one double/broken shift on one day. This assumption is made to ensure more feasible solutions to the scheduling problem exist.

3. No stochasticity in service times. During the planning procedure TWB uses expected service times for each visit. Actual visits may take longer or shorter but this is not known in advance. This assumption is in line with TWB's current routing and scheduling process.

4. The driving distances and times are based on the Euclidean distance. This Euclidean distance method is used in TWB current routing and scheduling process and therefore assumed to be valid.

5. Routes can only start on rounded minutes and the start time is selected to minimize the waiting time. This is in line with TWB's current routing and scheduling process. Travel times between visits are not rounded.

6. All nurses have a travel time of 7.5 minutes and a travel distance of four kilometers to all clients from the nurse's home location. The planner can only choose the order of visits and not the home location of nurses. Therefore, time and distances from and to a nurse's home are fixed for all nurses.

7. Nurses wait until the time window of a visit starts before starting the visit.

8. All time windows retrieved from TWB's data base are correct.

Assumption six receives more attention because it has large implications for the problem. Assumption six is expected to increase the fairness between nurses of the same skill level. Consider the following example, there are four shifts in three days and two available nurses. One nurse living close to the cluster, the other living further away and the two shifts on a single day are a double/broken shift. In that case, the nurse living closer to the cluster will always be assigned to the double/broken shift because of the lower paid travel time in case of a double/broken shift. This leads to an imbalanced allocation of double/broken shifts to nurses which is undesirable.

Furthermore, assumption six has two implications for the HHCRSP that needs to be solved. As stated in Section 3.1 the routing part of the HHCRSP can be described as a site-dependent multi-depot vehicle routing problem with time windows. Assumption six states that all nurses have the same home location. Therefore, the routing problem solved in this work reduces to a site-dependent vehicle routing problem with time windows. The second implication of assumption six, is that it ensures that the routing problem of each day is independent from the other days. The different days are independent because all nurses have the same home location. So, it does not matter which nurse drives which route during the creation of routes.

4.3 Overall solution approach

In Section 3.3.3 literature considering a similar problem are discussed. All of these works use a heuristic solution approach. Additionally, the sizes of TWB's instances are larger than works considered in literature (Table 4). So, this further encourages the use of an heuristic. This work uses a multi-phase solution approach. The flowchart of the solution approach is displayed in Figure 6.

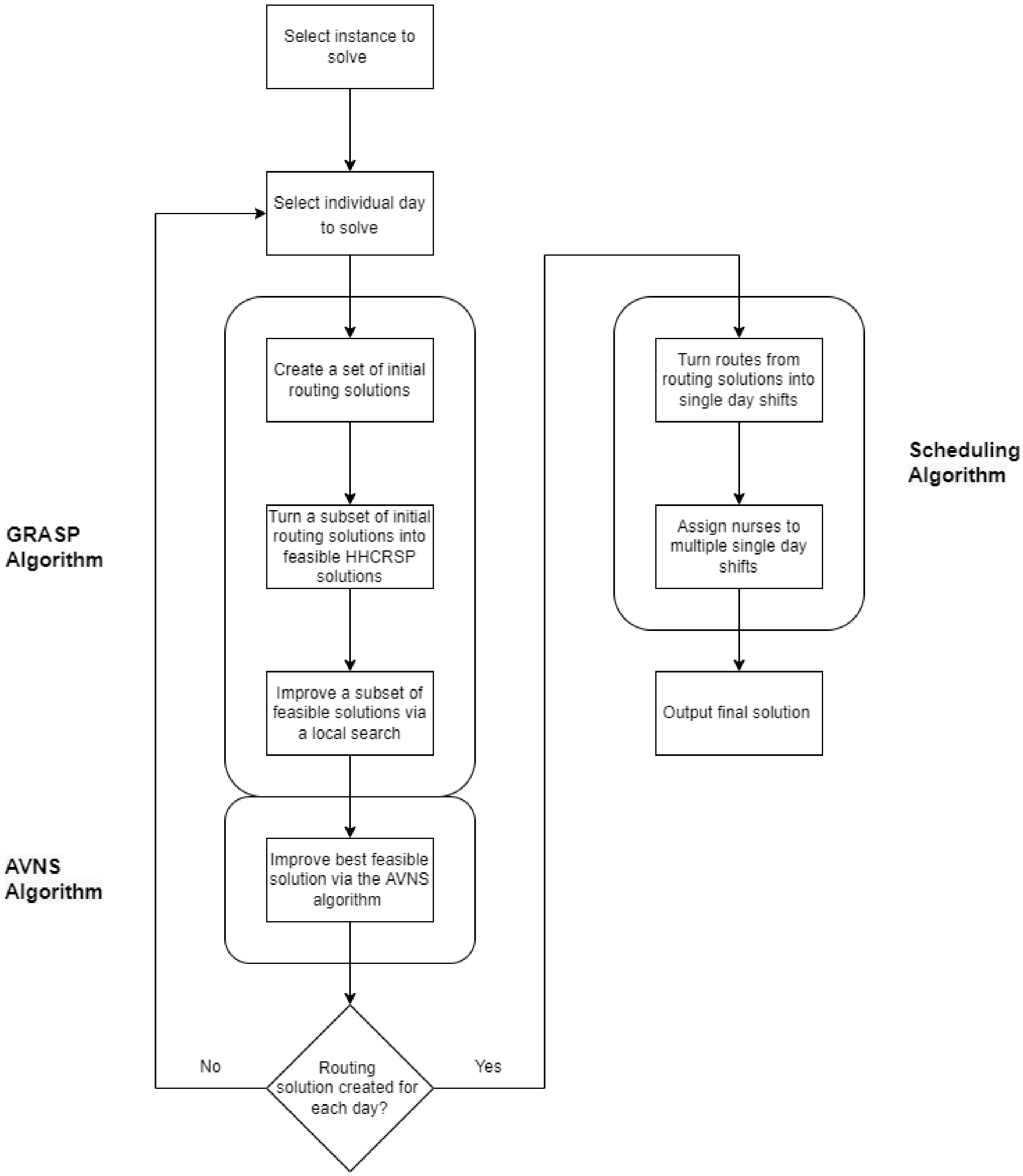

Figure 6: Flowchart of the proposed solution approach.

The solution approach is the following: first, an initial feasible routing solution is created for each day. This initial feasible routing solution is created using a problem specific multi-stage sequential Greedy Randomized Adaptive Search Procedure (GRASP) algorithm. A sequential GRASP is used instead of a parallel GRASP because these have proven to be superior in case of critical feasibility [3]. The GRASP algorithm consists of three stages. In the first stage, a set of initial solutions is created. In the second stage, a subset of promising stage 1 solutions are turned into routing solutions that ensure a valid overall HHCRSP solution. In the third stage, a subset of stage 2 solutions is optimized via a local search. The solution generated by the GRASP heuristic is improved by using an adaptive variable neighborhood search (AVNS). Both the GRASP and AVNS algorithm make use of an in-route salary cost lower bound. Therefore, this lower bound receives special attention. The goal of the GRASP and AVNS algorithm is to minimize the in-route salary costs. The GRASP-AVNS algorithm has a maximum run time of two hours for each individual day. Finally, nurses are assigned to shifts using a two stage greedy approach. In the first stage, routes are turned into shifts with the goal of minimizing the number of nurses on a single day. In the second stage, nurses are assigned to shifts with the goal of minimizing overall costs. This results into the final solution of the HHCRSP. The individual parts of the solution approach are further discussed in the following sections.

4.4 Lower bound

The lower bound of the in-route salary cost receives special attention because of the usage in the solution approach. As indicated in Section 2.6.3, 95% of the total cost are the in-route salary cost. The in-route salary costs of a single visit is dependent on four different terms. The service time of a visit, the travel time between two visits, the required skill level (and consequently hourly salary costs) of the nurse performing the visit and the time window of the visit. The trips from and to the depot/ nurse home location are excluded from these in-route salary costs (even in case of double/broken shifts). The service time of a visit is a fixed value and cannot be optimized. Furthermore, the Euclidean distance method uses a minimum travel time between visits (Section 2.6.1). This gives a lower bound for the duration of a visit (including travel time).

The lower bound assumes that each visit occurs at the cheapest possible start time, given by the visit's time window. Here, the assumption is made that the travel time is before the visit starts, not after performing the visit. Finally, the lower bound assumes that each visit is the last visit within a route. This means only travel time before the visit has to be accounted for. The minimum in-route salary cost for that visit is calculated by multiplying the visit duration with the salary of the minimum required skill level and adding the additional compensation based on the time window of a visit. The equation to calculate the lower bound in-route salary cost for a visit is shown in Equation 4.

$$LBV_v = (ST_v + MinTravel) \cdot Y_{SV_v} \cdot (1 + Z_v) \tag{4}$$

Here, ST_v is the service time of visit v, $MinTravel$ is the minimum travel time between two visits. Y_{SV_v} is the minimum hourly salary cost for that visit and Z_V accounts for the additional compensation based on the day and time of day. The lower bound of four different visits can be seen in Table 5.

Visit	**1**	**2**	**3**	**4**
Start time window (hour)	18.5	19	20	21
Service time (ST_v)	1.5	0.5	1.1	0.5
Skill level	3-IG	3	3-IG	2
Regular salary (Y_{sv_v})	27.23	24.52	27.23	21.19
Percentage additional compensation (Z_v)	0	0	20.16	22
Lower bound (LBV_v)	43.57	14.71	39.27	15.51

Table 5: Lower bound calculations. A minimum travel time of 6 minutes (0.1 hour) is used. Nurses receive 22% additional salary after 20:00.

The calculation of the lower bound of visits one and two is straightforward. The minimum travel time is added to the service time and this combined minimum visit time is multiplied with the regular salary. Visit three is different. Here, the service starts at 20:00 but the travelling time to the visit is still before 20:00. So, only 20.16% of additional salary compensation is required in the cheapest scenario. Finally, visit four is in it's entirety after 20:00 and therefore 22% of additional salary compensation is paid.

The next step is combining the lower bound of multiple visits into a lower bound of a route. The lower bound of a route is the sum of the lower bound of all visits within the route minus the cost related to the travel time to the first visit. The travelling time to the first visit is excluded since this is a trip from a nurses home to a first visit and is therefore not part of the in-route salary costs. So, the lower bound in-route salary cost of the visits in Table 5 is 110.34. The lower bound of the entire solution in-route salary cost is calculated by summing the lower bounds of the individual in-route salary costs.

4.5 GRASP

The GRASP algorithm used in this work can be separated into three different stages. In the first stage, a set of initial solutions is created. An initial solution is created by constantly adding one visit to the solution, until all visits are added. Routes resulting from stage 1 can result in an invalid overall HHCRSP solution because they could violate the minimum shift length constraint in the scheduling problem. Therefore, the minimum shift length constraint is turned into a minimum route length constraint in GRASP stage 2. The goal of stage 2 is to ensure that no routes violate the minimum route length constraint. So, all solutions resulting from stage 2 contain routes that lead to a valid routing solution of the HHCRSP. The solutions from stage 2 are optimized via a local search in stage 3. Stage 3 finalizes the GRASP procedure. The three GRASP stages are covered in detail in the following sections. This section is finalized with a section on selecting promising intermediate solutions between GRASP stages and the computation time of the GRASP algorithm.

4.5.1 GRASP stage 1: creation of initial solution

The goal of GRASP stage 1 is to create a set of initial solutions that can be optimized in later GRASP stages. An initial routing solution is created in GRASP stage 1. Pseudo code of GRASP stage 1 can be seen in Algorithm 1.

Algorithm 1 Initial solution

```
1:  GRASP_init solutions = []
2:  while time < Maxtime do
3:      Current solution = []
4:      while Nr. unassigned visits != 0 do
5:          Start new route
6:          Determine feasible visits
7:          while Nr. feasible visits != 0 do
8:              Insert unassigned visit into route
9:              Nr. unassigned visits = Nr. unassigned visits - 1
10:             Determine feasible visits
11:     Add Current solution to GRASP_init solutions
```

Line 1 creates a variable to store the GRASP stage 1 solutions. Line 2 indicates the stopping criterion of GRASP stage 1. Line 3 sets the current solution to an empty solution, ensuring that a solution is started from zero. Line 4 indicates that a GRASP iteration is finished and the next iteration is started. An empty route is created in line 5. Line 6 determines all feasible visits that can be inserted into the route. Here, feasible visits are ranked based on a ranking procedure. Line 7 starts the sequential route building procedure. Visits are added to the route until no further visits can be assigned. Line 8 inserts a visit into the route. Line 9 ensures that the number of unscheduled visits is reduced. Line 10 determines all possible insertions (similar as line 6). Finally, each GRASP solution is stored in line 11. The determination of feasible visits, their rank (lines 6 & 10) and the insertion of a visit (line 8) are covered in more detail in the following sections.

Determining if inserting a visit is feasible

A visit can be inserted into a route if the skill linking and time window constraint of the visit are met. Additionally, the resulting route length must be below the maximum route length. Section 2.3.3 indicates a maximum route length of 5.5 hours for TWB's problem. However, A nurse is not allowed to work more than ten hours on a day. So, a lower maximum route length is used to ensure that nurses can work multiple routes per day. The tuning of this parameter can be seen in Section 5.7. Finally, a maximum route length of five hours is selected.

The start time can also have an influence on whether or not a route is feasible. For instance, a route can have waiting time which results in a route being longer than the maximum route length. Therefore, Savelsbergh [33] forward time slack method is used to determine the start time of a route. This method ensures that the waiting time within a route is minimized. It is possible that multiple start times result in the same minimum waiting time. In that case, the earliest start time resulting in a minimum waiting time is selected as start time of the first visit.

Determining the cost of inserting a visit

The insertion technique used in this work is an adaption of Solomon's insertion heuristic [36]. In Solomon's heuristic, the next visit is added to a route based on the additional travelled time and distance when including that visit. In this work, the best insertion is dependent on three terms. These are the skill level of a visit, the cost difference compared to the lower bound in-route salary cost of that route and the start of the time window. Here, the skill level dominates the other two terms and the cost difference dominates the time window term. So, the highest level visit, with the lowest cost difference, with the earliest time window receives the best rank.

Inserting a visit

The GRASP algorithm determines which visit is inserted based on a restricted candidate list (RCL). Only the best X visits (based on the previously described ranking procedure) are placed in the RCL. All visits within the RCL have an equal chance to be selected. Experiments to determine the RCL length are performed in Section 5.4. A RCL of four is selected based on these results. An exception is made in the first GRASP iteration, here an RCL of one is used. This means that the visit with the best ranking is always inserted in the first iteration, which makes the first iteration fully deterministic.

4.5.2 GRASP stage 2: ensuring feasibility

The goal of GRASP stage 2 is to turn a solution resulting from GRASP stage 1 into a feasible solution. Two separate local searches are used in stage 2, these are local search 1 (LS1) and local search 2 (LS2). The goal of LS1 is to reduce the total number of routes and the goal of LS2 is to turn any route that violates the minimum route length constraint into a feasible route. Pseudo code of GRASP stage 2 can be seen in Algorithm 2.

Algorithm 2 Ensuring feasibility

1: $GRASP_{inter}$ *solutions* = []
2: **for** I in Nr. $GRASP_{init}$ *solutions* **do**
3:     Current solution =$GRASP_{init}$ *solutions*[I]
4:     Determine individual route length
5:     **if** Any individual route length < $MISh$ -1 hours **then**
6:         Determine possible moves LS1
7:         **while** Possible moves != 0 **do**
8:             Carry out best move
9:             Determine possible moves LS1
10:     Determine individual route length
11:     **if** Any individual route length < $MISh$ hours **then**
12:         Determine possible moves LS2
13:         **while** Possible moves != 0 **do**
14:             Carry out best move
15:             Determine individual route length
16:             **if** All individual route length > $MISh$ **then** Break
17:             Determine possible moves LS2
18:     Add Current solution to $GRASP_{inter}$ *solutions*

Line 1 creates a new variable to store all solutions from stage 2. Line 2 creates a for loop that moves through the solutions resulting from stage 1. Line 3 selects a stage 1 solution as current solution. Line 4 determines the route length of each route in the current solution. Line 5 determines whether or not LS1 is called for the current solution. Line 6 determines all possible actions in LS1. Line 7 starts a while loop that ends when there are no further actions possible in LS1. Line 8 carries out the best action and line 9 determines the actions for the next LS1 iteration. Line 10 determines the route length of each individual route (similar as line 4). If any route is below minimum route length then LS2 is entered in line 11. Line 12 determines all possible LS2 actions. Line 13 enters the while loop that ends if there are no further improvements possible using LS2. The best LS2 action is carried out in line 14 after which the route length of all routes is determined again in line 15. If all routes are longer than three hours then the algorithm breaks out of the while loop in line 16. If there are still routes that are too short then the possible LS2 actions are determined in line 17. Finally, the solution is added to the GRASP stage 2 solution set in line 18. LS1 and LS2 are discussed in more detail in the following sections.

Local search 1 (LS1)

As mentioned previously, the goal of LS1 is reducing the number of routes. Solutions resulting from GRASP stage 1 can have very short routes, occasionally even routes with only a single visit. A route is called a very short route if it is more than 1 hour too short. In those cases, LS1 is called to try to move these visits into other routes. This would reduce the number of routes that do not meet the minimum route length constraint. LS1 uses a reinsertion operator.

- Reinsertion operator: This operator takes one visit from a route and places that visit at a new location. This new location can be in the same route but also in another route.

A reinsertion is accepted in LS1 in one of the following two cases.

- Case 1: A visit from a very short route is reinserted into another route that does not violate the minimum route length constraint.
- Case 2: A visit from a route that does not violate the minimum route length constraint is reinserted into another route that does not violate the minimum route length constraint if this reinsertion reduces the in-route salary costs.

Case 1 reinsertions are prioritized over case 2 reinsertions. The ranking of all case 1 movements is equal. Case 2 reinsertions are ranked based on their in-route salary costs reduction. Case 1 reinsertions could to reduce the number of routes. Whereas case 2 reinsertions change the current solution structure to possibly allow a new case 1 reinsertion in later iterations while reducing the in-route salary cost. LS1 is continued until no case 1 and case 2 reinsertions are possible.

Local search 2 (LS2)

The goal of LS2 is to turn a solution that contains routes that violate the minimum route length constraint into a feasible solution. LS2 uses the same reinsertion operator as LS1. However, a reinsertion in LS2 is only accepted if it increases the route length of a route that violates the minimum route length constraint. The goal is to do this without increasing the required nurse skill level of the route. For instance, if an ADL level route is too short then a 3-IG visit is only allowed to be inserted if no ADL, level 2 and level 3 visits can increase the length of the route that is too short.

4.5.3 GRASP stage 3: improving solution performance

The goal of GRASP stage 3 is to reduce the in-route salary cost and driving distance of the solutions resulting from GRASP stage 2. The solution with the lowest in-route salary cost after stage 3 is selected as the final GRASP solution. GRASP stage 3 uses three different operators to improve the solution.

- Reinsertion operator: This operator takes one visit from a route and places that visit at a new location. This new location can be in the same route but also in another route.
- Swap operator: This operator takes two visits and swaps these visits. These two visits can be from the same route but also from different routes
- outer-route 2-opt. This operator swaps entire sections of routes with each other. For instance, the beginning of route A is followed by the end part of route B and vice versa.

Pseudo code of GRASP stage 3 can be seen in Algorithm 3.

Algorithm 3 GRASP stage 3

```
1: GRASP_final solution = [], Best solution cost = ∞
2: for I in Nr. GRASP_inter solutions do
3:     Current solution = GRASP_inter solutions[I]
4:     Imprinsert= 1, Imprswap = 1, Impr2opt = 1
5:     while Imprinsert + Imprswap + Impr2opt != 0 do
6:         while Imprinsert != 0 do
7:             Determine Possible reinsertions
8:             if Nr. Possible reinsertion = 0 then
9:                 Imprinsert = 0
10:                Break
11:            Carry out best reinsertion
12:            Imprswap = 1, Imrp2opt = 1
13:        while Imprswap != 0 do
14:            Determine Possible swaps
15:            if Nr. Possible swaps = 0 then
16:                Imprswap = 0
17:                Break
18:            Carry out best swap
19:            Imprinsert = 1, Imrp2opt = 1
20:        while Impr2opt != 0 do
21:            Determine Possible 2opts
22:            if Nr. Possible 2opts = 0 then
23:                Imp2opt = 0
24:                Break
25:            Carry out best 2opt
26:            Imprinsert = 1, Imrpswap = 1
27:    if Current solution cost < Best solution cost then
28:        Best solution = Current solution
29:        Best solution cost = Current solution cost
30: GRASP_final solution = Best solution
```

Line 1 creates a variable to store the best solution and creates a counter that keeps track of the cost of the best solution. Line 2 creates a for loop that loops through the stage 2 solutions. Line 3 sets a stage 2 solution as current solution. Line 4 sets the three checkers that ensure all operators are used. Line 5 enters the local search while loop. The local search continues until no improvements can be found using any of the three operators. Line 6 enters the improvement phase using the reinsertion operator. Line 7 calculates all possible reinsertion improvements. Lines 8 and 9 update the reinsertion counter to determine whether or not the reinsertion neighborhood is empty and at a local optimum. Line 10 ensures that the algorithm moves to the next operator if the current neighborhood is at a local optimum. Line 11 performs the best possible reinsertion and updates the current solution as well as the cost of the current solution. The best reinsertion is the reinsertion that leads to the largest in-route salary cost reduction. If no reinsertions result in an in-route salary cost reduction then the reinsertion that reduces the driving distance the most, without increasing in-route salary cost, is the best reinsertion. Line 12 updates the counters for the other operators, ensuring that these are used at least once in case the reinsertion operator leads to an improvement. Because an improvement using the reinsertion operator changes the solution structure and could allow for further improvements using the other two operators. The same steps are followed for the swap operator (lines 13 until 19) and the 2-opt operator (lines 20 until 26). The current solution is accepted as the best solution in lines 27 to 29 if it has a lower in-route salary cost than the current best solution. Finally, the best GRASP solution is stored as the final GRASP solution in line 30.

4.5.4 Intermediate solution selection & computation time

A key concept of the proposed GRASP approach is that it focuses only on promising intermediate solutions to reduce the overall computation time of the GRASP algorithm. The purpose and the technique of the intermediate solution selection procedure as well as the GRASP computation time is covered in the following sections.

Purpose of intermediate solution selection

Each GRASP stage serves a different purpose. GRASP stage 1 creates initial solutions. GRASP stage 2 turns these solutions into valid solutions and GRASP stages 3 improves the performance of these solutions. Preliminary results indicate that the majority (over 95%) of the computation time is spend in GRASP stage 2 and 3. Most of this computation time in stage 2 and 3 is wasted because only the best solution is maintained after the GRASP procedure. So, if it is possible to determine whether or not a solution is promising before GRASP stage 2 and 3 then the overall computation time can be reduced substantially.

Intermediate solution selection technique

The results displayed in Section 5.3 show that it is possible to determine whether or not a solution is promising before GRASP stage 2 and 3. The results show that the number of level 3-IG and level 3 routes used in a GRASP stage 1 solution are a good indicator for the performance of a solution after GRASP stage 3. A score value is given to each intermediate solution. This score is 2 times the number of level 3-IG routes plus the number of level 3 routes. An intermediate solution is moved to the next GRASP stage if the solution has a score value equal to or below X. X is the smallest score that ensures that at least 25% of the solutions are moved to the next GRASP stage. This intermediate solution selection procedure ensures that more computation time is spend on promising solutions, resulting in a shorter overall computation time. This intermediate solution selection procedure is used after both GRASP stage 1 and GRASP stage 2.

GRASP computation time

A downside of the intermediate solution selection procedure is that no time limit can be enforced over all GRASP stages. Because the computation time in stage 2 and 3 are dependent on the results of stage 1. Therefore, only a time limit on GRASP stage 1 can be enforced. The goal is to end up with an overall GRASP time of 1 hour. This is approximated by running GRASP stage 1 for 60 seconds on Monday in cluster Wouw (150 visits). The GRASP stage 1 time limit for other instances is calculated using the following set of equations. The derivation of these equations can be seen in Appendix B.

$$Power = (Nrpatients - 150) * 0.001 + 0.502 \tag{5}$$

$$Fraction = (Nrpatients/150)^{Power} \tag{6}$$

$$Maxtime = Goal/Fraction \tag{7}$$

4.6 Adaptive Variable Neighborhood Search

The best solution from the GRASP algorithm is moved to the AVNS algorithm to further reduce the in-route salary costs. First, regular VNS is explained. This is followed by an explanation of the AVNS used in this work.

4.6.1 VNS introduction

The variable neighborhood search heuristic is introduced by Mladenovic and Hansen in 1997 [30]. In general, a VNS consists of two steps. A shaking procedure to move from the current solution to a neighboring solution and an improvement step using a local search to improve the neighboring solution. If the cost of the improved neighboring solution is below the cost of the current solution then the improved neighboring solution is accepted as the current solution. The benefit of the shaking procedure is that it allows the algorithm to escape local minima to find better solutions. This procedure of performing shakes and improving neighboring solutions is continued until a stopping criterion is met to finish the algorithm.

4.6.2 AVNS algorithm

The adaptive variable neighborhood search in this work consists of an adaptive shaking procedure and a local search. Pseudo code of the AVNS algorithm can be seen in Algorithm 4.

Algorithm 4 AVNS

1: $AVNS_{Final}$ *solution* = [], Iterwithout = 0
2: Best solution = $GRASP_{final}$ *solution*
3: Best solution cost = $GRASP_{final}$ *solution* cost
4: **while** time < Totaltime **do**
5:     Determine Nr. shakes
6:     Creating neighboring solution
7:     Optimize neighboring solution
8:     **if** Part of neighboring solution cost < Part of Best solution cost **then**
9:         Update Best solution
10:         Update Best solution cost
11:         Iterwithout = 0
12:     **else**
13:         Iterwithout = Iterwithout + 1
14: $AVNS_{Final}$ *solution* = Best solution

A variable to store the final routing problem solution and a variable to keep track of the number of iterations without improvements in the AVNS algorithm are created in line 1. The final GRASP solution is set as the initial solution of the VNS algorithm in lines 2 and 3. The AVNS algorithm is executed until a total time limit (two hours) is reached (line 4). This total time limit is used for both the combined GRASP and AVNS algorithm. So, a longer GRASP computation time results in a shorter AVNS computation time. Line 5 determines the number of shakes performed in the current AVNS iteration. The actual shakes of the AVNS iteration are performed in line 6 to end up with a neighboring solution. The newly created neighboring solution is optimized using a local search in line 7. The local search of Section 4.5.3 is used as optimization method. If the optimized neighboring solution has parts that are better than the current best solution (line 8) then the best solution is updated in lines 9 and 10. In that case, the number of iterations is set back to zero. If the best solution is not improved, then the number of iterations without improved is increased by one. Finally, the final routing solution is stored in line 14. This concludes the routing algorithm. The determination of the number of shakes, the selection of the actual shake and the partial updating method is further discussed in the following sections.

Number of shakes

The goal of a shake is to move to a neighboring solution and start a new local search with the neighboring solution as start point to find a better solution. However, it is possible that all neighbors of a current solution are explored without finding the overall best possible solution. To avoid this problem, the number of shakes in the AVNS in this work are increased if no improvement is found after a number of iterations. The number of shakes in an AVNS iteration can be seen in Table 6.

Nr. iterations without improvement	**≥0**	**≥25**	**≥50**	**≥100**	**≥150**
Nr. shakes	1	2	4	6	8

Table 6: Number of shakes per AVNS iteration without improvement.

Selecting a shake

An outer-route 2-opt operator (Section 4.5.3) is used as shaking operator in this AVNS because of two reasons. The first reason is that the outer-route 2-opt operator changes large parts of the solution in a single operation. The second reason is that it works well with the local search from Section 4.5.3. The local search moves through the reinsertion, swap and outer-route 2-opt operator in a cyclic fashion. So, the first operator in the local search is always the reinsertion operator. If the reinsertion operator would be used as shaking operator, then this gives the algorithm the chance to directly return to the best known solution in the local search. Lowering the chance of the algorithm to escape the local optimum.

The next step is selecting the two visits after which the routes are swapped by the outer-route 2-opt operator. Both visits are selected randomly, but a different distribution is used. A combination of two separate distributions is used to select the first visit.

1. Uniform distribution: A uniform distribution gives the same probability to each visit to be selected in the shaking procedure.

2. Lower bound based distribution: The lower bound distribution gives a higher probability to visits that are within routes that have a large in-route salary cost difference compared to the lower bound.

In the uniform distribution, each visit has an equal chance to be selected. The lower bound based distribution gives a higher probability to visits in routes that have a bigger in-route salary cost reduction potential. The reasoning is that this increases the chance of a cost reduction after the shake, since it increases the chance that a shake is carried out in a sub-optimal part of the solution. A joint distribution of distribution one and two is used to select visit 1. Here, each distribution has a weight of 50%. Visit 2 is selected using the uniform distribution.

The final step is determining if a shake is a feasible shake. A shake is valid if it meets both of the following criteria.

- Criterion 1: The neighboring solution after the shake does not violate any of the constraints introduced in Section 4.1.
- Criterion 2: The shaking procedure does not increase the required nurse skill levels for both routes.

A shake that does not meet criterion 2 is not accepted because it leads to a substantial cost increase and therefore most likely does not result in a cost reduction after optimization. For instance, if a 3-IG and an ADL route are swapped by the outer-route 2-opt operator then the shake is only valid if it outputs a 3-IG and ADL route. If both routes would become a 3-IG route then this would lead to substantially higher in-route salary costs, because a 3-IG nurse receives a higher hourly salary than an ADL nurse.

Updating the solution

The shakes discussed in the previous section are independent from each other. So, it is possible that two shakes do not influence each other when multiple shakes are performed. For example, one shake swapped two evening routes and the other swapped two morning routes. The following situation can occur: one shake results in an in-route cost reduction, while the other results in an in-route cost increase. In this situation, the solution is partially updated to ensure that only the routes resulting in a cost reduction are included in the new best solution. If both shakes result in a cost reduction then the routes resulting from both shakes are included in the new best solution.

4.7 Scheduling problem

The task in the scheduling problem is to assign nurses to the created routes. The scheduling problem is divided into two stages. First, the routes resulting from the routing problem are turned into shifts. Then, the nurses are assigned to shifts to finalize the HHCRSP solution approach.

4.7.1 Scheduling problem stage 1: creating shifts

The goal of scheduling problem stage 1 is to combine multiple routes via breaks and create double/broken shifts. The pseudo code creating shifts can be seen in Algorithm 5.

Algorithm 5 Creating shifts

```
1: Determine possible breaks
2: Combine routes with breaks
3: Determine possible double shifts
4: Combine routes with double shifts
5: Turn remaining routes into regular shifts
```

Line 1 is used to find all combinations of routes that can be combined via a break. Two routes can be combined via a break if the constraints from Section 4.1 are not violated and if both routes require a nurse from the same skill level. Routes are connected via a break and turned into shifts in line 2. Here, possible breaks with a minimum additional break time are prioritized to ensure that the break is as short as possible for a nurse. After line 2, no routes can be combined with a break anymore. The next step is to determine whether two routes can be combined in a double/broken shift (line 3). Two routes can be combined in a double/broken shift if the constraints from Section 4.1 are not violated and if both routes require a nurse from the same skill level. Routes are combined into double/broken shifts in line 4. Here, combinations that result in the shortest time between shifts are prioritized. Finally, the remaining routes cannot be turned into double/broken shifts anymore. These remaining routes are turned into regular shifts, without any changes (line 5). Additional information on the combination of shifts into double/broken shifts can be seen in the following section.

Double/broken shifts

The combination of shifts into double/broken shifts is expected to have an influence on the employee satisfaction level. This is explained by the following example.

There are two days and two shifts on each day. The shifts on each day can be combined in a double/broken shift. Finally, there are two nurses available and both can work two shifts. The nurses have an equal skill level. This results in two ways to assign the shifts. Nurses can both work a double/broken shift which means they work only one of the two days. However, the nurses could also work one shift each on a single day. This means they do not work a double/broken shift but have to work both days. Which one of the two options is preferred is actually down to personal preferences of nurses. The solution approach proposed in this work always combines shifts into a double/broken shift in situations similar to the example.

4.7.2 Scheduling problem stage 2: assigning nurses

The goal of scheduling problem stage 2 is to assign nurses to the shifts created in scheduling problem 1. Pseudo code showing the procedure of assigning nurses to shifts is shown in Algorithm 6.

Algorithm 6 Assigning nurses

```
 1: Fraction overtime = 0
 2: Available nurses = All nurses, Unassigned Shifts = All shifts
 3: while Not all shifts assigned to employees do
 4:     Select best nurse
 5:     while best nurse can work more shifts do
 6:         Determine possible shifts to assign
 7:         if Nr. possible shifts > 0 then
 8:             Assign best shift to nurse
 9:         else
10:             Current nurse not available anymore
11:             Break
12:     if No nurses available anymore AND not all shifts assigned then
13:         Available nurses = All nurses, Unassigned Shifts = All shifts
14:         Fraction overtime = Fraction overtime + 0.01
```

The fraction of overtime allowed per nurse is set to zero in line 1. All nurses are set as available nurses and all shifts are set as unassigned shifts in line 2. Line 3 enters the while loop that assigns all nurses to shifts. The best nurse is selected in line 4. The best nurse is the available nurse with the lowest skill level that has the largest amount of working hours in their contract. The while loop in line 5 is used to assign shifts to the best nurse. Line 6 determines all shifts that can be assigned to the best nurse. A shift can be assigned to a nurse if the nurse has a sufficient skill level to perform all visits within the shift, if the total working time remains under the contract hours plus total overtime limit and if a nurse will not work more than 6 days in a week. If a shift can be assigned to the best nurse (line 7) then the best shift is assigned (line 8). The best shift is the possible shift with the highest in-route salary cost. If no shifts can be added to the current nurse (line 9) then the current nurse is no longer available (line 10). The algorithm then breaks out of the while loop (line 11) and returns to line 3 to continue the assignment process. If no nurses are available anymore and there are still unassigned shifts (line 12) then the current solution is set back to the empty solution (line 13) and the allowed fraction of overtime is increased (line 14). So, the first solution where all shifts are assigned to nurses without violating the overtime limit is accepted as the final HHCRSP solutions. This finalizes the assignment method and the solution method of the HHCRSP. More detail on the selection of the best nurse and shift is given in the following section.

Best nurse & best shift

The best nurse is the available nurse with the lowest skill level that has the largest amount of working hours in their contract. The best shift for the best nurse is the possible shift with the highest in-route salary cost.

Here, the in-route salary cost are calculated using the salary related to the skill of the best nurse if the skill of the best nurse is above the required skill to work the shift. It sounds counter intuitive to assign the route with the highest in-route salary cost to the best nurse, but this is explained by the following example:

There are two shifts remaining to be scheduled. One level 2 shift with a duration of five hours and one level 3 shift with a duration of four hours. One level 3 and one 3-IG nurse are available and both can perform one shift each. In that situation, the level 3 nurse is assigned to the level 2 shift and the 3-IG nurse is assigned to the level 3 shift. This results in five hours of level 3 nurse working time and four hours of level 3-IG working time. Assigning the shifts the other way around results in five hours of 3-IG working time and four hours of level 3 working time, which would lead to higher overall salary costs.

4.8 Conclusion

In this chapter, we answer the third research question: *How should the solution approach for the home healthcare routing and scheduling problem be generated?*. First, we develop a problem description that gives insight in the optimization problem that is solved in this work. The problem description indicates that all constraints have to be taken into account as hard constraints, aside from the contract hour constraint. The performance of a solution is judged based on the in-route salary costs, the amount of required overtime and the number of nurses. A multi-phase solution approach is proposed. In the first phase, a three stage GRASP procedure is proposed to generate high quality routing solutions. This followed by an AVNS algorithm in phase two to further improve the quality of the created routes. In the final phase, Nurses are scheduled to work the routes created in phase one and two. The nurses are scheduled to minimize total costs. In the next chapter, we perform experiments to determine the settings of the algorithm to generate high quality HHCRSP solutions.

5 Algorithm tuning

In this chapter, we answer the fourth research question: *How can the solution approach generate feasible and high quality solutions?*. First, we discuss the experimental setup in Section 5.1. Next, multiple parameters of the HHCRSP algorithm are tuned. We start with the tuning of the local search in GRASP stage 3. This experiment is conducted first because the results after GRASP stage 3 are used as benchmark in subsequent GRASP tuning experiments. Furthermore, the GRASP stage 3 solution is used as initial solution in the AVNS tuning. The local search of GRASP stage 3 is analyzed in Section 5.2. In Section 5.3, the selection of intermediate solutions moved from GRASP stage 1 to stage 2 and from GRASP stage 2 to stage 3 is discussed. The length of the restricted candidate list is determined in Section 5.4, which finalizes the tuning of the GRASP algorithm. Parameters of the AVNS algorithm are tuned after the tuning of the GRASP algorithm is finalized. The selection and tuning of the AVNS algorithm is discussed in Section 5.5. The distribution of computation time between the GRASP and AVNS algorithm is discussed in Section 5.6. Experiments to determine an appropriate maximum route length for the GRASP-AVNS are performed in Section 5.7. Experiments on how to assign nurses to shifts are performed in Section 5.8. The validation of the solution approach is discussed in Section 5.9. Finally, we conclude this chapter in Section 5.10. All experiments are performed in chronological order.

5.1 Experimental setup

This section aims to provide insight in the experimental setup used in this work. The selected instances are discussed in Section 5.1.1. The experimental parameters are discussed in Section 5.1.2. All experiments are performed on a laptop with an i-10750H processor of 2.6 GHz and 16 GB RAM using pypy. Pypy is selected instead of regular python because results indicate it reduces computation time by 75%.

5.1.1 Instances

Routes performed by nurses with a skill level of 3-IG or lower from cluster Kroeven-Tolberg, Wouw, Centrum-Westrand and Heilig Hart are retrieved from TWB's database and used as instances. In each cluster, routes from an entire week in February are collected. This leads to a total of 28 different routing instances. The database provides the nurses, clients and visits of the instances. The database provides all required information, aside from visit's time windows. All time windows have to be updated manually and a substantial amount (30-50%) of time windows have to be estimated. A more detailed description of the preparation of the instances is provided in Section 2.4.1. The generalizability of the instances is not studied because the preparation of instances is a very time consuming process.

5.1.2 Experimental parameters

The final part of the experimental setup are the experimental parameters. The values of the experimental parameters are discussed in the context analysis (Chapter 2). A list of the experimental parameters can be seen below.

- The maximum route length (MRL) is 5.5 hours.
- The minimum break length (MIB) is 0.5 hours.
- The maximum break length (MAB is 2 hours.
- The minimum shift length ($MISH$) is 3 hours.
- The maximum working hours of a nurse on a day ($MAWH$) is 10 hours.
- Nurse hourly salary cost are 17.48, 21.19, 24.52, 27.23 Euro for skill level ADL, 2, 3, 3-IG respectively.
- Additional salary compensation is dependent on day and time of day with 22% on weekdays between 20:00 and 22:00 and 44% between 22:00 and 24:00. 38% on Saturday between 7:00 and 8:00 and between 12:00 and 22:00, 49% from 22:00 until 24:00. 60% on Sundays.

5.2 Tuning of local search operators

The tuning of operators of the local search used in GRASP stage 3 (Section 4.5.3) is performed in this section. The tuning of the local search is important because the local search influences the quality of a final solution. Therefore, this is the first conducted experiment. Ten different intermediate GRASP results from GRASP stage 2 from the Monday in Kroeven-Tolberg are optimized during this experiment using different operators. The reinsertion, swap and outer-route 2-opt operator are used. Preliminary results indicated that a combination of all three operators is promising. But, the outer-route 2-opt operator has the lowest influence. Therefore, the outer-route 2-opt operator is only selected after the reinsertion and swap operator have found a local optimum at least once. Four different experiments are performed. The goal of the local search is to minimize the in-route salary costs as well as the driving distance in all experiments. The local search is a best improvement local search, which means that the best improvement is performed in each iteration. Results of the experiments can be found in Table 7.

1. Experiment 1: Reinsertion → Swap → outer-route 2-opt version 1. In this experiment, the reinsertion operator is followed by the swap operator and outer-route 2-opt. If the swap operator improves the solution then the reinsertion operator is the next selected operator. If the swap operator does not improve the solution then the outer-route 2-opt operator is the next selected operator

2. Experiment 2: Reinsertion → Swap → outer-route 2-opt version 2. In this experiment, the reinsertion operator is followed by the swap operator and outer-route 2-opt. The outer-route 2-opt operator is always selected after the swap operator.

3. Experiment 3: Swap → Reinsertion → outer-route 2-opt version 1. In this experiment, the swap operator is followed by the reinsertion operator and outer-route 2-opt. If the reinsertion operator improves the solution then the swap operator is the next selected operator. If the reinsertion operator does not improve the solution then the outer-route 2-opt operator is the next selected operator

4. Experiment 4: Swap → Reinsertion → outer-route 2-opt version 2. In this experiment, the swap operator is followed by the reinsertion operator and outer-route 2-opt. The outer-route 2-opt operator is always selected after the reinsertion operator.

Experiment	**1**	**2**	**3**	**4**
GRASP 1	**1961.73**	**1961.73**	1962.11	1962.84
GRASP 2	1971.91	1971.33	1971.37	**1970.72**
GRASP 3	1987.70	**1983.47**	1985.12	1985.18
GRASP 4	1997.65	1997.49	**1997.06**	1997.18
GRASP 5	1991.98	1992.37	**1981.14**	1984.18
GRASP 6	1987.48	**1986.67**	1987.61	1987.61
GRASP 7	1978.85	**1978.73**	1993.02	1993.08
GRASP 8	1987.24	**1986.30**	1987.18	1988.46
GRASP 9	1999.97	**1997.60**	1998.91	1998.91
GRASP 10	1974.75	**1974.59**	1978.79	1981.53

Table 7: In-route salary cost after local search using different operator settings. Ten GRASP stage 2 results from the Monday in Kroeven-Tolberg are used as initial solution. Maximum route length is 4.75 hours. An RCL of six is used in the GRASP approach. An RCL of one is used in the GRASP 1 solution. Displayed costs are in-route salary costs. The local search is a best improvement local search.

Table 7 indicates that each experimental settings has led to the best obtained solution at least once. However, the local search used in experiment 2 has led to the best result in 7 out of 10 cases. Therefore, the settings of experiment 2 are the local search setting used in the final solution approach.

5.3 Promising solution selection

In this section, the procedure of selecting promising intermediate solutions in the GRASP procedure is discussed. The goal of selecting only promising intermediate solutions is to reduce the overall computation time while still finding good solutions. Preliminary results indicate that the majority of computation time (over 95%) is spend in GRASP stages 2 and 3. So, if a solution can be discarded after GRASP stage 1 then this results in substantially shorter computation times. The development of the intermediate solution selection procedure is divided into two sections. First, the obtained solutions without selecting a limited set of intermediate solutions are discussed in Section 5.3.1. This is followed by experiments to determine the intermediate solution selection procedure in Section 5.3.2.

5.3.1 Overview of all solutions

First, an overview of results obtained after 200 GRASP iterations can be seen in Table 8. No intermediate solution selection approach is used during this experiment.

Solution	Routes stage 1	Score	Routes stage 2	Score	Routes stage 3	Score	Cost
1	6-5-4-5	17	6-5-4-5	17	6-4-5-5	16	1945.81
2	6-6-4-6	18	6-4-5-6	16	6-4-5-5	16	1947.00
3	7-4-4-5	18	6-4-5-5	16	6-4-5-5	16	1953.81
4	7-4-4-5	18	7-3-4-6	17	6-4-4-6	16	1954.91
5	8-4-5-5	20	8-4-4-5	20	7-5-4-5	19	1956.36
6	7-4-5-4	18	7-4-5-4	18	7-3-5-5	17	1956.48
7	6-4-5-5	16	6-3-6-5	15	6-3-6-5	15	1958.57
8	6-5-4-5	17	6-5-4-5	17	6-5-4-5	17	1961.06
9	7-4-4-7	18	7-4-4-6	18	7-4-4-6	18	1961.67
10	*7-4-3-6*	*18*	*6-4-4-5*	*16*	*6-4-4-5*	*16*	*1961.73*
191	9-3-6-3	21	9-3-5-3	21	9-3-5-3	21	2027.33
192	8-4-3-6	20	8-4-2-5	20	8-4-2-5	20	2027.84
193	8-4-3-6	20	8-4-3-5	20	8-4-3-5	20	2032.99
194	7-5-4-6	19	7-4-5-5	18	7-4-5-5	20	2033.30
195	7-5-4-5	19	7-5-4-3	19	7-5-4-3	18	2036.36
196	8-4-5-3	20	7-5-4-3	19	7-5-4-3	19	2039.33
197	7-5-4-4	19	7-5-4-3	19	7-5-4-3	19	2039.41
198	8-4-4-5	20	8-4-3-4	20	8-4-3-4	20	2039.62
199	7-5-5-4	19	7-5-5-4	19	7-5-5-4	19	2042.29
200	8-5-3-5	21	8-4-4-3	20	8-4-4-3	20	2052.41

Table 8: Best and worst GRASP results of 200 iterations. Routes indicate the required nurse skill to perform all routes in each stage. Here, the first term are the required number of 3-IG routes and the last term are the number of ADL routes. The score is obtained by the number 3-IG routes times 2, plus the number of level 3 routes. Results are obtained using a maximum route length of 4.75 hours and a RCL of six. Displayed costs are in-route salary costs. Solution ten is the result from the first GRASP iteration which is created with a RCL of one and is therefore fully deterministic.

Table 8 shows the ten best, and ten worst solutions obtained from the GRASP procedure. The required nurse skill levels to work all routes are displayed for the results after each GRASP stage. The score is obtained by multiplying the number of 3-IG routes times two and adding the number of level 3 routes. So, the score is an indication of the number of required high level nurses. The obtained results clearly show that most of the best solutions have a low score whereas most of the worst solutions have a high score. This difference in scores is already visible after stage 1, and most of the computation time is spend in stage 2 and 3. So, if only promising solutions are moved from stage 1 to the other stages then this could substantially reduce the overall computation time. So, the results in Table 8 show that the score could be used as indicator on whether or not a solution is promising and should be evaluated further in following GRASP stages.

Furthermore, Table 8 shows that the solution obtained with a RCL of one is promising (solution 10). A RCL of one means only the best visit is inserted during GRASP stage 1. This removes the randomness of the GRASP algorithm and makes the first iteration fully deterministic. The results indicate that this does lead to a promising solution. Therefore, the first GRASP iteration is fully deterministic in all following experiments. Experiments on how to select promising solutions are performed in the following section.

5.3.2 Intermediate solution selection

In this section, multiple experiments to select promising intermediate solutions are performed. The intermediate solution selection is dependent on the score of the intermediate solution in all different experiments.

The different experiments to select intermediate solutions can be seen below. Three different instances are used for the experiments. These are the Monday and Tuesday in Kroeven-Tolberg and the Monday in Wouw.

1. No intermediate solution selection. This experiment is included to determine whether or not other intermediate solution selection procedures discard promising solutions.
2. Stage 1 iteration 1 solutions selection. In this experiment, the solution from GRASP stage 1 of the first iteration (with a RCL of one) is used as benchmark to discard or keep solutions. Only solutions with a score similar to, or lower than the first iteration are moved to GRASP stage 2. All GRASP stage 2 solutions are moved to GRASP stage 3.
3. Stage 1 & 2 iteration 1 solutions selection. This experiment is similar to experiment 2. However, in this experiment the same intermediate solution selection procedure is performed after GRASP stage 2, using the solution of GRASP stage 2 of the first iteration as benchmark.
4. 25% selection. In this experiment, all solutions with a score below a given value X are moved to the next stage. X is the smallest score that ensures that at least 25% of the solutions are moved to the next stage.
5. 10 & 50% selection. All solutions with a score below a given value X are moved to the next stage. X is the smallest score that ensures that at least 10% of the solutions are moved from stage 1 to stage 2. Additionally, X is the smallest score that ensures that at least 50% of the solutions are moved from stage 2 to stage 3.
6. 10% selection. All solutions with a score below a given value X are moved to the next stage. X is the smallest score that ensures that at least 10% of the solutions are moved to the next stage.

Experiment 1 is used to determine whether or not the intermediate solution selection procedure in other experiments discard promising solutions. Experiments 2 and 3 use the first iteration as a benchmark to discard solution. This may be a promising approach because the first iteration uses a RCL of one and is therefore fully deterministic. Experiments 4,5 and 6 use the score of all solutions after stage 1 to develop a benchmark. Here, experiment 6 results in the lowest benchmark score. However, this benchmark may be too low which results in discarding too many solutions. Results of the experiments can be seen in Tables 9, 10 and 11.

Experiment	**1**	**2**	**3**	**4**	**5**	**6**
Nr. initial runs	200	200	200	200	200	200
Nr. to stage 2	200	86	86	86	30	30
Nr. to stage 3	200	86	17	47	29	11
Best Cost	1945.81	1945.81	1947.01	1945.81	1945.81	1958.57
Mean Cost	1989.22	1981.78	1970.56	1975.16	1975.22	1975.79
Run time (s)	10801	5053	2860	3772	1785	1213

Table 9: Instance 1: Monday Kroeven-Tolberg intermediate solution selection results. Maximum route length of 4.75 hours and a RCL of six. First iteration uses a RCL of one. Displayed costs are in-route salary costs.

Experiment	**1**	**2**	**3**	**4**	**5**	**6**
Nr. initial runs	200	200	200	200	200	200
Nr. to stage 2	200	1	1	98	28	28
Nr. to stage 3	200	1	1	43	27	6
Best Cost	1934.16	1972.72	1972.72	1934.16	1934.16	1951.76
Mean Cost	1995.91	1972.72	1972.72	1982.01	1985.34	1967.84
Run time (s)	12778	327	332	4086	2023	1043

Table 10: Instance 2: Tuesday Kroeven-Tolberg intermediate solution selection results. Maximum route length of 4.75 hours and a RCL of six. First iteration uses a RCL of one. Displayed costs are in-route salary costs.

Experiment	1	2	3	4	5	6
Nr. initial runs	200	200	200	200	200	200
Nr. to stage 2	200	151	151	84	27	27
Nr. to stage 3	200	151	106	36	27	6
Best Cost	1430.38	1430.38	1430.38	1431.92	1431.92	1432.91
Mean Cost	1487.17	1481.96	1477.66	1470.55	1471.92	1469.07
Run time (s)	4517	3899	3446	1662	912	582

Table 11: Instance 3: Monday Wouw intermediate solution selection results. Maximum route length of 4.75 hours and a RCL of six. First iteration uses a RCL of one. Displayed costs are in-route salary costs.

The results in Tables 9, 10 and 11 show that the GRASP computation time can be reduced substantially without a substantial increase objective value. However, not all intermediate solution selection procedures generate promising results. Experiments 2 and 3 do not lead to promising results in instance 2 and 3. In instance 2, the benchmark score of the first iteration is too low which leads to only one GRASP result with high costs. In instance 3, the benchmark score of the first iteration is not tight enough which results in high computation times. Experiment 6 shows fast computation times but also does not lead to promising solution in instance 1 and 2. In both cases, the intermediate solution selection procedure discards too many promising solutions. The best results are obtained with the settings from experiments 4 and 5. Both are able to substantially reduce the computation time without increasing costs.

Additional experiments are performed to make a selection between the settings of experiment 4 and 5. The goal of these additional experiments is to evaluate both experiment 4 and 5 using a similar computation time. This is achieved by increasing the number GRASP stage 1 iterations in experiment 5. The performance of both settings are compared by using different random seeds in instance 1. The random seeds ensure that different visits from the RCL are selected. The results can be seen in Table 12.

	4 S1	5 S1	4 S2	5 S2	4 S3	5 S3	4 S4	5 S4	4 S5	5 S5
Nr. initial runs	200	400	200	400	200	400	200	400	200	400
Nr. to stage 2	86	55	90	54	99	48	86	56	79	160
Nr. to stage 3	47	53	48	51	46	45	54	54	42	159
Best Cost	1945.81	1945.69	1942.46	1942.46	1948.78	1948.78	1943.06	1954.01	1950.26	1950.26
Mean Cost	1975.16	1973.88	1980.79	1983.04	1981.29	1980.84	1982.47	1982.63	1980.96	1983.94
Run Time (s)	4907	4683	4750	4506	4996	4139	5215	4634	4382	10200

Table 12: Monday Kroeven-Tolberg results. Settings of experiment 4 and 5 using 5 different seeds. Maximum route length of 4.75 hours and a RCL of six. First iteration uses a RCL of one. Displayed costs are in-route salary costs.

The results indicate that the same objective value is obtained in three of the five different experiments (seed 2,3 and 5). Furthermore, experiment 4 leads to a better result using seed 4 and experiment 5 leads to (slightly) better results using seed 1. The results from seed 4 indicate that the intermediate solution selection procedure from experiment 5 is too tight, which results in cutting promising solutions and results in higher costs. Furthermore, the solution selection procedure from experiment 5 leads to a substantially higher computation time when random seed 5 is used. So, the settings used in experiment 4 result in a more robust GRASP approach that reduces computation time but still generates promising solutions. Therefore, the settings used in experiment 4 are used in the final solution approach.

5.4 Restricted candidate list length

The GRASP procedure in this work uses a RCL. Only the best X visits are included in this RCL. The GRASP algorithm randomly selects the next visit from the visits within the RCL. The length of the RCL (X) is a tuning parameter. A low value of X may result in very similar GRASP solutions which are unable to find a global optimum. Furthermore, a high value of X may result in inefficient GRASP solutions because it places worse visits in the RCL. All experiments use the same number of stage 1 solutions. The results from the GRASP algorithm using different RCL lengths can be seen in Table 13. The first iteration always uses a RCL of one and is therefore fully deterministic.

RCL	2	3	4	5	6	8	10
Nr. initial runs	200	200	200	200	200	200	200
Nr. to stage 2	139	112	71	125	86	91	72
Nr. to stage 3	70	62	33	30	47	66	28
Best Cost	1944.21	1944.15	1944.15	1945.83	1945.81	1956.48	1954.01
Mean Cost	1967.23	1968.59	1967.43	1969.96	1975.16	1987.71	1991.89

Table 13: Monday Kroeven-Tolberg restricted candidate list length tuning. A maximum route length of 4.75 hours is used. Displayed costs are in-route salary costs.

Table 13 shows that the best in-route salary cost solutions are obtained with a RCL length of three and four. A RCL length of two also leads to promising in-route salary costs solutions, but finds a slightly worse solution. RCL lengths above four do increase the in-route salary costs. A similar trend is observed with the mean cost. Here, a RCL of two leads to the best result but an RCL of three and four also lead to low mean costs. The mean cost increase when an RCL above four is used. Furthermore, the results indicate that a RCL of four results in less stage 2 and 3 iterations compared to using a RCL of three. This means an RCL of four is expected to have a shorter computation time, because less solutions are investigated in GRASP stage 2 and 3. Therefore, a RCL length of four is selected in the final solution approach because it leads to good results while requiring less stage 2 and 3 GRASP iterations compared to a RCL of three. This experiment finalizes the GRASP parameter tuning.

5.5 Adaptive variable neighborhood search tuning

The focus of this section is to provide more insight in the performance of different settings of the adaptive variable neighborhood search. The AVNS algorithm is used to further improve the solution obtained from the GRASP algorithm. Therefore, the tuning of the AVNS algorithm is performed after the tuning of the GRASP algorithm is finalized. The experiments in this section use different shaking techniques to create a neighboring solution. Finding good neighboring solutions is essential in an AVNS algorithm because this allows the algorithm to find better overall solutions. The local search described in Section 4.5.3 is used to improve the neighboring solution in all experiments. Preliminary results indicate three promising experiments. The different experiments are described below. The outer-route 2-opt operator is used as shaking operator in all experiments.

1. Progressive shaking. The number of shakes are dependent on the number of iterations without improvement. Here, more shakes are performed if no improvement is found after a number of iterations. The shakes are determined randomly. The number of shakes per iteration without improvements can be seen in Table 14.

2. Constant shaking. The number of shakes stays constant during this experiment. Six shakes are performed in each iteration during the shaking procedure. The shakes are determined randomly.

3. Adaptive progressive shaking. The number of shakes are dependent on the number of iterations without improvement. Here, more shakes are performed if no improvement is found after many iterations. The shakes are partially determined by a cost difference with the lower bound as described in Section 4.6.2. The number of shakes per iteration without improvements can be seen in Table 14.

Nr. iterations without improvement	≥0	≥25	≥50	≥100	≥150
Nr. shakes	1	2	4	6	8

Table 14: Number of shakes per AVNS iteration without improvement.

Ten different random seeds are used to determine the performance of each experimental setting. Furthermore, three different instances are used to investigate the behavior of the algorithm in different situations. The instances are selected because of the different number of visits per instance. Instance 1 is the Monday in Kroeven-Tolberg (213 visits), Instance 2 is the Monday in Wouw (150 visits) and instance 3 is the Monday in Heilig Hart (362 visits). In all cases, the best solution from GRASP solution with 200 GRASP stage 1 solutions is used as starting point of the (adaptive) variable neighborhood search algorithm. Each experiment has a computation time of 15 minutes. The results can be seen in Table 15. Individual experimental results can be seen in Appendix C.

instance	Experiment	Average	Minimum	Maximum
1	Progressive shaking	1938.15	1934.90	1942.51
1	Constant shaking	**1937.68**	**1933.95**	**1940.69**
1	Adaptive progressive shaking	1939.32	1936.56	1941.55
2	Progressive shaking	1415.60	1412.69	1419.71
2	Constant shaking	1414.31	**1408.16**	1421.30
2	Adaptive progressive shaking	**1413.62**	1410.18	**1418.86**
3	Progressive shaking	3098.79	3094.96	3104.80
3	Constant shaking	3099.15	3095.98	3104.35
3	Adaptive progressive shaking	**3098.26**	**3094.62**	**3104.22**

Table 15: (Adaptive) variable neighborhood search tuning results. Instance 1,2,3 are Monday Kroeven-Tolberg, Monday Wouw, Monday Heilig Hart. Maximum route length is 4.75 hours. Displayed costs are in-route salary costs.

The results in Table 15 show that the adaptive progressive shaking procedure generates the best average result in both the cluster Wouw and Heilig Hart. However, the constant shaking approach results in the best average in Kroeven-Tolberg. Furthermore, the constant shaking approach finds the best solution in cluster Wouw. The results indicate that there are no major differences between the three different experimental settings. So, the adaptive progressive shaking (experiment 3) is selected as shaking procedure in the final solution approach because it generates the lowest average in two of the three instances. This finalizes the AVNS algorithm tuning. The next step is to investigate how much computation time should be allocated to the GRASP and AVNS algorithm in the final solution approach.

5.6 Computation time allocation

In this section, the allocation of computation time between the GRASP and AVNS algorithm is studied. The allocation of computation time is studied to optimize the performance of the combined GRASP-AVNS algorithm. A total computation time of two hours is selected. However, setting an exact GRASP computation time is impossible because of the intermediate solution selection. Therefore, the experiment that only uses the GRASP algorithm is allowed to overshoot the two hour computation time limit. Three different instances are investigated during this analysis. These are the Monday in Kroeven-Tolberg (213 visits), the Monday in Wouw (150 visits) and the Monday in Heilig Hart (362 visits). The computation time of GRASP algorithm is set by the goal value introduced in Equations 5-7. The different goal values of minutes spend in the GRASP algorithm are shown below.

- Goal value 0. In this experiment, the time spend in the GRASP algorithm is minimized and only 1 GRASP iteration is performed. This means the maximum computation time is spend on the AVNS algorithm.
- Goal value 15. In this experiment, the goal is to spend around 15 minutes in the GRASP algorithm. The remaining time is spend in the AVNS algorithm.
- Goal value 30. In this experiment, the goal is to spend around 30 minutes in the GRASP algorithm. The remaining time is spend in the AVNS algorithm.
- Goal value 60. In this experiment, the goal is to spend around 60 minutes in the GRASP algorithm. The remaining time is spend in the AVNS algorithm.
- Goal value 125. In this experiment, the goal is to spend all computation time in the GRASP algorithm. No computation time is spend on the AVNS algorithm.

The results of the experiments can be seen in Figure 7,8 and 9.

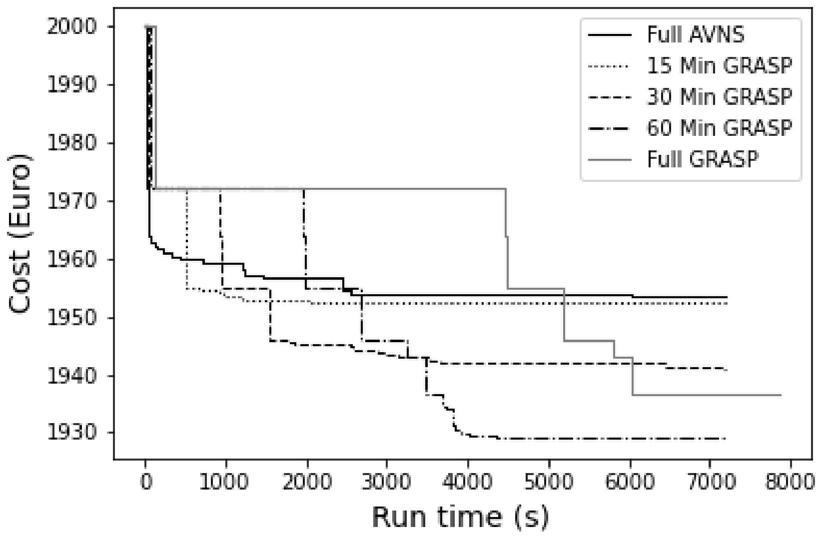

Figure 7: Best found objective value versus computation time on Monday in Kroeven-Tolberg. Costs are in-route salary costs. Maximum route length is 4.75 hours and a RCL of four is used. First iteration uses a RCL of one.

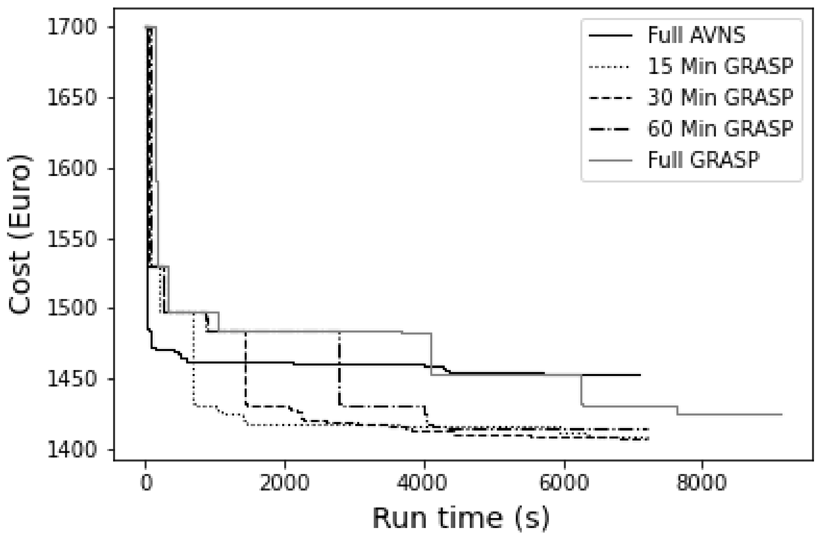

Figure 8: Best found objective value versus computation time on Monday in Wouw. Costs are in-route salary costs. Maximum route length is 4.75 hours and and a RCL of four is used. First iteration uses a RCL of one.

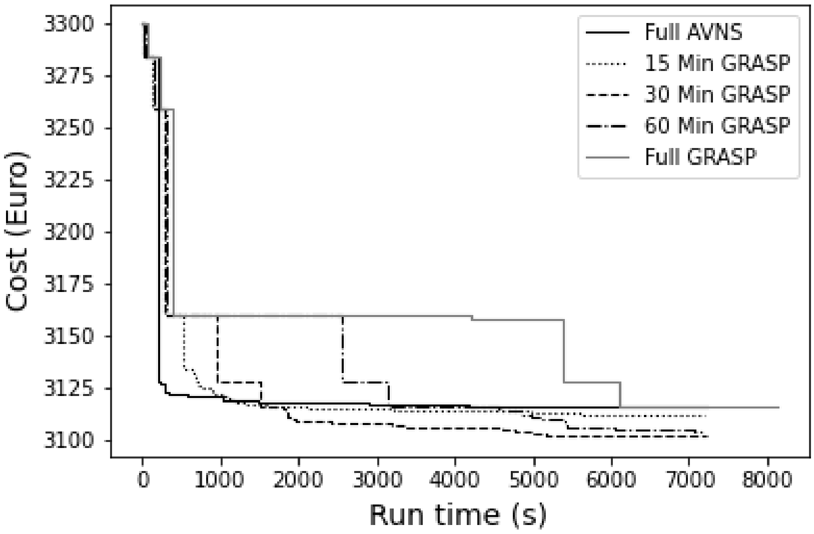

Figure 9: Best found objective value versus computation time on Monday in Heilig Hart. Costs are in-route salary costs. Maximum route length is 4.75 hours and a RCL of four is used. First iteration uses a RCL of one.

Figures 7, 8 and 9 show similar results. In all cases, allocating the maximum amount of computation time to the AVNS algorithm does not lead to promising results. Furthermore, the Full GRASP solution does not result in the best obtained solution either. Therefore, a combination of both the GRASP and AVNS algorithm is the most promising. The 30 and 60 minutes of computation time spend in the GRASP algorithm seem to be the two most promising experimental settings. 30 minutes of computation time of GRASP works better in both Wouw and Heilig Hart whereas 60 minutes of computation time of GRASP works better in Kroeven-Tolberg. The in-route cost difference between the two experimental settings are small in both Wouw and Heilig Hart, but a substantial difference occurs in Kroeven-Tolberg. This means the 60 minutes of GRASP results in the best overall performance in these three different instances. Therefore, the goal is to spend 60 minutes of computation time in the GRASP algorithm in the final solution approach.

5.7 Route length tuning

The next tuning parameter that is considered in the tuning of the solution approach, is the maximum route length in the routing problem. The tuning of the maximum route length is the final tuning parameter in the GRASP-AVNS algorithm. The selected maximum route length influences the shift length of a nurse. The shift length is crucial when combining multiple shifts via a break or into a double/broken shift. A nurse is only allowed to work ten hours on a single day. The time a nurse travels back to, and from their home in a double/broken shift counts as working time as well. All nurses have a travel time to the first client of 7.5 minutes. So, two routes can always be combined into a double/broken shift if a maximum route length of 4.875 hours is used. A longer route length may lead to two different situations. Situation 1: Increasing the route length means more visits are placed in the routes which results in a lower number of routes and therefore requires less nurses. Situation 2: Increasing the route length means fewer routes can be combined via a break or into double/broken shifts and therefore requiring more nurses. Three different instances are considered in these experiments. These are the Monday in Kroeven-Tolberg, Wouw and Heilig Hart. The maximum route length is changed with 15 minutes in each experiment and only quarters of an hour are used as maximum route length. The results from the maximum route length experiments can be seen in Table 16.

	Cost	Nr. 3-IG	Nr. 3	Nr. 2	Nr. ADL	Total Nr. nurses
Kroeven Tolberg, 4,75 hours	1929.03	4	3	2	5	14
Kroeven Tolberg, 5 hours	1928.36	4	3	3	4	14
Kroeven Tolberg, 5.25 hours	1939.36	4	3	3	4	14
Kroeven Tolberg, 5.5 hours	1945.77	4	2	4	5	15
Wouw, 4,75 hours	1411.41	5	2	2	3	12
Wouw, 5 hours	1406.90	3	3	1	3	10
Wouw, 5.25 hours	1407.21	3	3	1	3	10
Wouw, 5.5 hours	1406.94	3	2	2	3	10
Heilig Hart, 4,75 hours	3104.02	6	5	4	6	21
Heilig Hart, 5 hours	3098.89	6	6	4	6	22
Heilig Hart, 5.25 hours	3109.35	5	7	5	6	23
Heilig Hart, 5.5 hours	3101.37	6	6	4	7	23

Table 16: Maximum route length results in three different instances. The number of nurses indicate the required nurses with that skill level to work the shifts. Displayed costs are in-route salary costs.

The results in Table 16 show that a different maximum route length has an influence on the characteristics of the created solution but without a clear trend. Therefore, it is expected that all maximum route duration settings lead to high quality solutions. But based on these results, a maximum route length of five hours is selected. The maximum route length of five hours is selected because it leads to the lowest in-route salary costs in all three instances. Furthermore, the maximum route length of five hours also leads to the lowest number of required nurses when the combination of all three instances is considered (14+10+22). This finalizes the tuning of the GRASP-AVNS algorithm.

5.8 Nurse scheduling procedure

The final parameter of the solution approach that is tuned, is how nurses are scheduled. Here, different techniques to assign nurses to shifts are investigated. The assignment of nurses to shifts has an influence on cost but also influences the continuity of care (Section 2.5.3). The continuity of care is an indicator of the number of different nurses visiting a client and is an important client satisfaction indicator. Furthermore, different assignment techniques can also result in different amounts of overtime. Three different experiments are conducted. In all experiments, the selected nurse is still the best nurse as described in Section 4.7.2. Routes are already turned into (double/broken) shifts before conducting these experiments. The three experiments are described below.

- Experiment 1: Cost minimization. In this experiment, the nurses are assigned to shifts in order to minimize cost using a greedy approach.
- Experiment 2: Continuity of care maximization. In this experiment, nurses are assigned to shifts in order to maximize the continuity of care using a greedy approach.
- Experiment 3: Random assignment. In this experiment, nurses are randomly assigned to shifts. Here, the next nurse that is scheduled is still the best nurse as described in Section 4.7.2. However, the best nurse is assigned to a random feasible shift instead of the best shift. This ensures that the obtained solution is still feasible.

Ten different random seeds are used to determine the performance of the random assignment experiment. The full week of Kroeven-Tolberg is the selected instance in all experiments. The results of the experiments can be seen in Table 17. Only the minimum, average and maximum results of the random assignment procedure are shown.

Experiment	1	2	3		
			Minimum	Average	Maximum
Total cost (Euro)	15954.52	15976.83	15972.67	16008.35	16049.79
Continuity of care	0.413	0.425	0.371	0.380	0.395
Overtime (Hour)	0	0	0	0	0

Table 17: Performance of different nurse assignment techniques. Only minimum, average and maximum are shown in case of the random assignment. A full week in cluster Kroeven-Tolberg is used as instance in all experiments.

Table 17 shows that the different assignment techniques have an influence on the total cost and continuity of care. No overtime is required in all performed experiments. The results indicate that both the minimum cost and the maximum continuity of care approach outperform the random assignment method. The random assignment method results in a lower quality of care in all ten iterations and generates a solution that results in higher total costs on average. The difference between the cost minimization and the continuity of care maximization approach is limited. The cost minimization approach leads to lower total cost but slightly increases the continuity of care. In this work, the costs are the primary performance indicator. Therefore, the cost minimization approach is used as scheduling approach in the final solution approach. This finalizes the tuning of the solution approach.

5.9 Validation

In this section, the validation of the proposed solution approach is discussed. It is important to validate the created solutions to ensure that results obtained in subsequent experiments are valid and of high quality. The focus of this validation is on the feasibility & performance of the routes created by solving the routing problem (GRASP-AVNS algorithm). In all cases, only the routing solution investigated. The cost of a route is determined by assuming that the route is performed by a nurse with the lowest, sufficient nurse skill (It is assumed an ADL route will be performed by an ADL nurse). All routing solutions do not violate any of the constraints described in Section 4.1. The created routes can be validated in the following three ways.

1. Employee review: The routes obtained by solving the routing problem are reviewed by the planner and a level 5 district nurse to indicate whether or not the created routes are valid.
2. In-route working time lower bound: The duration of all routes cannot be shorter than the duration of all visits plus the minimum travelling time between all visits. If the created routes are shorter than this lower bound then the created routes cannot be valid. However, a solution that has a working time that is very close to this lower bound is a high quality solution.
3. In-route salary cost lower bound: The in-route salary cost of all routes cannot be lower than the lower bound of the in-route salary costs. The lower bound of the in-route salary costs is introduced in Section 4.4. If the created routes have a lower in-route salary cost than this lower bound then the created routes cannot be valid. However, a solution that has an in-route salary cost that is very close to this lower bound is a high quality solution.

5.9.1 Employee review

The routes created on the Monday in Kroeven-Tolberg have been reviewed by the planner and a senior district nurse of cluster Kroeven-Tolberg. Both employees indicated that the routes were feasible, but that they do have undesirable characteristics. These undesirable characteristic are the result of the (lack of) data stored in TWB's database. Two main examples of lack of data are discussed.

- The first example is that each separate registration is stored in the database instead of each visit. This is a problem because a single visit in practice can have more than one registration, resulting in multiple visits in the final data set. This means that a single visit with multiple registrations could actually be performed by two different nurses when the routes are created by the routing algorithm. Avoiding these mistakes is difficult because the database does not show whether or not two subsequent visits to the same client are actually a single visit with multiple registrations or two separate visits that could be performed by two separate nurses.
- The second example is that the database does not indicate whether or not two different clients live together. If two clients do live together (for instance, husband and wife) then it is inconvenient that both are helped

by a different nurse if the time windows of both visits are similar. It is expected that this characteristic substantially reduces the overall client satisfaction. However, at this point in time this cannot be avoided because this information is not available in TWB's database.

5.9.2 In-route working time

The validation based on the in-route working time is straightforward. The in-route working time of a solution is obtained by subtracting the travel time between a nurse's home location and a client from the actual working time. The lower bound of the in-route working time is calculated in two steps. First, the service times of all visits are added together to end up with a total service time. Then, the minimum travel time between visits are added based on the minimum travel time used in the Euclidean distance method. During this analysis, all seven days of the week are combined to give a better overall view. The results of the four clusters are displayed separately. Results are displayed in Table 18.

Cluster	**Kroeven-Tolberg**	**Wouw**	**Centrum-Westrand**	**Heilig Hart**
LB working time (H)	578.83	382.78	698.08	911.85
Actual working time (H)	581.92	402.39	698.85	917.45
Above LB (%)	0.53	5.12	0.11	0.61
Diff LB (H)	0.21	2.22	0.01	0.49

Table 18: Comparison of actual in-route working time with the lower bound of the in-route working time. The table displays the combined result of seven different days from each cluster. LB = lower bound. H = hour. Diff LB = smallest deviation from LB on a single day.

Table 18 shows that the obtained solutions do not violate the lower bound in-route working time duration. Furthermore, the results in cluster Kroeven-Tolberg, Centrum-Westrand and Heilig Hart show that the actual in-route working time is very close to the lower bound of the in-route working time. A larger deviation occurs in cluster Wouw. However, this is expected because Wouw is best described as a rural cluster whereas the other three clusters are best described as urban clusters. In a rural cluster, the driving distances between visits are larger. This means less visits can be reached within the minimum travel time used by the Euclidean distance method, which results in a larger deviation from the lower bound. The results indicate that the routing algorithm creates routes that are close to the in-route working time lower bound and therefore creates efficient routes.

5.9.3 In-route salary costs

The validation of the in-route salary cost is an extension of the in-route working time analysis. The lower bound in-route salary cost uses the lower bound in-route working time as starting point and further assumes that each visit is performed at the cheapest moment and by the cheapest possible nurse (100% skill linking). More information on the lower bound of the in-route salary cost can be seen in Section 4.4. The results of the in-route salary cost analysis can be seen in Table 19.

Cluster	**Kroeven-Tolberg**	**Wouw**	**Centrum-Westrand**	**Heilig Hart**
LB in-route salary (Euro)	14026.95	9609.07	17188.35	22619.18
Actual in-route salary (Euro)	14354.84	10512.45	17423.64	23106.45
Above LB (%)	2.32	9.40	1.37	2.15
Diff LB (Euro)	25.68	118.24	14.55	48.34

Table 19: Comparison of actual in-route salary cost with the lower bound of the in-route salary cost. The table displays the combined result of seven different days from each cluster. LB = lower bound. Diff LB = smallest deviation from LB on a single day.

The results in Table 19 are in line with the results discussed in the previous section. None of the routing solutions created by the GRASP-AVNS algorithm result in a lower in-route salary cost than the lower bound. So, this indicates that the obtained routing solutions do not have an in-route salary cost that cannot be achieved, which indicates that they are feasible routing solutions. Furthermore, the in-route salary costs in cluster Kroeven-Tolberg, Centrum Westrand and Heilig Hart are within 3% of the lower bound which indicates that the GRASP-AVNS algorithm generates high quality solutions. The smallest deviation from the lower bound (14.55) is obtained on the Tuesday in Centrum-Westrand. 264 visits need to be scheduled at that day.

A cost difference of 14.55 Euro is tiny. Because, a cost difference of 14.63 Euro is obtained if a 3-IG nurse works 1.5 hours of ADL visits in total, and all other visits are performed in the cheapest possible fashion. So, a cost difference of 14.55 away from the lower bound is a very good indication that the GRASP-AVNS algorithm produces high quality solutions. A larger deviation from the lower bound is observed in cluster Wouw. This is expected because Wouw is a rural cluster. Which means the travel time between visits is more likely to be longer than the minimum travel time and therefore results in a larger deviation from the lower bound. This does not necessarily mean that the algorithm performs worse in rural instances. This just means that the used lower bound is less applicable for rural areas. Overall it can be concluded that the algorithm produces high quality routes.

5.10 Conclusion

In this chapter, we answer the fourth research question *How can the solution approach generate feasible and high quality solutions?*. We start with tuning multiple parameters of the solution approach. First, the different steps of the GRASP approach are tuned to ensure that the GRASP algorithm produces feasible, high quality solutions. Different settings of the AVNS algorithm are tested to further improve the performance of the solution. We tune the maximum route length to minimize the total number of nurses on a single day. Multiple techniques to assign nurses to shifts are investigated, which finalizes the tuning of the solution approach. The chapter ends with validating the routes created by the proposed solution approach. The results indicate that the GRASP-AVNS algorithm is able to generate high quality solutions that are close to the lower bounds of the in-route working time and in-route salary costs. In the next chapter, we compare the performance of the algorithmic solution with the solution created by the planners of TWB. Furthermore, we perform additional numerical experiments that are valuable for TWB.

6 Numerical experiments

In this chapter, we answer the fifth research question: *What is the influence of different instances on the performance of the planning and scheduling approach?*. This chapter starts by solving the instances of the four clusters using the proposed solution approach in Section 6.1. The results from Section 6.1 function as benchmark in all following experiments. The effect of combining the four cluster in the region of Roosendaal is covered in Section 6.2. An experiment where the skill levels of nurses are changed, is performed in Section 6.3. The effect of reducing the number of late visits (after 22:00) is discussed in Section 6.4. Finally, we conclude this chapter in Section 6.5.

6.1 Individual clusters

In this section, the instances belonging to the four clusters are solved using the proposed solution approach from Chapter 4. The obtained solutions are compared with the original solutions created by the planners of TWB (from Chapter 2). This comparison is divided into three different parts. First, the solutions are compared based on solution characteristics (for instance number of breaks). The solutions are compared based on their utilization of nurses in Section 6.1.2. Finally, the solutions are compared based on their performance in Section 6.1.3. The results are shown in a single table in Appendix D.

6.1.1 Characteristics comparison

The characteristics of the created solutions are compared with the original solutions created by the planners of TWB in this section. The characteristics of the original and the algorithmic solutions are displayed in Table 20.

Cluster	**K-T (O)**	**K-T (A)**	**Wouw (O)**	**Wouw (A)**
Nr. routes	133	134	89	103
Nr. breaks	5	2	10	4
Nr. double/broken shifts	25	32	14	28
Nr. shifts	103	100	65	71
Hours worked after 22:00	12.37	5.64	7	8.34
Nr. illegitimate assignments	31	0	19	0
Nr. time window violations	247	0	176	0
Cluster	**C-W (O)**	**C-W (A)**	**HH (O)**	**HH (A)**
Nr. routes	175	163	209	207
Nr. breaks	63	3	15	8
Nr. double/broken shifts	33	47	41	50
Nr. Shifts	110	113	153	149
Hours worked after 22:00	7.96	4.57	20.48	12.93
Nr. illegitimate assignments	88	0	22	0
Nr. time window violations	379	0	399	0

Table 20: Comparison between the current routing and scheduling process of a week in all clusters and the algorithm planning and scheduling process based on the characteristics of the solution. K-T = Kroeven-Tolberg, C-W = Centrum-Westrand, HH = Heilig Hart. O = the result from the original planning and scheduling approach. A = the result created by the proposed algorithm.

Table 20 shows that there are similarities and differences between the solution created by the planner of TWB and the algorithm. The first observation is that the number of routes and shifts in both approaches are similar. However, there is a difference how these routes are turned into shifts. The original planning and scheduling approach results into substantially more breaks than the results from the algorithm. Consequently, the solutions from the algorithm result into a larger number of double/broken shifts. The largest difference in number of breaks occurs in Centrum-Westrand because that cluster uses 15 minute breaks and then has two 15 minute breaks within a single shift, which results into a huge number of breaks. The difference in combining routes is a result from the different start times of a route. Breaks are primarily used to connect morning and early (around 12:30) afternoon shifts in the original planning and scheduling approach. However, the results from the algorithm do not have fixed early afternoon shifts. The algorithm mostly creates early afternoon shifts that already start at the end of the morning. This means that the early afternoon shifts overlap with morning shifts and therefore cannot be connected via a break to a morning shift. The algorithm primarily places breaks between early afternoon shifts and late afternoon shifts (around 15:00). The different start time of the early afternoon shift results into fewer breaks in the solutions obtained from the algorithm.

A different characteristic is the number of hours worked after 22:00. The algorithm is able to reduce this working time after 22:00 in all clusters aside from Wouw. It is expected that the algorithm reduces the working time after 22:00 because nurses receive additional income after 22:00 on all days aside from Sundays. So, the results in Wouw are unexpected. The results in cluster Wouw can be explained because Wouw is the cluster with the lowest number of evening visits. So, it is expected that it is more cost effective to have more working time after 22:00 instead of having one additional evening route that results in waiting time because there are not enough visits. The final characteristics are the number of illegitimate assignments and time window violations. An illegitimate assignment is an assignment of a nurse to a visit that is above the nurse's skill level. The solution created by the algorithm does not contain any of these assignments, whereas the original planning and scheduling approach does. Furthermore, the original results do violate a substantial number of time windows (around 22% in each cluster) whereas the solution created by the algorithm does not violate any time windows. Though, it has to be noted that a substantial amount of the time windows (30-50%) had to be estimated.

So, the results in this section indicate that there are substantial differences between the routes created in the original planning and scheduling approach and the routes created by the GRASP-AVNS algorithm. The routes created by the algorithm result into more double/broken shifts, which would reduce the employee satisfaction level. However, The algorithm also reduces the working time after 22:00 in most situations which would increase the employee satisfaction level. So, the effect of the different characteristics of both solution approaches on the employee satisfaction level is inconclusive. Finally, the results indicate that the algorithm does not violate any of the time window constraints whereas the original planning and scheduling approach does.

6.1.2 Nurse utilization comparison

In this section, the nurse utilization of the originally created solutions is compared with the nurse utilization of the results created by the algorithm. The results are displayed in Table 21.

Cluster	K-T (O)	K-T (A)	Wouw (O)	Wouw (A)
Nr. nurses	31	31	22	22
Nr. of level 3-IG nurses	8	8	12	12
Nr. level 3 nurses	10	10	6	6
Nr. level 2 nurses	12	12	2	2
Nr. level ADL nurses	1	1	2	2
Total working hours available	669.31	669.31	438.84	438.84
Total working time (hour)	587.96	589.92	416.20	409.39
Total in-route working time (hour)	581.85	581.92	405.05	402.39
Total overtime hours	56.63	0	40.17	0
Hours 3-IG in-route working time	157.49	141.41	213.62	204.61
Hours level 3 in-route working time	185.02	217.06	123.94	144.74
Hours level 2 in-route working time	221.79	206.53	32.59	21.24
Hours ADL in-route working time	17.55	16.92	34.91	31.80
Cluster	**C-W (O)**	**C-W (A)**	**HH (O)**	**HH (A)**
Nr. of nurses	44	40	44	44
Nr. of level 3-IG nurses	12	8	15	15
Nr. level 3 nurses	14	14	13	13
Nr. level 2 nurses	11	11	13	13
Nr. level ADL nurses	7	7	3	3
Total working hours available	855.72	855.72	927.00	927.00
Total working time (hour)	717.50	710.60	937.81	929.95
Total in-route working time (hour)	701.09	698.85	917.37	917.45
Total overtime hours	53.33	0	119.40	25.19
Hours 3-IG in-route working time	208.24	162.72	319.67	322.52
Hours level 3 in-route working time	217.29	268.12	297.84	276.82
Hours level 2 in-route working time	172.95	168.93	248.55	256.80
Hours ADL in-route working time	101.83	99.08	51.29	61.30

Table 21: Comparison of nurse utilization between the current routing and scheduling process of a week in all clusters and the algorithm planning and scheduling process. K-T = Kroeven-Tolberg, C-W = Centrum-Westrand, HH = Heilig Hart. O = the result from the original planning and scheduling approach. A = the result created by the proposed algorithm. Algorithm uses a fixed travel time of 7.5 minutes between clients and nurse home locations.

Table 21 shows that there are similarities and differences between the original and algorithm planning and scheduling approach. The main similarity are number of required nurses. The algorithm requires the same number of nurses in all clusters, aside from Centrum-Westrand. In cluster Centrum-Westrand, four fewer 3-IG nurses are required to work all shifts. Differences occur when the total working time is investigated. The algorithm is able to substantially reduce the total working time in three of the four clusters (only a small increase in Kroeven-Tolberg is observed). However, it has to be noted that the algorithm uses a fixed travel time of 7.5 minutes between clients and nurse home locations whereas the original planning and scheduling approach uses the actual travel time between clients and nurse home locations. So, the in-route working time is a better indicator of the actual working time. The results show that the algorithm does create more efficient routes since it substantially reduces the in-route working time in cluster Centrum-Westrand and Wouw whereas similar working times are observed in Kroeven-Tolberg and Heilig Hart. The largest difference is observed in the total amount of required overtime. The overtime is reduced in all four clusters and overtime is only required in Heilig Hart. Heilig Hart always requires overtime because the available working hours are actually lower than the total working hours.

The results indicate that the algorithm aims to reduce the in-route working time of high level nurses. This is most apparent in cluster Centrum-Westrand where four fewer 3-IG nurses are required. However, this is also observed in the other clusters that have an excess of working time available (Kroeven-Tolberg and Wouw). In all of these clusters, the working time of 3-IG nurses is reduced substantially. This is not observed in Heilig Hart because Heilig Hart requires the entire workforce and can therefore not reduce the working hours of high level nurses. So, the nurse scheduling results indicate that the overtime can be reduced substantially and that the 3-IG working time can be reduced as long as there is enough total working capacity within that cluster.

Both of these results also show that the algorithm outperforms the current routing and scheduling approach with respect to nurse usage.

6.1.3 Performance comparison

In this section, the performance of the routes created by the algorithm are compared with the routes created by the planners of TWB. Furthermore, the performance of the final algorithmic solution is compared with the routing in-route salary costs (in-route salary costs before assigning nurses) and the lower bound in-route salary cost by defining a cost saving potential. The results of this performance analysis can be seen in Table 22.

Cluster	**K-T (O)**	**K-T (A)**	**Wouw (O)**	**Wouw (A)**
Total costs (Euro)	16074.90	15954.52	12214.83	11887.45
Total salary costs (Euro)	15730.71	15585.88	11623.74	11468.13
Total in-route salary costs (Euro)	15584.53	15374.51	11470.36	11276.01
Routing in-route salary costs (Euro)	-	14354.84	-	10512.45
Lower bound in-route salary costs (Euro)	-	14026.95	-	9609.07
Total kilometer compensation (Euro)	344.19	368.64	591.08	419.32
Total in-route driven distance (km)	683.24	753.37	1141.38	1079.34
Percentage skill linking	49.3	57.2	47.7	48.0
Continuity of care	0.524	0.416	0.454	0.446
Cluster	**C-W (O)**	**C-W (A)**	**HH (O)**	**HH (A)**
Total costs (Euro)	19124.07	18889.98	26398.60	25543.05
Total salary costs (Euro)	18482.41	18462.72	25555.61	24924.70
Total in-route salary costs (Euro)	18383.73	18150.62	24953.79	24590.66
Routing in-route salary costs (Euro)	-	17423.64	-	23106.45
Lower bound in-route salary costs (Euro)	-	17188.35	-	22619.18
Total kilometer compensation (Euro)	541.67	427.26	842.99	618.35
Total in-route driven distance (km)	652.14	785.71	1199.72	1358.97
Percentage skill linking	63.8	71.2	55.0	60.0
Continuity of care	0.533	0.407	0.497	0.359

Table 22: Performance comparison between the current routing and scheduling process of a week in all clusters and the algorithm planning and scheduling process. K-T = Kroeven-Tolberg, C-W = Centrum-Westrand, HH = Heilig Hart. O = the result from the original planning and scheduling approach. A = the result created by the proposed algorithm. Algorithm uses a fixed travel time of 7.5 minutes between clients and nurse home locations.

Comparison with original routes

The results of the comparison with the original routes show a clear trend, the solutions created by the algorithm outperform the solutions created by the planners of TWB in all clusters with respect to costs. It has to be noted that the algorithm uses a fixed travel time of 7.5 minutes between clients and nurse home locations whereas the original planning and scheduling approach uses the actual travel time between clients and nurse home locations. Therefore, the in-route salary costs are the most reliable performance indicator when comparing algorithmic results to the original solutions. The results indicate a combined in-route salary cost reduction of 1000.61 Euro of the four clusters. The total in-route salary cost of the original solution of the four clusters is 70392.41 Euro. So, the results indicate an expected cost reduction of 1.42%. Furthermore, the results from the individual clusters allow for the creation of a 95% confidence interval of the in-route route salary cost reduction. The results show an average in-route salary cost reduction of 250.15 $\pm$ 61.25 Euro per cluster per week.

The results also show that the percentage skill linking is increased in all four cluster. This is expected to increase the nurse satisfaction level because more nurses perform visits at their own skill level. The opposite trend is visible with respect to the continuity of care. The continuity of care decreases in all four clusters which would reduce the client satisfaction level. This decrease in continuity of care occurs because the proposed algorithm does not aim to maximize this performance indicator. However, Braekers et al. [7] indicated that a drastic increase in the service level of clients can be obtained by only a slight increase in total cost. So, this decrease in continuity of care is a result from the selected algorithm and can be reduced by adapting the algorithm.

Cost saving potential

In this section, the focus is on the cost saving potential. The cost saving potential is defined as the cost difference between the total in-route salary costs of the original solution and the lower bound in-route salary costs. This cost saving potential consists of three separate terms that are discussed below.

1. Potential of implementing a routing and scheduling algorithm. The potential cost saving of a routing and scheduling algorithm is the difference between the total in-route salary costs of the original solution and the solution created by the algorithm.
2. Potential of improved workforce scheduling. The routing in-route salary costs assume that the perfect workforce is available. So, the cost saving potential by optimizing both the workforce and workforce scheduling approach is the difference between the algorithmic in-route salary costs and the routing in-route salary costs.
3. Potential of a better routing algorithm. The final cost saving potential is the cost difference between the routing in-route salary costs and the lower bound in-route salary costs. This cost difference indicates how much money can be saved by improving the routing algorithm. However, it has to be noted that no valid solution can have a total in-route salary cost below this lower bound. Furthermore, it is very likely that the actual minimum in-route salary cost is above the lower bound of the in-route salary cost. So, it is unlikely that this potential can be fully utilized.

The cost saving potentials of each cluster can be seen in Table 23. The table shows the cost saving potential of each potential in Euros and as percentages of the total cost saving potential.

Cluster	**K-T**	**Wouw**	**C-W**	**HH**
Term 1 (Euro)	210.02	194.35	233.11	363.13
Term 2 (Euro)	1019.67	763.56	726.98	1484.21
Term 3 (Euro)	327.89	903.38	235.29	487.27
Term 1 percentage	13.5	10.4	19.5	15.6
Term 2 percentage	65.5	41.0	60.8	63.6
Term 3 percentage	21.1	48.5	19.7	20.9

Table 23: Comparison of the separate cost saving potential terms. K-T = Kroeven-Tolberg, C-W = Centrum-Westrand, HH = Heilig Hart. Percentages do not always sum up to 100% because of rounding errors.

The results in Table 23 show a clear trend. In all clusters, the cost reduction achieved by the current planning and scheduling algorithm is not the major cost reduction potential. Improving the workforce and the workforce scheduling procedure (term 2) is expected to lead to the largest cost reduction in all clusters aside from cluster Wouw. The potential of an improved routing algorithm (term 3) is the largest in rural cluster Wouw. However, as previously mentioned, the lower bound is less applicable in rural clusters. So, this potential cannot be fully utilized. Therefore, it can be concluded that improving the workforce and workforce scheduling is expected to result in the largest cost reduction. Two experiments to improve the workforce scheduling and the composition of the workforce are performed. Experiments where all clusters are combined are performed in Section 6.2 to see if combining the clusters results into better routes and allows for a better workforce scheduling. In Section 6.3, experiments are performed to gain more insight in what the optimal workforce would be for TWB.

6.2 Combination of clusters

The goal of this section is to determine whether or not the performance of the routing and scheduling approach is improved by combining the four clusters. Three different experiments are performed. These are discussed below.

- Experiment 1: Full combination. In this experiment, the data of all four clusters is combined and a new routing & scheduling solution is created.

- Experiment 2: Nurse combination. In this experiment, the routes created by solving the individual clusters (Section 6.1) are maintained but the scheduling of nurses in all clusters is combined. Only a new scheduling solution is created in this experiment.
- Experiment 3: Nurse combination version 2. In this experiment, the routes created by solving the individual clusters (Section 6.1) are maintained but the scheduling of nurses in all clusters is combined. Only a new scheduling solution is created in this experiment. Individual nurses are allowed to work the same amount of overtime as in the original algorithmic solution from Section 6.1.

The results from the three experiments and the solution obtained by solving the clusters separately can be seen in Table 24. Experiment three is included because the results from Section 6.1.2 indicate that overtime in the algorithmic solution occurs in cluster Heilig Hart. Therefore, experiment three is performed where the nurses of cluster Heilig Hart are allowed to work the same overtime as in the algorithmic solution of the individual cluster to specifically focus on the costs and not on reducing overtime.

	A	**1**	**2**	**3**
Nr. routes	607	574	607	607
Nr. breaks	17	19	19	19
Nr. double/broken shifts	157	157	174	174
Nr. shifts	433	398	414	414
Hours worked after 22:00	31.48	37.90	31.48	31.48
Nr. illegitimate assignments	0	0	0	0
Nr. time window violations	0	0	0	0
Nr. of nurses	134	133	138	135
Nr. of level 3-IG nurses	41	40	45	42
Nr. level 3 nurses	44	44	44	44
Nr. level 2 nurses	36	36	36	36
Nr. level ADL nurses	13	13	13	13
Total working hours available	2890.86	2890.86	2890.86	2890.86
Total working time (hour)	2639.86	2668.81	2644.27	2644.27
Total in-route working time (hour)	2600.61	2629.56	2600.61	2600.61
Total overtime hours	25.19	0	0	31.54
Hours 3-IG in-route working time	831.26	857.81	837.98	805.16
Hours level 3 in-route working time	906.74	909.53	909.17	919.55
Hours level 2 in-route working time	653.50	653.56	647.33	669 78
Hours ADL in-route working time	209.10	208.66	206.29	206.29
Total costs (Euro)	72275.00	73376.58	72402.34	72225.15
Total salary costs (Euro)	70441.43	71237.67	70550.24	70373.06
Total in-route salary costs (Euro)	69391.80	70232.35	69388.89	69224.24
Routing in-route salary costs (Euro)	65397.38	65694.95	65397.38	65397.38
Lower bound in-route salary costs (Euro)	63443.55	63475.73	63443.55	63443.55
Total kilometer compensation (Euro)	1833.57	2138.90	1852.09	1852.09
Total in-route driven distance (km)	3977.39	5250.42	3977.39	3977.39
Percentage skill linking	60.5	64.7	61.2	62.0
Continuity of care	0.397	0.224	0.237	0.247

Table 24: Results of the planning and scheduling problem in Roosendaal. A = the solution created by the algorithm by solving the four clusters individually. 1 = The results from the full combination of the four clusters. 2 = The results of only combining the nurse scheduling procedure of the four clusters. 3 = The results of only combining the nurse scheduling procedure of the four clusters, but allowing the same amount of overtime for specific nurses as in the algorithmic solution of the individual clusters.

6.2.1 Experiment 1: full combination

The results from fully combining the four clusters show mixed results. The results indicate that fewer routes are necessary which also results in fewer shifts that need to be worked by nurses. Furthermore, the results indicate that fewer 3-IG nurses are required to perform all visits. The primary benefit of combining all clusters is that the amount of overtime is reduced. However, the combination of clusters also has substantial downsides.

The results indicate that all total costs indicators are expected to increase. A second downside is that the created routes are of a lower quality. This can be seen by the increase of the total working time and the routing in-route salary costs. The created routes are of a lower quality because the size of the instances that need to be solved are increased substantially. This results in fewer iterations in the GRASP-AVNS algorithm which leads to a lower quality of routes. The third downside is a substantial reduction in continuity of care. This indicates that a client is less frequently visited by the same nurse. However, as previously mentioned, the decrease in continuity of care is partially the result from the selected algorithm and is expected to be reduced by adapting the algorithm. So, the results indicate that the full combination of all clusters results into lower quality routes, with higher costs, but is able to reduce the required overtime.

6.2.2 Experiment 2: nurse combination

The previous section indicates that combining clusters results into less efficient routes. Therefore, a second experiment is performed where only the scheduling of nurses is investigated. The original routes created for the individual clusters are maintained during this experiment. Table 24 shows that this generates more promising results than experiment 1. The results indicate that all overtime can be avoided by only combining the scheduling of nurses. However, the results also indicate that an increase in total costs but a decrease in in-route salary costs is expected. However, this decrease in in-route salary costs is negligible. Furthermore, a decrease in continuity of care is expected. The decrease in continuity of care can be (partially) attributed to the selected algorithm but the increase in total costs is surprising. It is proposed that the cost increase is a direct results from the reduction of overtime of nurses which is investigated in experiment three.

6.2.3 Experiment 3: nurse combination version 2

Table 24 shows that a cost reduction is expected when the scheduling of nurses is combined and the same amount of overtime is allowed. This can be seen by the total costs (-49.85 Euro), total salary costs (-68.37 Euro) and total in-route salary costs (-167.56). This cost reduction can be explained by the reduced working time of the expensive 3-IG nurses. The results of experiment two and three show that a trade off exists between overtime and total costs. Allowing more overtime results in lower costs and vice versa. This is because nurses do not receive additional monetary compensation for working overtime according to the collective labor agreement [14]. However, overtime is paid via a 'time for time' principle in practice. This means a nurse has to work less hours in the subsequent time period if the nurse worked overtime during the current time period. Therefore, allowing nurses to work overtime in the current time period is expected to reduce overall costs but this automatically means more expensive 3-IG nurses have to be scheduled in subsequent time periods which is expected to increase costs. So, allowing lower level nurses to work overtime when this is not necessary is not expected to reduce costs when multiple time periods are considered.

6.2.4 Combination of clusters conclusion

The results in this section indicate that combining clusters is expected to improve the scheduling of nurses. However, If clusters are being combined then only the scheduling of nurses should be combined. This is because the routes created by the GRASP-AVNS algorithm are less efficient because more visits need to be planned, which results in fewer iterations from the GRASP-AVNS algorithm. Finally, the results show that allowing nurses to work overtime has short-term advantages but these advantages are expected to vanish when multiple time periods are considered. Though, it has to be noted that a continuity of care reduction of at least 0.15 is observed in all experiments. Which indicates that, on average, a client is visited by 1.5 more nurses compared to the algorithmic solution obtained in Section 6.1, if the client has ten different visits throughout the investigated time span.

6.3 Changing workforce

In this section, the effect of changing TWB's workforce is investigated. It is proposed that the cost difference between the routing in-route salary cost and full solution in-route salary cost occurs because of a discrepancy between the requirements of TWB's clients and the skill of TWB's nurses. First, experiments are performed where the skill levels of nurses are changed to find an optimal workforce. The performance of the separate clusters is compared in Section 6.3.2 because TWB already has one cluster that has a different workforce compared to the other clusters. Finally, this section ends with a conclusion in Section 6.3.3.

6.3.1 Workforce experiments

Data from TWB indicates that TWB primarily has high level (level 3 and 3-IG) nurses whereas most of the visits require a low level skill (ADL and level 2). Therefore, the skill levels of high level nurses are changed in two different experiments to find a more suitable workforce.

- Experiment 1: Change to ADL. In this experiment, the nurse skill level of individual nurses is changed to ADL level using a greedy approach. Only the scheduling procedure is changed, the routes created in Section 6.1 are used. The number of hours a nurse is available to work remains unchanged.
- Experiment 2: Change to level 2. In this experiment the nurse skill level of individual nurses is changed to level 2 using a greedy approach. Only the scheduling procedure is changed, the routes created in Section 6.1 are used. The number of hours a nurse is available to work remains unchanged.

Currently, the ADL skill level is related to trainees. So, the difference between the results of experiment 1 and 2 also indicate whether or not there is a benefit of actually considering the ADL skill level for actual employees (and not just trainees). The effect of changing the skill level to lower levels can be seen in Figures 10 and 11. Both experiments are performed in Kroeven-Tolberg.

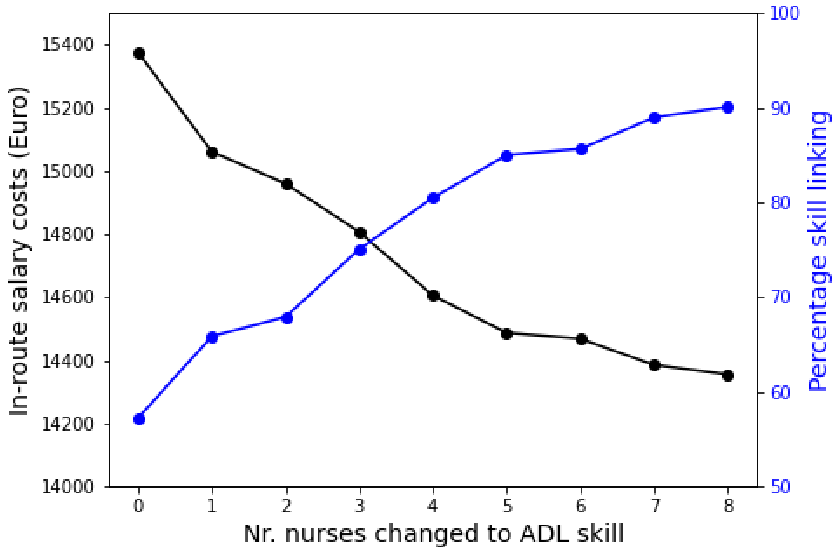

Figure 10: Effect of changing skill level of nurses to ADL level on in-route salary costs and percentage skill linking in Kroeven-Tolberg.

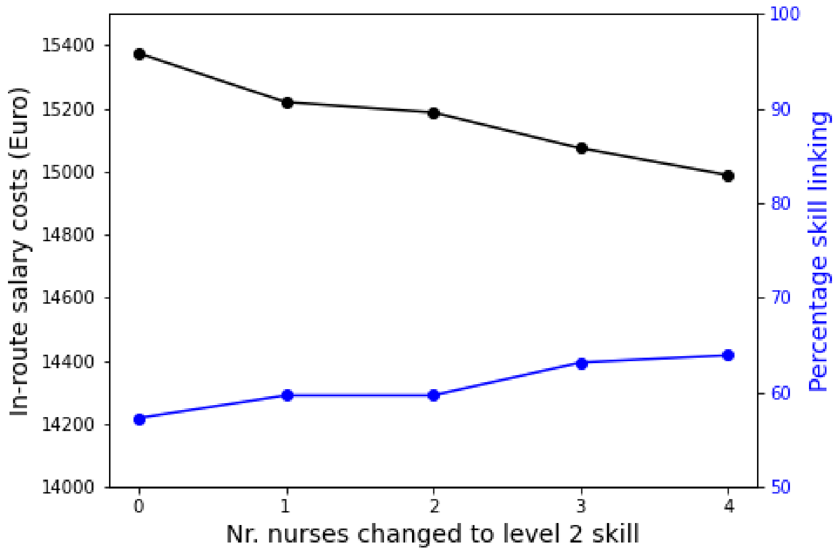

Figure 11: Effect of changing skill level of nurses to level 2 on in-route salary costs and percentage skill linking in Kroeven-Tolberg.

Figures 10 and 11 show a clear trend. In both cases, the in-route salary cost is reduced and the percentage skill linking is increased. The results indicate that there is an excess of high level nurses. The effect of changing the skill level of nurses on the percentage skill linking is explained by the following example.

If a 3-IG level nurse is changed to the ADL skill then this directly increases the percentage skill linking because this ADL nurse now only performs ADL visits. However, this change has larger consequences for the obtained solution. The single change to an ADL nurse also ensures that other nurses have to work fewer shifts below their skill level, which again increases the percentage skill linking. So, changing a single 3-IG level nurse to the ADL skill also ensures that other level 2, level 3 and 3-IG nurses perform more visits on their nurse skill level. The final results from both experiments can be seen in Table 25.

	Regular	**ADL**	**Level 2**
Nr. routes	134	134	134
Nr. breaks	2	2	2
Nr. double/broken shifts	32	32	32
Nr. shifts	100	100	100
Hours worked after 22:00	5.64	5.64	5.64
Nr. illegitimate assignments	0	0	0
Nr. time window violations	0	0	0
Nr. of nurses	31	29	29
Nr. of level 3-IG nurses	8	6	6
Nr. level 3 nurses	10	6	6
Nr. level 2 nurses	12	9	16
Nr. level ADL nurses	1	8	1
Total working hours available	669.31	669.31	669.31
Total working time (hour)	589.92	589.92	589.92
Total in-route working time (hour)	581.92	581.92	581.92
Total overtime hours	0	0	0
Hours 3-IG in-route working time	141.41	125.79	125.79
Hours level 3 in-route working time	217.06	129.47	129.47
Hours level 2 in-route working time	206.53	150.94	309.74
Hours ADL in-route working time	16.92	175.73	16.92
Total costs (Euro)	15954.52	14929.67	15568.34
Total salary costs (Euro)	15585.88	14561.03	15199.70
Total in-route salary costs (Euro)	15374.51	14354.85	14988.34
Routing in-route salary costs (Euro)	14354.84	14354.85	14354.85
Lower bound in-route salary costs (Euro)	14026.95	14026.95	14026.95
Total kilometer compensation (Euro)	368.64	368.64	368.64
Total in-route driven distance (km)	753.37	753.37	753.37
Percentage skill linking	57.2	90.0	63.9
Continuity of care	0.416	0.504	0.457

Table 25: Final results of changing the skill level of employees. In the ADL experiment nurse skills are changed to ADL skill level. In the level 2 experiment nurse skills are changed to level 2 skill.

Table 25 shows promising results. The results indicate that the routes can be performed by nurses of a lower skill level. This can be seen by the number of nurses per skill level in Table 25. The number of low skill level nurses (ADL & level 2) increases while the number of high skill level nurses (level 3 & 3-IG) decreases. A second observation is that an optimal workforce is created by changing the nurse skill levels to ADL level. This can be observed by the total in-route salary costs. These are equal to the routing in-route salary costs. This means that all routes in the solution are performed by a nurse that has the skill level that matches the visits within a route. The next observation is that the continuity of care increases. It is proposed that the increase in continuity of care occurs because of a combination of two terms.

- Term 1: A client usually has recurring visits with the same skill level on multiple days. For example, a client requires help getting dressed each day.
- Term 2: A nurse can only work routes that are equal or below their skill level. So, reducing the skill level of a nurse means they can work fewer routes.

The combination of term 1 and 2 actually means that decreasing the skill level of nurses is expected to increase the continuity of care. For example, in case of the optimal workforce then all routes are performed by nurses with the correct skill level. Furthermore, these routes usually contain the same clients because recurring visits usually occur at the same skill level. So, a 3-IG nurse primarily works 3-IG routes that mostly contain clients that require 3-IG visits. This means that a 3-IG nurse performs less visits at lower skill levels, which means a client that has visits with a lower skill level is less likely to be visited by a 3-IG nurse. This increases the continuity of care because, on average, a client is visited by fewer nurses. However, whether or not the continuity of care increases by optimizing the workforce should be studied in more detail to draw more reliable conclusions.

Finally, the results indicate that changing nurses to the ADL skill results in a larger cost reduction and a higher percentage skill linking than changing the skill level of nurses to level 2.

6.3.2 Workforce comparison

In this section, the performance and workforce of the separate clusters are compared to each other. The in-route salary costs of the solutions created by the planners of TWB are compared to the routing in-route salary cost obtained by the algorithm. The routing in-route salary costs are the lowest in-route salary cost found by the proposed algorithm. So, the routing in-route salary cost can be used as benchmark to judge the performance of the original routing and scheduling approach of each cluster. The results can be seen in Table 26.

Cluster	**Kroeven-Tolberg**	**Wouw**	**Centrum-Westrand**	**Heilig Hart**
Nr. of level 3-IG nurses	8	12	12	15
Nr. of level 3 nurses	10	6	14	13
Nr. of level 2 nurses	12	2	11	13
Nr. of level ADL nurses	1	2	7	3
Original in-route salary cost	15584.53	11470.36	18383.73	24953.79
Routing in-route salary cost	14354.84	10512.45	17423.64	23106.45
Percentage above Routing	8.6	9.1	5.5	8.0
Percentage skill linking	49.3	47.7	63.8	55.0
Continuity of care	0.524	0.454	0.533	0.497

Table 26: Comparison of the performance of the four clusters. Percentage above routing is the percentage that the original in-route salary cost is above the routing in-route salary cost.

Table 26 shows results that are in line with the observations in Section 6.3.1. The results show that cluster Centrum-Westrand has substantially more ADL nurses compared to the other clusters. Furthermore, the results indicate that the performance of cluster Centrum-Westrand is better than the other clusters. Centrum-Westrand has the smallest percentage above the routing in-route salary cost, has the highest percentage skill linking and the highest continuity of care in the original solutions. So, the results in Centrum-Westrand also indicate that a better performance of the routing and scheduling approach is expected when TWB employs more ADL nurses.

6.3.3 Changing workforce conclusion

The results from both sections indicate that TWB should consider hiring nurses with a lower skill level. The results show multiple benefits without any drawbacks. The costs are expected to decrease substantially because nurses perform fewer visits below their skill level. The employee satisfaction level is expected to increase because of a higher percentage skill linking. Finally, also the client satisfaction level is expected to increase because the continuity of care is increased. The results in Section 6.3.1 indicate that the best results are obtained if TWB considers the ADL function as an actual skill level instead of considering it as a trainee function.

6.4 Changing late visits

In this section, the effect of changing the time windows of late visits is investigated. Reducing the number of late visits (after 22:00) is expected to have two advantages. Advantage one is that the employee satisfaction level is expected to increase because the number of hours a nurse has to work after 22:00 is reduced. The second advantage is that reducing the number of late visits results in a cost reduction because nurses receive additional salary if they work after 22:00.

The latest end time window of a visit is 23:00 in the original instances. The time windows in the created instance are changed such that the latest end time window is at 22:00. The time window of a visit is changed if the end of a visits time window is after 20:00. The end time window of a visit is changed by Equations 8-10. The width of a time window remains similar. So, the start time window of a visit is moved forward by the same amount.

$$X = OldEndTW - 20 \tag{8}$$

$$Y = X \cdot \frac{2}{3} \tag{9}$$

$$NewEndTW = 20 + Y \tag{10}$$

The equations indicate that a visit that had an end time window of 23:00 now has an end time window of 22:00. However, if the end time window of a visit was 21:00 then the end time window of that visit becomes 20:40. The time windows of these earlier visits are also moved forward to avoid that an excess of visits occurs between 21:00 and 22:00. The results of the performed experiment can be seen in Table 27.

	Regular	**less late visits**
Nr. routes	134	137
Nr. breaks	2	2
Nr. double/broken shifts	32	44
Nr. shifts	100	91
Hours worked after 22:00	5.64	0.57
Nr. illegitimate assignments	0	0
Nr. time window violations	0	0
Nr. of nurses	31	31
Nr. of level 3-IG nurses	8	8
Nr. level 3 nurses	10	10
Nr. level 2 nurses	12	12
Nr. level ADL nurses	1	1
Total working hours available	669.31	669.31
Total working time (hour)	589.92	592.32
Total in-route working time (hour)	581.92	581.32
Total overtime hours	0	0
Hours 3-IG in-route working time	141.41	146.82
Hours level 3 in-route working time	217.06	215.31
Hours level 2 in-route working time	206.53	202.75
Hours ADL in-route working time	16.92	16.44
Total costs (Euro)	15954.52	15981.51
Total salary costs (Euro)	15585.88	15600.05
Total in-route salary costs (Euro)	15374.51	15311.84
Routing in-route salary costs (Euro)	14354.84	14218.27
Lower bound in-route salary costs (Euro)	14026.95	13886.39
Total kilometer compensation (Euro)	368.64	381.45
Total in-route driven distance (km)	753.37	736.77
Percentage skill linking	57.2	60.7
Continuity of care	0.416	0.415

Table 27: Effect of changing the time window of late evening visits. Displayed results are full week results. The experiment is performed in Kroeven-Tolberg.

Table 27 shows some expected but also some unexpected results. The expected results are that the hours worked after 22:00 are reduced substantially. It has to be noted that working time after 22:00 is still possible because the time windows indicate when a visit is allowed to start, not when it has to be finished. Furthermore, the results indicate that a similar working time of nurses per skill level is observed and that the percentage skill linking and continuity of care do not change substantially. The unexpected results can be seen in the costs. The results indicate that the total costs are expected to (slightly) increase even though a reduction in in-route salary costs is expected. This can be explained by the increase in the number of double/broken shifts and the reduction of total number of shifts. More double/broken shifts means that the final solution contains more paid trips between a nurse home location and a client which results in higher total costs. The effect of having more double/broken shifts on the employee satisfaction level is not directly clear as indicated in Section 4.7.1.

So, reducing the time windows of late visits is expected to (slightly) increase the total costs while the effect on the employee satisfaction level is inconclusive because the number of double/broken visits is increased even though the working time after 22:00 is reduced.

6.5 Conclusion

In this chapter, we answer the fifth research question: *What is the influence of different instances on the performance of the planning and scheduling approach?* We solve the instances from the individual clusters using the proposed algorithm and the results indicate that a saving of 250.15 ± 61.25 Euro per cluster per week can be achieved. Furthermore, the results indicate that less overtime is required at the cost of having less regular breaks and more double/broken shifts. We perform experiments where all four clusters in the Roosendaal region are combined. The results indicate that this allows for a better nurse allocation which is able to further reduce overtime. However, the results indicate that no substantial cost savings are expected. Experiments where the skill level of nurses are changed are performed. The results indicate that it is promising for TWB to consider the ADL skill as an actual employee level, instead of only having trainees with the ADL skill. The results indicate a potential cost reduction of 1024.85 Euro in cluster Kroeven-Tolberg in that week. Finally, the instance where no time window of a visit ends after 22:00 is investigated. The results indicate that it is possible to reduce the working time after 22:00 but this does slightly increase the total costs and the number of double/broken shifts. In the next chapter, we develop the conclusions and recommendations that stem from this research.

7 Conclusion & recommendations

The first step of this research is gaining insights in the current routing and scheduling approach. The current routing and scheduling solution is created manually by the planners of TWB. The results indicate that the performance of the current routing and scheduling process is sub-optimal. The manually created solutions score sub-optimal on three different performance metrics. The first is that the manually created solutions contain assignments of nurses to visits that cannot be performed by a nurse of that skill level. Furthermore, the results indicate that nurses have worked overtime even though there are sufficient regular working hours available. Finally, a relatively low percentage skill linking is observed which indicates inefficiencies in the routing and scheduling approach.

In the next step, we investigated literature to find how other researchers have solved problems similar to TWB's problem. The planning and scheduling procedure of TWB is best described as a home healthcare routing and scheduling problem (HHCRSP). The primary difference between TWB's instances and instances investigated in other works, is that TWB's instances contain substantially more visits compared to other works. The literature search showed that both the GRASP and VNS algorithm are used in HHCRSP variants similar to TWB's case.

We selected a solution approach that decomposes the HHCRSP in a separate routing and scheduling problem. We created a GRASP-AVNS algorithm to create the routes and a greedy scheduling approach is used to assign nurses to the created routes. The primary focus in this work is the GRASP-AVNS algorithm. Here, a routing solution is created by first creating initial solutions (GRASP stage 1). This is followed by two local searches to ensure that the obtained routing solutions results in feasible overall HHCRSP solutions (GRASP stage 2). The solutions are then improved using a local search (GRASP stage 3) after which the best obtained GRASP solution is improved by the AVNS algorithm. Finally, nurses are assigned to shifts using a two-stage scheduling algorithm. Routes are turned into shifts (scheduling stage 1) and nurses are assigned to these shifts (scheduling stage 2). The results of the GRASP-AVNS algorithm are compared with a lower bound of the solution. This comparison with the lower bound indicates that the GRASP-AVNS algorithm generates high quality solutions.

We use the proposed solution approach to solve multiple instances from TWB. First, the algorithmic created solutions are compared with the solutions created by the planners of TWB. The results indicate that the algorithm can reduce the required overtime of nurses while also generating feasible solutions without any illegitimate assignments. Furthermore, the results indicate that an in-route salary cost reduction of 250.15 $\pm$ 61.25 Euro per cluster is expected (95% confidence interval). This equals an annual expected cost reduction of 143085.80 $\pm$ 35035 Euro. This cost saving amounts into an expected total cost reduction of 1.42 $\pm$ 0.35 percent. However, the majority of these total costs are fixed and cannot be optimized. Therefore, a cost saving potential is calculated. The cost saving potential indicates a maximum cost reduction compared to the original solution created by the planners of TWB. The results show that the algorithm is able to obtain 14.75 $\pm$ 3.02 percent of this entire cost saving potential. Though, it must be noted that the current algorithm does results in an average continuity of care reduction of 0.095. Which indicates that, on average, a client is visited by 0.95 more nurses compared to the original solution created by the planners of TWB, if the client has ten different visits throughout the investigated time span.

The next performed experiment aims to answer the main research question: *What is the effect of combining multiple clusters in the routing and scheduling process on the number of required nurses and costs for TWB?.* Three different experiments are performed to answer this research question.

1. Full combination of clusters
2. Only combining the scheduling process of clusters
3. Only combining the scheduling process of clusters while still allowing for overtime of nurses that also have to work overtime in the algorithmic solution

Experiment one indicates that combining the multiple clusters reduces the required amount of overtime but also results in an increase of total cost. However, the results from experiment two show that all overtime can be avoided but that more double/broken shifts are required. This also results in an expected combined weekly total cost increase of 127.34 Euro. The results from experiment three indicate that a larger total salary cost reduction is possible when nurses work overtime. However, overtime is paid via a 'time for time' principle. So, allowing less expensive nurses to work overtime (experiment three) will reduce the performance of subsequent time periods which reduces the performance of the routing and scheduling approach for subsequent time periods. Concluding, the results from this work indicates that only combining the scheduling process of nurses (experiment two) generates the most promising results because it reduces overtime without a substantial increase in costs. Though, it has to be noted that a substantial decrease in continuity of care of 0.16 is observed compared to the algorithmic solution of the individual clusters.

The results of the individual clusters indicate that a substantial cost reduction is still possible during the assignment of nurses. Therefore, experiments are performed to find the optimum workforce of TWB. The results indicate that the current workforce contains an excess of high level employees (level 3-IG and 3) but has a shortage of low level employees (level 2 and ADL). During this experiment the skill of nurses is downgraded to the ADL level. The results indicate that a cost reduction of 1019.66 Euro per week is expected in cluster Kroeven-Tolberg by having a workforce that consists of more ADL employees. Extrapolating this cost reduction, indicates a maximum annual expected cost saving of 583245.52 Euro by hiring more ADL employees. Furthermore, results indicate that hiring more ADL employees is also expected to improve other performance indicators such as the percentage skill linking and the continuity of care. Though, it must be mentioned that the ADL skill level is currently related to trainees at TWB. Therefore, the same experiment is performed where nurses are downgraded to level 2 skill. In that case, the results indicate a maximum weekly cost saving of 386.17 Euro (220889.24 Euro annually). Furthermore, hiring more level 2 employees is also expected to increase other performance indicators, but hiring more ADL employees is beneficial.

Finally, We performed experiments where the time windows of visits are adjusted in such a fashion that no time windows of visits end after 22:00. The results indicate that no cost saving is expected and the working time after 22:00 is reduced. However, the results indicate that this results into more double/broken shifts. So, whether the visits after 22:00 should be reduced can be judged best by the nurses of TWB since it is not expected to have a major cost influence.

The contribution of this work to literature is two fold. We developed a HHCRSP algorithm that decomposes the problem in a separate routing and scheduling problem. The resulting daily routing problems are independent and this allows for a decomposition of the routing problem into individual days. This allows the algorithm to find solutions for HHCRSPs containing a large number of visits. The second contribution is that the proposed algorithm shows whether or not there is a discrepancy between the workforce of the home healthcare organization and the requirements of its clients. The results show that this discrepancy has a substantial influence on total costs. To our understanding, the influence of this discrepancy is an untouched topic in literature.

Concluding, this work indicates that creating the routes and schedules via an algorithm has substantial advantages for TWB. An annual cost saving of 143085.80 $\pm$ 35035 Euro is expected and the created solution is fully feasible. TWB should not fully combine multiple clusters because this leads to more expensive HHCRSP solutions. TWB could partially combine clusters by only combining the scheduling of nurses. This allows for a reduction of overtime without substantially increasing total costs. Finally, TWB should consider the ADL skill level as an actual skill level and hire ADL skilled employees since this is expected to substantially reduce the total costs while also increasing performance indicators related to the nurse and client satisfaction level.

7.1 Recommendations

Several additional recommendations for TWB are suggested based on the developed routing and scheduling algorithm. The recommendations are divided into two sections. First, topics suitable for follow up research are discussed. This is followed by recommendations for future versions of the proposed algorithm.

7.1.1 Future research

Based on the results in this work, three separate topics can be interesting for future research at TWB. These are the effect of aiming for a higher continuity of care, optimizing the day that visits are performed and reducing the number of double/broken shifts. The three topics are introduced below.

Scheduling approach

The results in this work indicate that the routing and scheduling solutions created by the proposed solution approach decrease the continuity of care. The decrease in continuity of care can be primarily attributed to the nurse scheduling approach, and not to the routing approach. This can be observed by the results in Section 6.3. Here, the results indicate that a higher continuity of care is possible by reducing the skill level of nurses. However, that automatically means that this scheduling solution is also feasible without reducing the skill level of nurses. So, a higher continuity of care can be reached by changing the scheduling procedure. Therefore, further research in the scheduling procedure with the focus on the trade off between continuity of care and costs is recommended. Furthermore, this new scheduling research could take additional topics into account such as the fixed day off of a nurse and reducing the number of morning shifts after an evening shift. The results from this research could also indicate whether the created routes result in a sufficient continuity of care. If the results indicate that the continuity of care is not sufficient then a different routing algorithm, that takes the continuity of care into account, is necessary for TWB.

Day of visit

The second limitation is that the day that a visit occurs is fixed at TWB. The day a visit occurs is a result from the care plan of a client. However, the day that some visits take place is sub-optimal. For instance, TWB indicates that it is also performing visits on Sundays that could be performed on other days. So, performing these visits on a different day is expected to be more cost effective. The possibility of changing the day that a visit is performed could be a suitable topic for future research at TWB.

Reducing double/broken shifts

The final topic that could be interesting for future research is a different approach to breaks and double/broken shifts. The current algorithm creates results that contain substantially more double/broken shifts than the original solutions created by the planners of TWB. There are two options to reduce the number of double/broken shifts. The first option is to adapt assignment problem stage 1 to not combine all possible shifts into a double/broken shifts. However, a different approach to including breaks might be better. It may be better to schedule breaks at a fixed time of the day (for instance during lunch) and already take these breaks into account in the routing algorithm. However, the algorithm in this work cannot be changed easily to include breaks at a fixed time during the day. So, if this is deemed necessary then a different routing and scheduling algorithm has to be created.

7.1.2 Algorithm improvements

The final recommendations are on further improvements of the proposed algorithm. Three different improvements can be identified. These are the inclusion of shared visits, the problem of the large skill discrepancy and the lower bound.

Shared visits

The proposed algorithm does not incorporate shared visits. However, TWB does have these shared visits in practice. Therefore, shared visits should be included in future versions of the algorithm. The algorithm can be extended by changing the time windows of the shared visits and creating a relation between the routes that contain the shared visit. So, it is expected that the concept of shared visits can be included within the algorithm without much additional effort. However, it has to be noted that TWB does not store which visits are shared visits. So, TWB should also store which visits are shared visits to allow for a practical implementation of a routing and scheduling algorithm.

Skill discrepancy

The second improvement of the proposed algorithm stems from the large skill discrepancy between TWB's workforce and its visits. The proposed algorithm creates routes that assume a perfect workforce is available. However, this work indicates that there is a large discrepancy between the actual and the perfect workforce. Therefore, the algorithm used in a practical implementation should create routes based on the actual available workforce. It is expected that the proposed algorithm can be extended to take this into account.

Lower bound

The final topic is the lower bound used in this work. The results indicate that this lower bound works very well for urban clusters, but not so well for rural clusters. Therefore, the lower bound should be adapted to ensure that the lower bound is better applicable in rural clusters as well. A second downside of the lower bound is that it uses the minimum travel time from the Euclidean distance method. This limits the generalizability of the currently proposed algorithm. The lower bounds used in the solution approach are expected to be altered without much additional effort.

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A Original single day results

The single day results from the original planning and scheduling approach are displayed in the tables in this appendix. Table A1 shows the results from Kroeven-Tolberg. Table A2 shows the results from Wouw. Table A3 shows the results from Centrum-Westrand. Table A4 shows the results from Heilig Hart.

Day	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
Nr. visits	213	223	211	229	226	228	202
Nr. 3-IG visits	44	35	28	35	37	33	29
Nr. level 3 visits	43	49	51	53	47	55	47
Nr. level 2 visits	59	60	60	67	67	66	62
Nr. ADL visits	67	79	72	74	75	74	64
Nr. nurses	12	15	15	17	17	15	12
Nr. level 3-IG nurses	3	5	4	4	4	3	3
Nr. level 3 nurses	3	5	4	6	6	4	4
Nr. level 2 nurses	5	5	7	6	6	8	5
Nr. ADL nurses	1	0	0	1	1	0	0
Nr. routes	19	20	18	20	20	19	17
Nr. 3-IG routes	6	8	6	6	6	5	4
Nr. level 3 routes	5	5	4	6	7	5	7
Nr. level 2	6	7	6	7	6	9	6
Nr. ADL routes	2	0	0	1	1	0	0
Nr. broken shifts	6	4	3	2	2	3	5
Nr. breaks	1	1	0	1	1	1	0
Nr. shifts shorter than 4 hour	7	8	5	6	3	5	6
Nr. shifts shorter than 3 hour	0	3	1	1	2	2	1
Nr. illegitimate assignments	8	0	4	2	5	10	2
Total costs (Euro)	2153.33	2155.78	2049.42	2170.00	2257.30	2405.82	2883.25
Total salary costs (Euro)	2090.02	2107.11	1984.71	2134.71	2210.69	2359.23	2844.24
Total kilometer compensation (Euro)	63.29	48.67	64.70	35.28	46.61	46.59	39.01
Total driven distance (km)	283.65	238.24	299.00	193.18	234.98	228.38	192.40
In-route salary costs (Euro)	2058.67	2091.56	1968.71	2119.46	2192.19	2337.90	2816.04
In-route driven distance (km)	106.48	96.82	96.88	95.13	100.81	95.20	91.92
Hours worked after 10 pm	3.01	1.38	2.73	1.94	1.18	1.15	0.98
Hours in-route working time	83.87	84.30	79.42	86.27	90.00	84.27	73.75
Hours 3-IG in-route working time	25.44	26.29	24.10	24.59	21.92	18.95	16.20
Hours level 3 in-route working time	25.09	24.80	18.93	27.60	33.56	25.20	29.84
Hours level 2 in-route working time	24.76	33.21	36.39	29.68	29.91	40.13	27.71
Hours ADL in-route working time	8.57	0	0	4.38	4.60	0	0
Nr. time window violations	34	25	20	35	55	43	35
Percentage skill linking	59.6	44.4	46.0	50.7	51.3	48.2	45.0

Table A1: Individual day results from cluster Kroeven-Tolberg.

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Nr. visits	150	153	122	151	146	148	135
Nr. 3-IG visits	29	32	32	33	37	36	38
Nr. level 3 visits	41	36	31	39	33	34	32
Nr. level 2 visits	28	30	27	28	26	27	20
Nr. ADL visits	52	55	32	51	50	51	45
Nr. nurses	10	10	9	13	12	10	9
Nr. level 3-IG nurses	4	5	7	7	6	6	4
Nr. level 3 nurses	4	2	3	3	4	3	3
Nr. level 2 nurses	1	2	1	1	1	0	0
Nr. ADL nurses	1	1	0	2	1	1	2
Nr. routes	14	14	12	16	15	14	12
Nr. 3-IG routes	6	7	7	9	8	8	6
Nr. level 3 routes	6	3	4	4	4	4	4
Nr. level 2	1	3	1	1	2	0	0
Nr. ADL routes	1	1	0	2	1	1	2
Nr. broken shifts	3	3	2	1	2	1	2
Nr. breaks between shifts	1	1	1	2	1	3	1
Nr. shifts shorter than 4 hour	1	1	2	5	4	4	3
Nr. shifts shorter than 3 hour	0	0	1	1	0	0	0
Nr. illegitimate assignments	2	1	1	3	3	4	5
Total costs (Euro)	1623.36	1674.30	1428.37	1706.62	1685.85	1932.62	2163.71
Total salary costs (Euro)	1561.51	1585.43	1346.92	1595.92	1609.18	1844.13	2080.65
Total kilometer compensation (Euro)	61.84	88.87	81.45	110.70	76.67	88.49	83.06
Total driven distance (km)	361.85	373.61	340.03	466.95	336.72	366.41	346.35
In route salary costs (Euro)	1540.49	1553.72	1331.55	1576.72	1583.18	1844.13	2040.16
In route driven distance (km)	160.15	180.95	140.93	171.51	181.74	151.81	154.29
Hours worked after 10 pm	0.55	1.41	1.13	1.24	0.92	0.42	1.33
Hours in route working time	60.36	60.73	49.88	61.57	61.05	59.78	51.67
Hours 3-IG in route working time	23.77	30.46	28.48	31.84	33.70	39.18	26.19
Hours level 3 in route working time	27.24	13.58	17.03	17.23	15.66	16.65	16.55
Hours level 2 in route working time	4.45	11.98	4.37	4.18	7.60	0	0
Hours ADL in route working time	4.90	4.71	0	8.32	4.10	3.95	8.93
Nr. time window violations	30	29	15	19	22	32	29
Percentage skill linking	44.6	49.7	38.5	47.0	51.3	39.9	62.9

Table A2: Individual day results from cluster Wouw.

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Nr. visits	260	264	262	248	261	250	230
Nr. 3-IG visits	46	52	50	43	57	46	41
Nr. level 3 visits	62	65	66	65	68	66	65
Nr. level 2 visits	55	51	50	47	48	48	39
Nr. ADL visits	97	96	96	93	88	90	85
Nr. nurses	24	24	24	21	22	22	20
Nr. level 3-IG nurses	6	6	5	6	9	6	5
Nr. level 3 nurses	9	9	8	6	5	6	6
Nr. level 2 nurses	6	7	6	5	5	6	5
Nr. ADL nurses	3	2	5	4	3	4	4
Nr. routes	32	36	33	29	32	31	28
Nr. 3-IG routes	10	8	9	9	14	10	8
Nr. level 3 routes	11	10	11	9	7	9	9
Nr. level 2	8	9	9	7	8	8	7
Nr. ADL routes	3	2	4	4	3	4	4
Nr. broken shifts	8	3	4	6	4	6	2
Nr. breaks between shifts	10	9	9	9	8	10	8
Nr. shifts shorter than 4 hour	7	8	7	6	5	8	9
Nr. shifts shorter than 3 hour	1	0	1	1	3	0	1
Nr. illegitimate assignments	17	10	13	13	11	13	11
Total costs (Euro)	2594.96	2624.01	2555.89	2436.29	2720.25	2779.0	3313.67
Total salary costs (Euro)	2516.67	2552.33	2475.66	2342.49	2636.13	2708.39	3250.74
Total kilometer compensation (Euro)	78.29	71.69	80.23	93.80	84.12	70.61	62.93
Total driven distance (km)	374.61	348.02	385.27	432.58	392.88	342.20	308.75
In route salary costs (Euro)	2500.24	2533.03	2475.66	2339.12	2604.16	2688.31	3243.21
In route driven distance (km)	92.67	97.71	93.75	94.19	91.82	93.90	88.10
Hours worked after 10 pm	0.52	1.45	0.70	2.12	0.77	1.80	0.60
Hours in route working time	103.53	103.58	103.53	96.95	104.81	99.43	88.53
Hours 3-IG in route working time	26.35	26.53	24.93	29.52	46.42	29.74	24.75
Hours level 3 in route working time	38.07	38.61	35.75	27.98	22.38	26.53	27.97
Hours level 2 in route working time	26.08	30.58	25.83	21.78	23.48	25.07	20.13
Hours ADL in route working time	13.02	7.85	17.01	17.66	12.52	18.09	15.68
Nr. time window violations	52	49	56	69	46	56	51
Percentage skill linking	58.1	60.2	69.0	60.9	60.9	68.4	69.5

Table A3: Individual day results from cluster Centrum-Westrand.

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Nr. visits	362	359	348	369	384	340	341
Nr. 3-IG visits	75	84	59	84	79	70	69
Nr. level 3 visits	87	86	87	91	90	81	82
Nr. level 2 visits	81	75	82	80	87	78	83
Nr. ADL visits	119	114	120	114	128	111	107
Nr. nurses	26	21	23	25	23	20	19
Nr. level 3-IG nurses	7	6	7	9	8	8	6
Nr. level 3 nurses	9	8	6	8	8	5	6
Nr. level 2 nurses	8	6	9	6	6	6	6
Nr. ADL nurses	2	1	1	2	1	1	1
Nr. routes	33	31	31	30	29	27	28
Nr. 3-IG routes	12	13	12	12	11	12	13
Nr. level 3 routes	11	9	7	10	9	6	6
Nr. level 2	8	8	11	6	6	8	8
Nr. ADL routes	2	1	1	2	3	1	1
Nr. broken shifts	7	9	6	3	5	5	6
Nr. breaks between shifts	3	2	2	2	1	2	3
Nr. shifts shorter than 4 hour	10	10	13	4	2	3	5
Nr. shifts shorter than 3 hour	3	3	3	2	1	2	4
Nr. illegitimate assignments	3	1	5	4	7	2	0
Total costs (Euro)	3558.82	3618.71	3292.58	3527.85	3623.48	3806.39	4970.77
Total salary costs (Euro)	3434.08	3451.72	3190.89	3433.72	3542.15	3671.45	4831.60
Total kilometer compensation (Euro)	124.74	166.99	101.69	94.13	81.33	134.94	139.17
Total driven distance (km)	566.61	602.40	472.60	448.61	393.79	470.94	482.88
In route salary costs (Euro)	3342.41	3317.52	3146.57	3407.26	3522.40	3557.13	4660.50
In route driven distance (km)	165.11	175.46	161.66	167.06	193.12	165.89	171.42
Hours worked after 10 pm	3.39	2.41	2.95	2.99	2.64	2.27	3.83
Hours in route working time	134.72	131.43	127.24	135.76	143.38	124.61	120.22
Hours 3-IG in route working time	40.27	49.23	44.04	48.61	46.65	45.71	45.16
Hours level 3 in route working time	51.97	44.04	34.21	50.82	50.33	33.44	33.03
Hours level 2 in route working time	34.35	34.25	44.21	27.19	30.83	40.40	37.32
Hours ADL in route working time	8.13	3.90	4.77	9.14	15.57	5.06	4.72
Nr. time window violations	61	52	45	67	75	52	47
Percentage skill linking	56.4	53.5	52.3	56.6	54.1	55.3	53.7

Table A4: Individual day results from cluster Heilig Hart.

B GRASP computation time derivation

In this appendix, the derivation of Equations 5-7 is discussed. The equations are derived from the computation times of the GRASP algorithm, using a fixed stage 1 computation time of 30 seconds in three different scenarios. The scenarios are the Mondays in Kroeven-Tolberg, Wouw and Heilig Hart. The number of visits of the instances and computation times of the GRASP algorithm can be seen in Table A5.

Cluster	**Kroeven-Tolberg**	**Wouw**	**Heilig Hart**
Nr. visits	213	150	362
Computation time (s)	2280	1868	3331

Table A5: GRASP computation time in 3 different scenarios using a a GRASP stage 1 computation time of 30 seconds.

The results in Table A5 show that a GRASP stage 1 time of 30 seconds results in a total computation time of 30 minutes. The results are used to determine the relation between the size of a scenario and computation times. These can be seen in Table A6.

Combination	**K-T & Wouw**	**HH & Wouw**	**HH & K-T**
Ratio computation time	1.22	1.783	1.46
Ratio of additional visits	1.42	2.413	1.7
Number of additional visits	63	212	149

Table A6: Relation between the computation time and the number of visits. In all cases, two different scenarios are compared.

The results clearly indicate that there is a relation between the ratio of additional visits and the ratio of computation time. The goal is to find a relation between the ratio of visits and the computation time. Therefore, A power law relation is proposed that relates the computation time to the ratio of visits.

$$\textit{Ratio computation time} \approx (\textit{Ratio visits})^X \tag{11}$$

Using Equation 11 gives three different values for X. The values for X are 0.565, 0.655 and 0.715. Now, X is calculated by using the number of additional visits as fitting parameter. This leads to the following set of equations to determine X:

$$Y + 63 \cdot Z = 0.565 \tag{12}$$
$$Y + 149 \cdot Z = 0.715 \tag{13}$$

Here, Y is a constant and Z is multiplied with the number of additional visits. Solving this system of Equations yields an Y of 0.455 and a Z of 0.00174. However, during this derivation of computation time an error has been made and the following system of equations has been solved:

$$Y + 63 \cdot Z = 0.565 \tag{14}$$
$$Y + 212 \cdot Z = 0.715 \tag{15}$$

This error has remained unnoticed during all experiments and results in an Y of 0.502 and a Z of 0.001. These numbers allow us to calculate a power (X) that relate the number of visits to the expected GRASP computation time. Finally, the GRASP stage 1 computation time is reduced such that the expected GRASP time equals the goal GRASP time. The calculation of the GRASP stage 1 time for the three used scenarios can be seen in Table A7.

Cluster	**Kroeven-Tolberg**	**Wouw**	**Heilig Hart**
Goal GRASP time (min)	30	30	30
Ratio of additional visits	1.42	0	1.783
Number of additional visits	63	0	212
Used X	0.565	0.502	0.714
Used ratio computation time	1.22	1	1.876
Used expected GRASP time (min)	36.6	30	56.28
Used GRASP stage 1 time limit (s)	24.6	30	16
Correct X	0.565	0.455	0.655
Correct ratio computation time	1.22	1	1.78
Correct expected GRASP time (min)	36.6	30	62.03
Correct GRASP stage 1 time limit (s)	24.6	30	14.5

Table A7: Calculation of GRASP stage 1 time limit for 3 different scenarios. Both the used and correct GRASP stage 1 time limit are shown.

The results indicate that the influence of the mistake is relatively small. The used method results into slightly larger GRASP stage 1 computation times in large scenarios. However, it has to be noted that this influence is still small as can be seen in Section 5.6, where the three different scenarios still have a similar GRASP computation time.

C Individual (A)VNS results

This appendix shows the individual run results of the AVNS tuning. Each run has a computation time of 15 minutes. The initial solution is the best obtained solution after 200 GRASP stage 1 iterations using that scenario. The individual run results can be seen in Table A8.

Seed	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Scenario 1, Exp 1	1934.90	1939.18	1941.22	1937.60	1938.31	1936.95	1937.25	1936.97	1936.64	1942.51
Scenario 1, Exp 2	1934.65	1939.12	1937.28	1940.69	1937.90	1939.64	1938.98	1933.95	1937.45	1937.14
Scenario 1, Exp 3	1937.86	1936.56	1939.73	1939.91	1937.38	1941.55	1936.99	1940.96	1941.35	1940.87
Scenario 2, Exp 1	1414.74	1414.66	1412.69	1415.74	1419.71	1417.51	1415.37	1415.86	1414.85	1414.86
Scenario 2, Exp 2	1416.71	1409.46	1416.84	1408.16	1412.72	1415.08	1421.30	1414.98	1417.78	1410.11
Scenario 2, Exp 3	1413.54	1411.86	1410.38	1414.40	1418.86	1417.26	1412.39	1410.18	1413.21	1414.08
Scenario 3, Exp 1	3094.96	3097.61	3104.80	3100.01	3100.11	3100.36	3099.98	3096.21	3098.46	3095.35
Scenario 3, Exp 2	3096.76	3097.01	3096.70	3100.09	3095.98	3101.58	3098.37	3104.03	3096.67	3104.35
Scenario 3, Exp 3	3099.57	3098.70	3098.26	3097.14	3095.72	3104.22	3096.39	3099.19	3098.74	3094.62

Table A8: (Adaptive) variable neighborhood search tuning results. Scenario 1,2,3 are Monday Kroeven-Tolberg, Monday Wouw, Monday Heilig Hart. Experiment 1,2,3 are progressive shaking, constant shaking and adaptive progressive shaking. Maximum route length is 4.75 hours. A RCL of four is used in the GRASP procedure. Displayed costs are in-route salary costs.

D Overview cluster results

In this appendix, the algorithmic results of the individual clusters are displayed in one single table to give a better overview. The results can be seen in Table A9.

Cluster	**Kroeven-Tolberg**	**Wouw**	**Centrum-Westrand**	**Heilig Hart**
Nr. routes	134	103	163	207
Nr. breaks	2	4	3	8
Nr. double/broken shifts	32	28	47	50
Nr. shifts	100	71	113	149
Hours worked after 22:00	5.64	8.34	4.57	12.93
Nr. illegitimate assignments	0	0	0	0
Nr. time window violations	0	0	0	0
Nr. of nurses	31	22	40	44
Nr. of level 3-IG nurses	8	12	8	15
Nr. level 3 nurses	10	6	14	13
Nr. level 2 nurses	12	2	11	13
Nr. level ADL nurses	1	2	7	3
Total working hours available	669.31	438.84	855.72	927.00
Total working time (hour)	589.92	409.39	710.60	929.95
Total in-route working time (hour)	581.92	402.39	698.85	917.45
Total overtime hours	0	0	0	25.19
Hours 3-IG in-route working time	141.41	204.61	162.72	322.52
Hours level 3 in-route working time	217.06	144.74	268.12	276.82
Hours level 2 in-route working time	206.53	21.24	168.93	256.80
Hours ADL in-route working time	16.92	31.80	99.08	61.30
Total costs (Euro)	15954.52	11887.45	18889.98	25543.05
Total salary costs (Euro)	15585.88	11468.13	18462.72	24924.70
Total in-route salary costs (Euro)	15374.51	11276.01	18150.62	24590.66
Routing in-route salary costs (Euro)	14354.84	10512.45	17423.64	23106.45
Lower bound in-route salary costs (Euro)	14026.95	9609.07	17188.35	22619.18
Total kilometer compensation (Euro)	368.64	409.32	427.26	618.35
Total in-route driven distance (km)	753.37	1079.34	785.71	1358.97
Percentage skill linking	57.2	48.0	71.2	60.0
Continuity of care	0.416	0.446	0.407	0.359

Table A9: Performance of the algorithmic solution approach of an entire week in all clusters.