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ROUTING AND SCHEDULING OF HOME SERVICES FACILITATING TRIP SHARING AND WALKING

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Part I
Preface

Acknowledgement

To begin this thesis, I would like to thank my supervisors, Manfred Gronalt and Patrick Hirsch, for the great amount of time and valuable feedback given, independent of how many deadlines and different versions of papers I imposed on them. I also want to thank Angel A. Juan for twice allowing me to stay one month at IN3-Open University of Catalonia in Barcelona and the ERASMUS program for supporting my research stays. Further thanks are given to all anonymous reviewers of the journal and conference publications who helped me to see the work from different perspectives. Feedback and data provided by the Austrian Red Cross, especially by Monika Wild, Johanna Reinisch, Reinhard Schmidt and Harald Pfertner, is also acknowledged as well as the financial support provided by the Austrian Research Promotion Agency (FFG) and the Austrian Ministry for Transport, Innovation and Technology (BMVIT).

Additionally, I would like to thank my parents for their ongoing support and my office colleagues for helping me to refocus me when work went slow and who pushed me when work went well. Most importantly though, I would like to thank my wife, Patricia, for never getting bored to listen to my remarks about waiting for referee answers and other more or less interesting details about my solution procedures. The multiple times she proofread my articles and this thesis alone deserves my deepest gratitude. Thanks to her and her constant smiles, it was easy to motivate oneself.

Lastly, I want to thank my study colleagues and lectures during my graduate and undergraduate studies. It was they who started my passions for operations research, supply chain management and logistics. Without this inspiration, this thesis would not have been possible.

- Christian Fikar

Summary

This cumulative thesis presents routing and scheduling procedures for home service providers to facilitate trip sharing and walking. Staff members are delivered to customers' premises and picked up after completion of service. Furthermore, walking between closely-located customers is enabled. To solve the corresponding optimisation problem, a two-stage matheuristic was developed in the first step, which combines set partitioning with a Tabu Search metaheuristic. Interdependencies and synchronisation issues resulting from the problem are solved by linear programming. Furthermore, the procedure implicitly aligns walking to vehicle routes by a walking-route improvement operator. In subsequent work, a discrete-event driven metaheuristic was developed, which focuses on efficiency and flexibility to allow adjustment of routing and scheduling plans in a dynamic environment. This is of high importance to enable flexibility and to support efficient real-world operations as cancellations and other unexpected events occur frequently.

To investigate the potentials of trip sharing and walking for home service providers, a numerical comparison to current business practices is given. Currently, most staff members operate a separate vehicle to reach clients' homes, which results in low vehicle utilization, a high demand for parking spots and high vehicle-related expenses. To tackle these issues, decision makers are provided with beneficial settings and challenges of implementing trip sharing concepts in various geographic client distributions. Computational experiments originate from real-world based data from the Austrian Red Cross, a major home health care provider in Austria. Results show that trip sharing allows one to substantially reduce the number of required vehicles and to circumvent parking problems. Furthermore, the numerical evaluations show that sub-urban areas where parking problems occur and clients are geographically distributed in a combination of clusters and random locations are especially suitable for trip sharing, in particular if service durations at clients are long. Nevertheless, travel times of staff members are prone to increase due to wait times for the service and resulting detours. Additionally, drivers of the transport systems have to be compensated. These costs need to be compared to savings achieved by a reduction of vehicles and reduced parking delays. As a result, by providing decision makers with optimisation procedures and by clearly stating trade-offs and benefits, future implementations of trip sharing are supported by this thesis.

Zusammenfassung

Diese kumulative Dissertation beschäftigt sich mit Optimierungsverfahren zur Einsatz- und Tourenplanung von Heimservicedienstleistern. Der Fokus liegt auf dem Einsatz von Trip Sharing Konzepten und der Forcierung von Gehwegen. MitarbeiterInnen werden zu den Wohnorten von KundInnen gebracht und anschließend, nach Fertigstellung der Tätigkeiten, wieder abgeholt. Zusätzlich ist es möglich kurze Distanzen zu gehen. Zur Lösung wurde eine Matheuristik entwickelt, welche das Problem mit Set Partitioning und einer Tabu Suche optimiert. Dabei wird ein lineares Optimierungsmodell gelöst, um Abhängigkeiten zwischen Touren zu behandeln und Synchronisierung von Fahrzeugen sowie MitarbeiterInnen zu garantieren. Gehwege werden während des Lösungsverfahrens mit Hilfe eines Operators verbessert. Ebenso wurde für dynamische Probleme eine ereignisorientierte Metaheuristik entwickelt, die den Fokus auf Effizienz und Flexibilität hat. Diese dient zur Umplanung von Einsatz- und Tourenplänen im Falle von kurzfristigen Einsatzänderungen und anderen unerwarteten Ereignissen.

Um das Potenzial von Trip Sharing für Heimservicedienstleister zu analysieren, wurde ein numerischer Vergleich mit der individuellen Nutzung von Fahrzeugen durchgeführt. Dies ist die derzeit überwiegende Mobilitätsform, führt allerdings zu einer geringen Fahrzeugauslastung, einem hohen Bedarf an Parkplätzen und zu hohen Kosten. Um dem entgegenzusteuern, werden EntscheidungsträgerInnen Studien für den Einsatz von Trip Sharing Konzepten in unterschiedlichen geographischen Verteilungen von KlientInnen präsentiert. Die Testrechnungen basieren auf anonymisierten Realdaten vom Österreichischen Roten Kreuz, einem wichtigen mobilen Pflegedienstleister in Österreich. Ergebnisse zeigen eine erhebliche Verringerung an benötigten Fahrzeugen und eine Minderung der Parkproblematik. Gebiete die unter einem Mangel an Parkplätzen leiden und suburbane Gebiete, in welchen KlientInnen sowohl in Clustern und zufällig verteilt sind, sind am besten für Trip Sharing Konzepte geeignet, vor allem wenn lange Servicezeiten auftreten. Fahr- und Wartezeiten hingegen erhöhen sich, auf Grund von Wartezeiten für den Transportservice und gefahrenen Umwegen. Ebenso fallen Kosten für die FahrerInnen des Transportservices an. Diese Kosten müssen mit den Einsparungen einer Verringerung der Fahrzeugsflotte und verringerten Parkplatzsuchzeiten abgewogen werden. Die Entwicklung von Optimierungsverfahren und das Aufzeigen von Potenzialen in dieser Arbeit unterstützen somit zukünftige Umsetzungen von Trip Sharing Konzepten und tragen zur Entwicklung von innovativen und nachhaltigen Mobilitätsformen bei.

Part II
Framework Paper

1 Background and Motivation

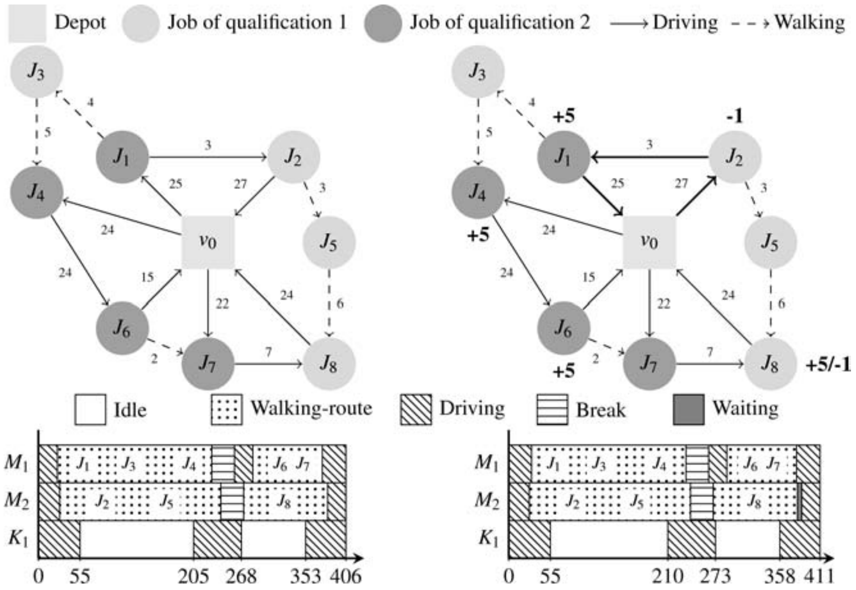
The home service industry offers services at the customers' home locations. Recently, such services are challenged by increased demand, which results in high organisational efforts. In urban settings, limited parking spaces and congestion further challenge operations, while providers aim to reduce costs and environmental footprints. One industry particularly impacted is home health care (HHC), which acts as a sample setting for this thesis. Nevertheless, similar challenges occur in various other home service industries such as maintenance and repair services. Currently, staff members mostly operate separate vehicles as primary mode of transport to reach clients. From this situation originates the motivation of this thesis: to investigate sustainable transport concepts for home service providers by development of innovative solution procedures. Encouraged by multiple governmental and intergovernmental organisations world-wide (ADB, 2010; EC, 2011; US-DOT, 2013), trip sharing (also referred as ride-sharing), where multiple travellers share one vehicle at the same time for their individual trips, is of high interest to providers. Furthermore, it can easily be combined with walking to further decrease the number of required vehicles. Real-world applications of trip sharing concepts, however, mostly focus on customer transportation, e.g., shared-taxis or dial-a-ride services. Organised trip sharing provided for employees is rarely investigated with the exception of widely-studied commuter carpools (e.g., Wartick, 1980; Teal, 1987; Ferguson, 1997). For details regarding trip sharing including potentials and challenges, refer to Furuhata et al. (2013).

In HHC operations, service durations tend to be long, resulting in low vehicle utilisation, especially in urban settings where driving distances between two clients are short. Through the implementation of transport services operated by professional drivers, nurses are delivered to clients' premises and picked up after completion of a service. Furthermore, nurses can walk short paths between two clients to reduce driving distances. This problem setting leads to interesting and challenging research questions. Nurses have to be routed and scheduled with the objective to reduce travel durations and under the consideration of various operational and regulative constraints such as time windows, qualification requirements, working and break regulations. In particular, interdependencies resulting from multiple trips on different vehicles and the need to synchronise vehicles and staff members are of high interest and little studied. In the problem studied in this thesis, a staff member has to be on board a vehicle before being delivered. To perform a pickup, the staff member and vehicle have to meet at the same place at the same time. Any discrepancy results in costly wait times and, in the worst case, infeasible routing and scheduling. Furthermore, changes are challenging to perform as each minor delay requires adjusting other pickup and delivery times, potentially even those of other staff members.

A simplified problem example as given in Fikar and Hirsch (2015b) is shown in Figure 1. Example 1 shows the daily operation plan for two nurses with one shared vehicle. Nurse M_1 performs a walking-route with three jobs after being delivered by the transport service. Before being picked up, a break is scheduled to comply with regulations and, at the end of the working day, the nurse is delivered back to the depot. Nurse M_2, in contrast, performs only three jobs and takes the break within the walking-route. Nevertheless, as the jobs of M_2 take longer, the schedule is synchronised resulting in no wait time at the pickup location at the end of the day. A small change in the vehicle routing, however, as shown in Example 2 of Figure 1, leads to additional wait times and increases the objective value of the optimisation problem.

To enable operations, solution procedures are developed in this thesis for both static and dynamic settings. Additionally, a numerical comparison of the transport concept facilitating trip sharing and walking to current business practices is additionally given. Therefore, the contribution of this thesis is twofold: planners are provided with solution methods to enable combined trip sharing and walking in realistic static and dynamic home service settings, while the performed analysis provides decision makers with implications and beneficial settings for potential implementations.

The remainder of this thesis is structured as follows: in Part II, related work is introduced in Section 2. Section 3 gives an overview of the studied problem and Section 4 presents main contributions of the journal articles. Results are discussed in Section 5 and concluding remarks are given in Section 6. In Part III, the journal articles constituting this cumulative thesis are provided. Furthermore, a curriculum vitae of the author is given in the Appendix.



Example 1. *The left side of Fig. 1 gives a relaxed example with two nurses (M_1 with $q_1^M := 2$; M_2 with $q_2^M := 1$) and one vehicle. Eight jobs have to be visited;* {1, 4, 6, 7} *with* $q_i^J := 1$ *and* $d_i := 45$ min *and* {2, 3, 5, 8} *with* $q_i^J := 2$ *and* $d_i := 105$ min. *Starting from the depot, the vehicle visits J_1 and J_2 and delivers a nurse at each stop. M_1 arrives at J_1 after 25 minutes, M_2 at J_2 after 28 minutes. Note that M_2 needs an additional minute longer compared to a direct delivery from the depot due to the delivery of M_1. After finishing their jobs, both nurses walk to their next jobs, where M_1 downgrades at J_3. Both nurses have to take a break* (r: = 30 min) *which is scheduled after a job. After completing the last job on their walking-routes, the vehicle picks them up and brings them back to the depot, as in the case of M_2, or to another job where M_1 starts a new walking-route.*

Example 2. *On the right side of Fig. 1, the visiting order of J_1 and J_2 is reversed. As a result, M_2 finishes the walking-route one minute earlier, while M_1 needs five minutes longer. Without interdependencies such a swap only requires an update and feasibility test in the corresponding tour. In our example, the vehicle has to pickup M_2 one minute earlier and M_1 five minutes later, which can lead to feasibility conflicts. Furthermore, at J_8, the nurse and the vehicle are no longer synchronised, which results in an additional, potentially infeasible, wait time of six minutes.*

Figure 1: Home service trip sharing problem facilitating walking (left); interdependencies between tours (right); M denotes nurses, J jobs, q_i^M and q_i^J qualification levels and requirements. (Fikar and Hirsch, 2015b)

2 Related Work

HHC routing and scheduling problems are predominantly modelled as an extension of the vehicle routing problem with time windows (VRPTW) and mostly focus on static problem settings where all data are known in advance. For details on the VRPTW, refer to Bräysy and Gendreau (2005a,b) and Kallehauge et al. (2005). Furthermore, most work considers the setting where each nurse operates a separate vehicle (e.g., Begur et al., 1997; Cheng and Rich, 1998; Trautsamwieser et al., 2011; Rasmussen et al., 2012; Trautsamwieser and Hirsch, 2014). To solve the corresponding routing and scheduling problems, exact solution approaches based on mixed-integer problem (MIP) formulations and various metaheuristic approaches were developed. Recent work further studies HHC routing with public transport (e.g. Hiermann et al., 2015; Rest and Hirsch, 2015), however, no prior work on trip sharing concepts for home service providers is found in the literature.

The articles in this thesis are the first works in the context of home service operations, which focus on the implementation of trip sharing combined with the additional option of walking short distances. The problem is modelled as an extended many-to-many multi-trip dial-a-ride (DARP) problem. An overview of DARPs, which deal with the optimization of door-to-door transportation of people, is given in Cordeau and Laporte (2007) and Parragh et al. (2008). The problem studied in this thesis differs from the classical DARP as follows: (i) In contrast to minimising the distance driven, the sum of drive times of the transport services and working times of all nurses are minimised under consideration of mandatory break and working time regulations. (ii) The transport services have to move nurses from a pickup to a delivery location, however, the next delivery location after a pickup is not fixed in advance, but decided during the solution procedure. For instance, while in a classical DARP, moving a passenger from location A to B is given, in the problem studied in this thesis, the solution procedure can decide where to deliver a staff member under the consideration that each client has to be visited exactly once within a corresponding time window. This introduces interdependencies and synchronisation constraints. A staff member's pickup time depends on when he/she was delivered and vehicles and staff members have to meet at the same place and time to perform a pickup operation. (iii) Not all movements have to be done with the transport services as staff members can walk between jobs.

Synchronisation constraints and interdependencies between multiple tours are emerging topics in the vehicle routing community. A classification and overview of these topics are given in Drexl (2012), who further states the importance of future work in this field due to the high number of corresponding real-world applications. Doerner et al. (2008) consider interdependent time windows in a blood donation collection problem. As donated blood is perishable, a maximum time limit is given from when the blood is donated until when it has to be delivered to the blood bank. As a result, multiple pickups have to be performed from a donation location during a day of operation, whereas the feasible time-interval between two pickups as well as the route length depend on each other. This is similar to the problem setting in this thesis where multiple routes of staff members are interdependent. To solve the problem, Doerner et al. (2008) propose various heuristics, an MIP formulation and a branch-and-bound algorithm. In the context of HHC services, synchronisation issues are mostly considered in respect to the provision of simultaneous or sequential services at clients' homes, i.e., a client requires multiple nurses at the same time or in a given order. Bredström and Rönnqvist (2008) introduce an optimisation-based heuristic to handle temporal synchronisation and precedence and list HHC services as a real-world application. A heuristic based on a sophisticated solution representation to schedule multiple nurses either simultaneously or in a given order is further proposed by Mankowska et al. (2014).

Synchronisation to share vehicles and resulting interdependencies are discussed in related vehicle routing problems (VRPs). Lin (2011) introduces a problem setting originating from real-world courier services and develops a two-stage heuristic to solve the corresponding problem. Heavy resources, e.g., a vehicle, can load lighter resources, e.g., a courier, and both can serve customers individually. As a result, the heavy vehicle delivers the lighter one at a certain location from where it performs an individual route. This setting is quite similar to the walking-routes performed in the problem setting of this thesis, however, Lin (2011) only allows the heavier resources to pick up the lighter ones at the last stop before returning to the depot. As a consequence, each light resource can only perform at maximum one route, which is a major difference to the presented work where staff members are constantly delivered and picked up to perform multiple walking-routes. Furthermore, of special interest to the given problem setting are VRPs with transfers or transshipments. To transfer goods or passengers, multiple vehicles have to meet at a given time and at the same location. A propagation algorithm is implemented by Qu and Bard (2012) to test feasibility of insertions in an aircraft transport problem with transshipments. Masson et al. (2014) study DARPs with transfers and propose a simple temporal problem to efficiently check the feasibility of inserting stops in vehicle routes. This method is further discussed in detail in Masson et al. (2013). Mandatory break regulations and the additional option of walking are not included. Additionally, transfers are not mandatory. In the problem studied in this thesis; however, transfers between multiple vehicles have to be performed as staff members are not only delivered to clients, but also picked up after completion of the services.

3 Problem Description

The problem, which uses HHC operations as a sample setting, consists of n jobs, m nurses and k vehicles and is defined on a complete graph $G = (V, A)$. The vertex set V includes pickups and deliveries for each job. Each arc $(i, j) \in A$ is indicated with a travel duration for driving and walking. The objective is to reduce the sum of travel times and wait times of nurses and drivers. Therefore, idle times of drivers at the depot are not included in order to only consider time spent for the operation of the transport services. Furthermore, time spent on breaks are not considered as they do not count as working time, i.e., are unpaid.

Each client requests a service of a fixed duration, which has to start within a time window and requires a certain qualification level of the nurse providing the service. These qualification levels are modelled hierarchically with a higher number representing higher qualifications and range from housework assistance to the provision of medical treatments at the clients' homes. Each service has to be performed by one of the given nurses and a single nurse typically serves multiple clients on a given day. To perform a service, a nurse needs to have at least the required qualification level of the customer. Additionally, a maximum deviation of qualification level higher than that which is required is allowed, however, a nurse can only perform a predefined number of jobs with a lower qualification requirement. Nurses further have to comply with working time and break regulations, indicating an upper limit on the working time as well as a defined time frame in which a mandatory break of a certain duration has to be scheduled.

All nurses start and end the working day at a single depot. To move between two jobs, nurses can either walk or be transported by one of the shared vehicles. To transport nurses, a given number of vehicles are available, each starting and ending the working day at the depot. These vehicles are operated by professional drivers who cannot serve any clients. Multiple nurses can be transported on a vehicle simultaneously as a long as the vehicle capacity is respected. Additionally, constraints limiting ride times, wait times and walking durations of nurses are included to consider employee satisfaction. Therefore, maximum ride times are based on the detour and resulting delay of delivering or picking up other nurses compared to driving on the shortest path. Cumulative wait times are bound by an upper limit between two walking-routes. Similarly, maximum walking durations between two customers and cumulative walking durations within a walking-route are limited. The objectives and constraints of the problem are summarised in Table 1. For a more detailed description of the considered problem, refer to the problem descriptions in Fikar and Hirsch (2015b) and Fikar et al. (2015e) in Part III of this thesis.

4 Materials and Contributions

The optimisation problem of routing and scheduling staff members facilitating trip sharing and walking is investigated in this thesis from three different perspectives. In the first instance, the problem was solved as a static DARP where all information is

Table 1: Objective and constraints based on Fikar and Hirsch (2015b)

Objective	
Nurses working times without service durations	Nurses' working times are calculated as the difference between when each nurse first leaves the depot at the start of the working day and when they return excluding mandatory breaks. From the objective value, constant service durations are deducted. Consequently, it includes times spent on vehicles, walked and waited.
Drivers working times	Durations which the vehicles are not in the depot are added to the objective value to represent drivers' working times.
Constraints	
Number of nurses	Limits the number of available nurses per qualification level.
Maximum walking duration	Limits the walking duration between two jobs.
Cumulative maximum walking duration	Limits the sum of walking durations between each delivery and pickup.
Maximum working time	Limits the working time of a nurse.
Maximum working time without a break	Nurses who work longer than this threshold have to take a break.
Breaks	Breaks are scheduled before or after a job and end at their start location. Before and after this break, no continuous working duration longer than the maximum working time without a break is allowed.
Time windows	Each job has to be started within its hard time window.
Maximum ride time	Limits nurses' detours between each pickup and delivery.
Qualification requirements and deviations	Jobs are performed by nurses at or to a certain degree above the job's qualification requirement.
Downgradings	A nurse can perform a predefined maximum number of jobs requiring lower qualifications.
Maximum waiting of nurses	The sum of waiting times is limited between each delivery and pickup of a nurse.
Depot constraint	A nurse starts and ends the working day at the depot and trips from/to the depot are performed with the transport service.
Number of vehicles	Limits the number of available homogeneous vehicles.
Load constraint	At any given time, the vehicle capacity cannot be exceeded.

given at the start of the planning horizon. Therefore, a matheuristic was developed and presented in Fikar and Hirsch (2015b). Next, an extensive numerical evaluation of trip sharing concepts from a policy perspective was conducted. It focuses on the comparison between trip sharing and the common industry practise where each staff members operates a separate vehicle. This work is presented in Fikar and Hirsch (2015a) and indicates beneficial settings for the implementation of trip sharing concepts. Lastly, a solution method for dynamic settings is introduced in Fikar et al. (2015e) to enable operations in real-world environments subject to cancellations and other uncertainties. Each topic is briefly discussed in the following subsections. To summarise, this cumulative thesis consists of the following publications, which can all be found in Part III of this thesis:

- Fikar, C; Hirsch, P. (2015b) A matheuristic for routing real-world home service transport systems facilitating walking. Journal of Cleaner Production 105, 300-310.
- Fikar, C; Hirsch, P. (2015a) Evaluation of a trip sharing concept for home

health care services. Submitted to Transportation Research Part A: Policy and Practice. 2nd Revision.

- Fikar, C; Juan, AA.; Martinez, E.; Hirsch, P. (2015b) A discrete-event driven metaheuristic for dynamic home service routing with synchronised trip sharing. European Journal of Industrial Engineering, in press.

All three publication are based on real-world data originating from the Austrian Red Cross and statistical distributions of HHC services. All data were anonymised to conceal clients' locations or other personal data of clients and staff members. In the data set, three different qualification levels are considered, ranging from housekeeping assistance to medical treatments. The planning horizon is one day and 30 instances were randomly generated. In a sub-urban area, 15 instances are located and 15 in an urban area. For each area, five instances with 75 jobs, five with 100 jobs and five with 125 jobs are given. To enable comparison and motivate future work, all instances and best solutions are publicly available at `http://www.wiso.boku.ac.at/en/production-and-logistics/research/instances/`. Table 2 gives an overview of the characteristics of the 100 client instances. Therefore, the urban and sub-urban instances use the same five distributions.

Additionally, the following selection of papers were authored or co-authored in

Table 2: Qualifications, time windows and service durations in the 100 client instances of Fikar and Hirsch (2015b). Time windows are indicated in minutes (e.g., 360 = 6am) (Fikar and Hirsch, 2015a)

	Time Window	Qualification 1				Qualification 2				Qualification 3			
	Earliest start	360	630	900	360	360	630	900	360	360	630	900	360
Instance	Latest start	630	900	1170	1170	630	900	1170	1170	630	900	1170	1170
1	# of clients	12	26	19	10	7	3	6	3	3	6	2	3
2		25	25	11	7	6	8	5	6	1	1	4	1
3		22	22	17	7	5	8	4	5	2	6	1	1
4		19	27	21	7	5	8	2	4	-	4	2	1
5		22	14	17	12	4	7	10	2	6	2	3	1
1	Avg. duration	61.3	71	66.3	49.5	47.1	65	50	65	50	42.5	45	35
2	in minutes	57.6	63	65.5	60	70	50.6	51	37.5	45	30	45	30
3		53.2	55.2	58.2	62.1	39	50.6	60	57	45	35	30	30
4		63.2	61.1	60.7	60	51	48.8	60	56.3	-	37.5	37.5	30
5		66.1	64.3	70.6	63.8	52.5	60	58.5	60	37.5	37.5	35	60

related fields. Only published journal article, submitted papers and book chapters are included. Methods and results of the previously listed papers contributed to these works.

- Berariu, R; Fikar, C; Gronalt, M; Hirsch, P. (2016) Training decision-makers in flood response with system dynamics. Disaster Prevention and Management 25(2), in press.

- Berariu, R; Fikar, C; Gronalt, M; Hirsch, P. (2015) Understanding the impact of cascade effects of natural disasters on disaster relief operations. International Journal of Disaster Risk Reduction 12, 350-356.
- Fikar, C; Gronalt, M; Hirsch, P. (2015c) A decision support system for coordinated disaster relief distribution. Initial Submission - Under Review.
- Fikar, C; Hirsch, P; Posset, M; Gronalt, M. (2015a) Impact of transalpine rail network disruptions: A study of the Brenner Pass. Initial Submission - Under Review.
- Gruler, A; Fikar, C; Juan, A; Hirsch, P; Contreras, C. (2015) A Simheuristic for the Waste Collection Problem with Stochastic Demands in Smart Cities. In: Rabe, M; Clausen, U (Eds.), Simulation in Production and Logistics, 49-58; Fraunhofer Verlag. Stuttgart, Germany. ISBN: 978-3-8396-0936-1.

4.1 Trip Sharing in a Static Setting

Facilitating trip sharing and walking in real-world home service operations results in complex optimisation problems. Vehicle and staff members have to be synchronised and various operational and regulative constraints need to be respected, while travel and wait times should be minimised. To assist planners, a matheuristic, which combines a Tabu Search metaheuristic with exact solution procedures, was developed to deal with the problem in a static setting, i.e., all data are known in advance. This method is introduced in Fikar and Hirsch (2015b) and is found in Part III of this thesis.

To the best of the author's knowledge, this work represents the first solution procedure which combines trip sharing with walking to route and schedule home service operations. Furthermore, it considers interdependencies between routes and synchronisation issues resulting from pickups and deliveries of nurses. As a result, the publication is furthermore one of the first works in the field of vehicle routing problems with synchronisation constraints. Figure 2 gives an overview of the developed matheuristic.

In the first stage, all feasible walking-routes are generated and promising ones are selected based on a set-partitioning model. This initial set of walking-routes is transferred to a biased-randomised savings heuristics, which, based on the tech-

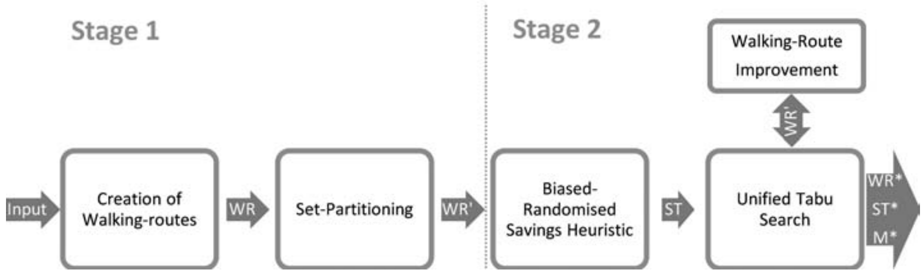


Figure 2: A matheuristic for static home service trip sharing problems (Fikar and Hirsch, 2015b)

niques presented in Juan et al. (2013), generates multiple initial solutions within a short time frame. The best initial solution is optimised by an extended Unified Tabu Search metaheuristic based on Cordeau and Laporte (2003). Therefore, to evaluate a solution, a linear programme is solved to find the optimal start times of vehicles and nurses in order to reduce wait times. Additionally, at certain stages during the optimisation runs, walking-routes are altered by a walking-route improvement operator to align routes of vehicles and staff members.
The computational studies indicate the strength of the algorithm to find feasible solutions of high quality compared to a second developed Tabu Search metaheuristic. Nevertheless, high computational times result, as a linear programme is solved at each solution evaluation to handle synchronisation issues, and, therefore, are a major limitation. Results further show a substantial reduction in the number of required vehicles and the high benefits of considering walking in solution procedure to achieve more sustainable real-world operations.

4.2 Trip Sharing from a Policy Perspective

The next aim was to provide decision makers with implications and indicate beneficial settings for the successful implementation of trip sharing concepts. Therefore, an extensive numerical evaluation was performed to compare the proposed trip sharing concept of Fikar and Hirsch (2015b) with the common practise of each nurse operating a separate vehicle. To enable such a comparison, a solution procedure to route staff members with separate vehicles was developed. Furthermore, the paper gives a brief overview of sustainability factors related to different modes of transport for HHC services. The resulting journal publication (Fikar and Hirsch, 2015a) is attached in Part III and is currently under review after two revisions.
In the computational experiments, the common practise of each nurse operating a

separate vehicle, further denoted as *allCars*, is compared to the trip sharing concept, denoted as *TripSharing*, in different geographic settings and under various parking delays. Additionally, the impact of different objectives of decision makers is discussed. Results show that *TripSharing* enables one to reduce the number of vehicles by up to 89 % in the analysed real-world based HHC instances compared to *allCars*. Nevertheless, travel and wait times of nurses increase substantially. Additionally, drivers of the transport service have to be compensated. Starting with an average parking delay of three minutes, *Trip Sharing* outperforms *allCars* in each of the test cases. Furthermore, results of the computational experiments indicate that *TripSharing* performs best if service durations at clients' homes are long, parking delays are high and in sub-urban areas where clients are distributed in a combination of clusters and random locations. Figure 3 compares the impact of different objectives on time driven by the drivers, multiplied by α, and the sum of time spent by nurses on board the transport service, walked and waited, multiplied by $1-\alpha$. The plot indicates that varying α slightly from the minimum of the summed driving and travel times only leads to small increases in the objective value. Furthermore, it shows that direct substitution between distances driven and walked is possible at low costs. This allows decision makers to adjust operational plans based on their preferences and cost structures.

As a result, the paper indicates in which geographic areas trip sharing is promising

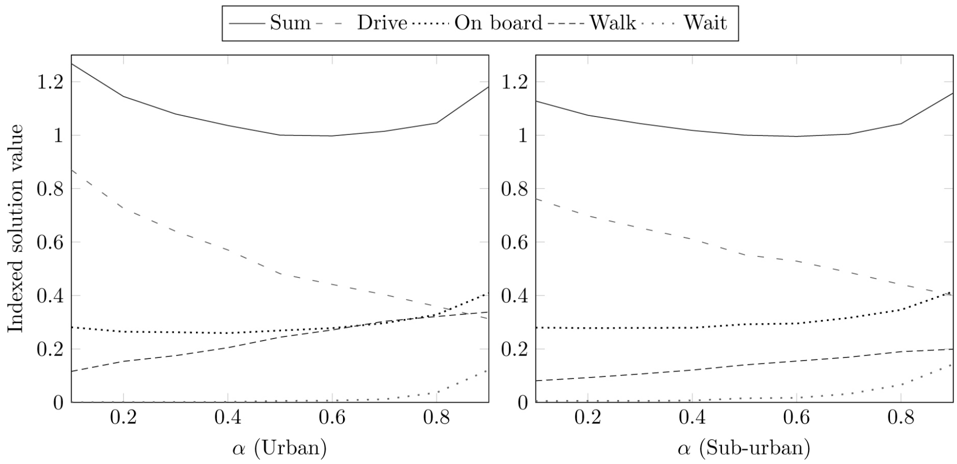


Figure 3: Indexed trade-offs between driving and nurses' travel times (Fikar and Hirsch, 2015a)

and gives decision makers indications about potential benefits, costs and risks of implementation. This is of high importance to develop policies to reduce the number of vehicles and to enable sustainable and efficient real-world operations. Nevertheless, the paper only considers static settings and focuses on minimising travel and driving times. Therefore, future work requires the analysis of potential uncertainties in daily operations due to trip sharing. Additionally, the consideration of social and environmental costs and benefits in the solution procedures are of high importance.

4.3 Trip Sharing in a Dynamic Setting

Real-world operations are subject to various uncertainties. As certain jobs may be cancelled or staff members may be delayed without prior notice, flexible and fast rescheduling and rerouting has to be enabled. With the aim to address the problem in a dynamic setting, a research collaboration with colleagues from IN3-Open University of Catalonia was initiated, which resulted in two one-month scientific stays of the author in Barcelona, Spain. The focus of this work, presented in Fikar et al. (2015e), is to introduce a flexible and highly efficient solution procedure for home service providers facilitating trip sharing and walking, which is easily extended and adjusted to changes in operational structures. The accepted version of the revised manuscript currently in press is found in Part III to this thesis.

To deal with uncertainties on the day of operation, a discrete-event driven metaheuristic was developed. The basic concept is as follows: at the start of the day, the discrete-event driven metaheuristic generates an operation plan. This plan is executed until the first disruption occurs. As the algorithm is based on a time-based view, the algorithm can be rerun with the current situation as an input (e.g., location of staff members, vehicles, open service requests). The most promising plan is applied until the next disruption occurs, at which point the procedure is once more rerun.

To generate a wide-range of promising solutions, the algorithm iteratively generates solutions based on the occurrence of various events. Each event is related to either a pickup, a delivery or the requirement to schedule the next stop of an agent, in the case of HHC operation, a nurse. All generated events are added to a list and are strictly processed in a sequential order. This circumvents the need to adjust previously committed complex timing-decisions and enables one to handle synchronisation constraints and interdependencies in an efficient way. An overview of the procedure is given in Figure 4.

By using biased-randomisation techniques (Juan et al., 2013) to vary start times, walking-routes and staff member movements in each run, multiple promising solutions are generated within a short time-frame. Different transport options are

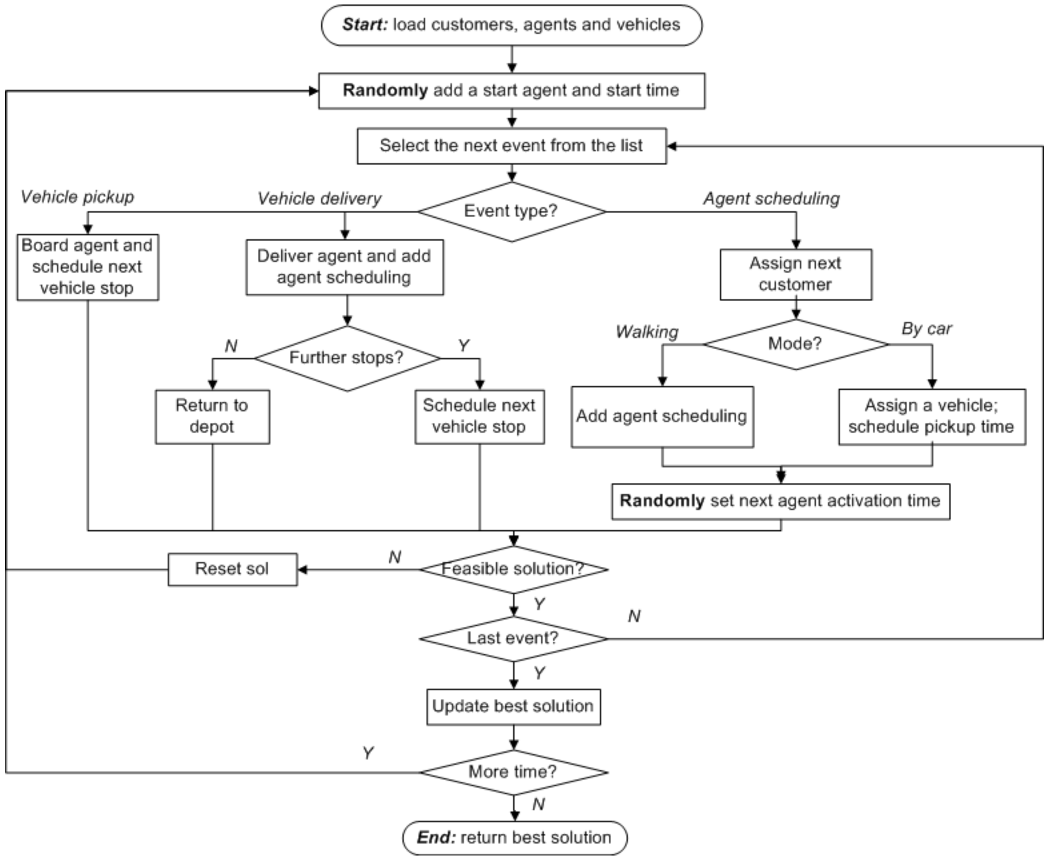


Figure 4: Overview of the descrete-event driven metaheuristic (Fikar et al., 2015e)

compared to indicate whether an agent should walk or request one of the transport service vehicles to be transported to the next client. In each step, feasibility checks are performed and, if infeasible, the generated solution is neglected and a new construction run is started. The solution procedure is run on multiple threads of the computer system and each thread works on a different set of pre-clustered walking routes. Additionally, an internal memory technique prefers promising combinations in the next iterations based on techniques inspired by simulated annealing (Kirkpatrick et al., 1983).

The discrete-event driven metaheuristic is benchmarked on the static instances provided in Fikar and Hirsch (2015b) and shows that solutions of high quality are quickly generated. In particular, it finds feasible solutions for each instance in less than 0.3 seconds. As a result, the matheuristic for the static version can be used to generate plans in advance, while the discrete-event driven metaheuristic enables one to adjust these plans on the day of operation. Additionally, a major advantage of the discrete-event driven method is its flexibility, which allows adding multiple additional real-world constraints by simply extending the feasibility checks without requiring one to perform major changes to the solution method. In a similar way, different modes of transport can be added by simply extending the evaluation options. Future work further aims to focus on finding robust routes in order to reduce the risk of route failures and infeasibilities resulting from sudden changes and delays. Preliminary results of this work are presented in Fikar et al. (2015d).

4.4 Additional Contributions in Related Fields

Methods and findings derived from the work on trip sharing concepts further enabled interesting research collaborations in related fields. The master's thesis of Lübke (2014), which was co-supervised by the author of this thesis, focuses on providing a solver-free version of the static solution procedure in Fikar and Hirsch (2015b) through the introduction learning-effects. Waste routing problems are similar to home services in respect to mandatory working time regulations and high uncertainties in demand. Taking a similar approach to the dynamic discrete-event driven home service solution procedure, a simheuristic is introduced in Gruler et al. (2015). It enables one to route waste collection vehicles quickly and efficiently in real-time. Furthermore, the optimisation is combined with a simulation to derive robust and low-risk solutions.

Similar to the routing and scheduling of nurses, disaster relief operations require coordinated routing and scheduling of operations. To support such operations, optimisation algorithms were combined with an agent-based simulation and GIS data in order to develop a decision support system for coordinated last-mile distribution of relief goods. Computational experiments of two real-world locations under various flooding scenarios are presented and benchmarked with an MIP formulation in Fikar et al. (2015b). Preliminary results of this work were further presented in Fikar et al. (2015a). Additionally in Fikar et al. (2015c), a decision support system to investigate the impact of rail network disruptions on transalpine rail freight movements is introduced and a case study focusing on the Austrian State of Tyrol and the Brenner Pass is presented.

In related co-authored work, the impact of cascade effects on disaster relief operations is studied in Berariu et al. (2015). Based on preliminary work presented in Berariu et al. (2014), a major flood and heat wave are analysed by facilitating system dynamics to show interdependencies between different sectors and the resulting consequences on critical infrastructure. This work was further extended in Berariu et al. (2016) to develop an educational tool for decision makers to improve understanding of flood relief operations. The developed system dynamics simulation is aimed to be used in professional training and allows the investigation of different deployment strategies of relief forces to assist the evacuation of victims and the protection of critical infrastructure during flood events.

5 Discussion

Facing severe parking situations in urban areas, the desire to reduce carbon footprints and ongoing urbanisation, home service providers are required to investigate innovative transport concepts to guarantee high service quality in the future. This is even more crucial to the HHC industry due to its high social importance and the expected increase in demand with an ageing population. Facilitating trip sharing and walking shows immense potential to reduce the size of the required vehicle fleet and to achieve more sustainable operations. Nevertheless, trade-offs between savings in vehicle-related costs and additional expenses for increases in travel-related working times due to detours and delays have to be closely investigated.

Solution methods to plan and route such services, however, are little studied and, furthermore, complex and challenging to solve. The presented solution procedures for the combination of trip sharing and walking in this thesis act as a first step to enable analysing such problems and aim to inspire future work. While the static matheuristic enables solving the problem in advance in order to generate initial operation plans of high quality, the discrete-event driven metaheuristic allows adjusting routes and schedules on the day of operation. In recent years, the issue of synchronisation constraints in VRPs received major attention in the scientific community, which is an important step to support future operations and to improve solution procedures dealing with such challenges. Other important factors such as mandatory working time regulations, the combination of various modes of transport and interdependencies between individual routes, however, are still rarely discussed.

During meetings with decision makers and interviews conducted with planners of HHC service providers throughout the course of this work, multiple arguments for the usage of trip sharing concepts and walking were mentioned. These include, among others, reduced driving stress for nurses, the possibility to enable employment of nurses without driver permits and reduced costs for vehicles. This is further supported by the numerical results presented in this thesis, which show a substantial reduction in the number of required vehicles and the high benefit of explicitly considering walking in solution methods. Nevertheless, complications resulting from trip sharing are important to be taken into consideration before implementation. As shown in the numerical evaluations and the comparison with current practices of operating separate vehicles, driving distance are prone to increase and drivers have to be compensated. Another potential drawback is the increased exposure to risks resulting from trip sharing as vehicle breakdowns and delays can have major impacts on the whole system's performance. In classical systems, where each staff member operates a separate vehicle, a vehicle breakdown only impacts one staff member, while in trip sharing systems, multiple staff members are affected due to the shared vehicle. This requires carefully developed risk management strategies and backup plans to enable operations. Furthermore, this can be supported by new solution procedures that focus on the generation of robust solutions in different risk scenarios.

Additionally, transport of home service staff members have manifold consequences on social factors such as employee and customer satisfaction. Studies surveying these groups would improve understanding and benefit future implementation of trip sharing concepts. This thesis further focused on the reduction of travel and driving times; however, no direct impact on the generation of emissions was investigated. As a consequence, important future work includes the development of multi-objective solution procedures. This enables wide-ranging analyses of the social and environmental impact of trip sharing and walking concepts for providers, staff members and clients. In particular, field tests are crucial implementing trip sharing concepts on a small test scale. Such tests will give clear implications of the potentials of trip sharing for home service providers and further will result in a range of interesting future research questions.

6 Conclusion

This thesis introduces solution procedures and provides a numerical evaluation of home service routing and scheduling facilitating trip sharing and walking. A matheuristic designed for static problems and a discrete-event driven metaheuristic for dynamic settings is proposed. While the former generates solutions of high quality to plan HHC services in advance, the latter enables fast and efficient rescheduling and rerouting on the day of operation. Benefits and potential drawbacks of combined trip sharing and walking is further numerically evaluated, indicating a high potential in settings where parking spots are limited and service durations are long. Independent of the setting, the number of required vehicles can be reduced substantially; however, professional drivers of the transport service have to be compensated. Nevertheless, with demand for home services expected to increase, ongoing urbanisation and stricter environmental regulations, providers have to investigate innovative transport concepts in order to stay competitive and to guarantee future service quality. Therefore, this thesis provides a first important step to investigate potentials of trip sharing concepts to assist decision makers and aims to motivate future work in related fields.

In conclusion, decision makers have to carefully analyse the impact of combined trip sharing and walking before implementation. While vehicle-related costs can be reduced substantially, costs related to travel and wait times are prone to increase. The success of facilitating trip sharing and walking depends on the cost structures and objectives of the providers as well as the geographic setting of the operation area. The developed solution procedures enable such a comparison and, as a result, support future implementation. Nevertheless, field tests are required to fully understand the impact of trip sharing and studies on staff and client satisfaction would benefit the acceptance of such innovative concepts.

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Part III
Journal Publications

This cumulative dissertation consists of three journal papers investigating the topic of routing and scheduling home services facilitating walking and trip sharing. Two of these articles were accepted for publication in international scientific journals and one is currently under review after two revisions:

- Fikar, C; Hirsch, P. (2015b) A matheuristic for routing real-world home service transport systems facilitating walking. Journal of Cleaner Production 105, 300-310.
  (Impact Factor 2014: 3.844; 5-Year Impact Factor 2014: 4.167)
- Fikar, C; Hirsch, P. (2015a) Evaluation of a trip sharing concept for home health care services. Submitted to Transportation Research Part A: Policy and Practice. 2nd Revision.
  (Impact Factor 2014: 2.789; 5-Year Impact Factor 2014: 3.563)
- Fikar, C; Juan, AA.; Martinez, E.; Hirsch, P. (2015b) A discrete-event driven metaheuristic for dynamic home service routing with synchronised trip sharing. European Journal of Industrial Engineering, in press.
  (Impact Factor 2014: 0.736; 5-Year Impact Factor 2014: 0.87)

The following section provides the final or current versions of these publications.

Journal of Cleaner Production 105 (2015) 300–310

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A matheuristic for routing real-world home service transport systems facilitating walking

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ABSTRACT

This paper provides a solution procedure for a state-dependent real-world routing and scheduling problem motivated by challenges faced in the urban home service industry. A transport service delivers staff members of different qualification levels to clients and picks them up after completion of their services. The possibility to walk to clients, interdependencies, time windows, assignment constraints as well as mandatory working time and break regulations are considered. The introduced matheuristic consists of two stages, identifying potential walking-routes and optimising the transport system. The presented numerical studies are performed with real-world based instances from the Austrian Red Cross, a major home health care provider in Austria. The results show that implementing walking and pooling of trips in solution procedures decreases the number of required vehicles substantially.

1. Introduction

Urbanisation causes various challenges like congestions and limited parking spaces for home service providers. This paper is motivated by a project performed with the Austrian Red Cross, a major home health care (HHC) provider in Austria; however, similar challenges occur in various home services such as appliance repair, routine maintenance and private tutoring. These services offer high social benefits for clients; nevertheless, they only contribute little to environmental sustainability (Halme et al., 2006). While public transport can be utilised in urban areas (e.g. Hiermann et al., 2013; Rest and Hirsch, 2013), it often lacks the flexibility of privately owned vehicle fleets due to infrequent service times and limited storage capacities for required equipment. As a result, most nurses operate separate vehicles, which leads to high fixed and operating costs as well as low vehicle utilisations, especially when facing long client service times. Additionally, a growing number of nurses are without driver's permits or reluctant to drive. Consequently, with HHC demand drastically increasing (Rest et al., 2012), novel sustainable concepts are required. This is further stimulated by stricter environmental regulations and the desire to decrease companies' ecological footprints. To achieve this, non-technology driven approaches are crucial (Moriarty and Honnery, 2013).

Motivated by these challenges, we introduce a solution procedure for the daily planning of HHC providers that operate multiple vehicles to deliver nurses to clients' homes and to pick them up after service is provided. Additionally, nurses can walk to clients. The presented work helps service providers to reduce their fleet and to lower fixed expenses while at the same time service quality is less impacted by the availability of parking spots. The pooling of trips as well as the option of walking can potentially decrease the environmental impact of the home service industry. The model is tested with instances based on real-world data. The contribution of this paper is twofold, namely describing this innovative real-world problem and providing a solution procedure to overcome current challenges. This supports decision-makers to investigate the impact of implementing transport systems, which facilitate both walking and trip pooling.

The remainder of this paper is organised as follows: Section 2 discusses related work. Section 3 defines the problem. Section 4 describes the two-stage solution procedure. Computational results are presented in Section 5 and concluding remarks in Section 6.

2. Related work

The introduced case has similarities with a broad range of problems such as the dial-a-ride problem (DARP), the truck and

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trailer routing problem (TTRP) and various real-world applications. DARPs, a special version of the pickup and delivery problem, occur in taxi and ambulance operations among others and deal with the transportation of customers from a pickup to a delivery location. Transport requests are predefined, which is a major difference to our problem where assignments are part of the optimisation. In most cases, the objective is to reduce the vehicles' drive times under maximum ride times, a user convenience constraint; however, a broad range of variants and extensions are found in the literature. For an overview of DARPs, refer to Cordeau and Laporte (2007), and Parragh et al. (2008).

Compared to the TTRP introduced by Chao (2002), where vehicles are uncoupled en-route as certain customers cannot be reached otherwise, sub-routes in our problem do not have to end at their start, but can end at any job. Furthermore, they can be continued on other vehicles and vehicles and nurses move individually at the same time. Lin (2011) introduces a two-stage heuristic for a real-world courier problem containing heavy resources, which carry lighter resources. These lighter resources, e.g. a courier, can pickup and deliver items independently after being unloaded by the heavier resource, which itself can serve clients. In contrast to our problem, the lighter resource can only re-join the heavier one at the last stop of the tour before returning to the depot. This also indicates that a lighter resource can only perform one sub-route. Compared to an independent strategy, lower average total costs and lower usages of heavy resources are achieved under certain conditions.

In the context of HHC, Trautsamwieser et al. (2011) consider different qualification levels, assignment constraints, working time regulations and mandatory breaks in daily planning, where each nurse operates a separate vehicle. An exact model and a variable neighbourhood search-based heuristic are proposed. Concerning working time regulations and mandatory breaks, related work is found in the context of various real-world applications. Nevertheless, despite their high importance in practice, only little attention is received in the literature. Goel (2009) proposes a large neighbourhood search to comply with European Community driving time regulations. Kok et al. (2010) show the significance of these regulations and the resulting increase in routes and durations. A restricted dynamic programming heuristic combined with a break scheduling heuristic is introduced.

Similarly, the impact of synchronisation and interdependencies on vehicle routing problems (VRP) is little analysed in the literature. Bredström and Rönnqvist (2008) describe real-world problems where including temporal synchronisation has a large impact on solution quality and feasibility. Solution approaches based on mixed integer programming are provided. To the best of our knowledge, Doerner et al. (2008) were the first to explicitly consider interdependent time windows in a real-world problem faced in blood transportation. As in our problem, a change in the sequence of one route can lead to infeasibility of all other routes. A mixed-integer programming model, three variants of heuristic solution approaches and a branch-and-bound algorithm are proposed. A survey by Drexl (2012) on synchronisation gives an extensive overview of its importance and the resulting challenges. Of special interest are VRPs with transfers or transshipments, where similar challenges are faced concerning feasibility testing and interdependencies as in our problem. Qu and Bard (2012) implement a propagation algorithm to check feasibility of insertions in an aircraft transport problem with transshipments. Masson et al. (2014) model the feasibility problem for a DARP with transfers as a simple temporal problem and use the Bellman-Ford-Cherkassky-Tarjan algorithm to solve it. None of these solution approaches consider mandatory break regulations or the additional option of walking to subsequent clients. Furthermore, both applications consider specific transfer locations and transfers are not mandatory. This is a major difference to our problem, where transfers occur at clients and have to be performed due to the time-lag between delivery and pickup.

In summary, a broad range of work has been done for related issues; however, published solution approaches are not directly applicable to our problem as various special characteristics are not considered.

3. Problem description

The problem is defined as an extended many-to-many multi-trip DARP. The following outlines the main differences to the classical DARP. (i) The objective is to minimise vehicles' drive times and working times over all nurses considering mandatory break and working time regulations. Service durations are constant and therefore excluded and breaks do not count towards working times. (ii) Transport requests are not predefined, but decided within the model. All jobs have to be served; however, individual requests depend on which nurse can be feasibly assigned at the lowest cost. Furthermore, this introduces interdependencies. The time at which a nurse has to be picked up from a job depends on when the nurse was delivered. (iii) Nurses can walk between jobs. Hence, not all jobs need to be visited by the transport service.

Input is a set J of n jobs ($i \in J$), each requiring a service with a certain qualification requirement q_i^J. To serve these jobs, the service provider has a set M of m nurses ($j \in M$), each associated with a qualification level q_j^M, and a set K of k vehicles ($h \in K$). Jobs can only be performed by a nurse of at least the same qualification level, i.e. $q_j^M \geq q_i^J$. To ensure employee satisfaction, the maximum deviation of qualification level and requirement is set to E, i.e. a nurse of level q_j^M can perform jobs of $[q_j^M - E, q_j^M]$. Additionally, the number of downgradings S, i.e. when an overqualified nurse performs a service, are limited. All jobs have to be started within a hard time window $[e_i, l_i]$, whereas e_i is the earliest and l_i the latest allowed start time. A service takes d_i time units; the service start time is denoted by B_i, while A_i^M and A_i^K denote the arrival time of the nurse and vehicle respectively.

The problem is defined on a complete graph $G = (V, A)$, where each job acts as a potential delivery and pickup location. As a consequence, the vertex set $V = \{v_0, v_1, \ldots, v_{2n+1}\}$ contains delivery vertices $D = \{v_1, \ldots, v_n\}$ and pickup vertices $P = \{v_{1+n}, \ldots, v_{2n}\}$ for all jobs. All tours start and end at a depot indicated by v_0 and v_{2n+1}. Each arc $(i, j) \in A$ is associated with a walking time $t_{i,j}^M$ and a driving time $t_{i,j}^K$. If utilised, the vehicle load Q_i is at least one, indicating the driver, who cannot serve any jobs. The maximum number of nurses on board is constrained by $C - 1$. Each vehicle can have multiple tours. Waiting of vehicles at any other place than the depot is not allowed and, as multiple drivers are available, the total time a vehicle can be utilised is not constrained.

The working time of a nurse is limited by H. If it exceeds R, a break of r time units has to be scheduled. This break starts before or after any job and ends at the same location. Furthermore, it has to be scheduled at a time so that between start or end of the working day and the break, no continuous working time longer than R exists. Maximum detours L of nurses due to other stops on the vehicles' tours must be observed to limit ride times. Therefore, the time spent between pickup and delivery on a vehicle's tour $t_{ij}^{K''}$ is compared to a direct transport ($t_{ij}^{K''} \leq t_{ij}^K + L$). Nurses can also walk to their next job; however, only if t_{ij}^M is below a predefined threshold F. Walking to any other places is not enabled. The cumulative walking time and cumulative wait time of a nurse between each delivery and pickup by the transport service are constrained by U and W respectively. Waiting at a job might result from arriving too early ($A_i^M < B_i$) or from waiting to be picked up ($B_i + d_i < A_{i+n}^K$).

Table 1 summarises the notation, Table 2 the objective and constraints of this problem.

3.1. Walking-routes

We define walking-routes as the job or sequence of jobs visited by a nurse between delivery and pickup by the transport service. If walking-routes consist of more than one job, delivery and pickup locations differ and nurses walk in between. Walking to and from the depot is not enabled as such routes do not have to be considered in the vehicle routing.

Example 1. *The left side of Fig. 1 gives a relaxed example with two nurses (M_1 with $q_1^M := 2$; M_2 with $q_2^M := 1$) and one vehicle. Eight jobs have to be visited; {1, 4, 6, 7} with $q_i^J := 1$ and $d_i := 45$ min and {2, 3, 5, 8} with $q_i^J := 2$ and $d_i := 105$ min. Starting from the depot, the vehicle visits J_1 and J_2 and delivers a nurse at each stop. M_1 arrives at J_1 after 25 minutes, M_2 at J_2 after 28 minutes. Note that M_2 needs an additional minute longer compared to a direct delivery from the depot due to the delivery of M_1. After finishing their jobs, both nurses walk to their next jobs, where M_1 downgrades at J_3. Both nurses have to take a break ($r := 30$ min) which is scheduled after a job. After completing the last job on their walking-routes, the vehicle picks them up and brings them back to the depot, as in the case of M_2, or to another job where M_1 starts a new walking-route.*

3.2. Interdependencies

Time-lags between deliveries and pickups introduce interdependencies between vehicles' and nurses' tours. To perform a pickup, the nurse and the vehicle have to be at the same vertex at the same time. To perform a delivery, the nurse has to be on board the vehicle. In the worst case, a change in one tour can lead to infeasibility of all other tours.

Example 2. *On the right side of Fig. 1, the visiting order of J_1 and J_2 is reversed. As a result, M_2 finishes the walking-route one minute earlier, while M_1 needs five minutes longer. Without interdependencies such a swap only requires an update and feasibility test in the corresponding tour. In our example, the vehicle has to pickup M_2 one minute earlier and M_1 five minutes later, which can lead to feasibility conflicts. Furthermore, at J_8, the nurse and the vehicle are no longer synchronised, which results in an additional, potentially infeasible, wait time of six minutes.*

As a result, time windows, working and break times have to be checked for feasibility and start times of each vehicle's tours have to be optimised. Note that the concept of forward slack time (Savelsbergh, 1992), which is often utilised to minimise waiting within one tour by postponing the start time to the optimal position, is not applicable in this setting as pickup times result from other tours' delivery times. Additionally, pickups and deliveries of one nurse might occur on different vehicles and postponing might be impossible due to later tours' start times. This might even require shifting earlier tours. Therefore, commonly used solution

Table 1
Notation.

Notation	Definition
n	Number of jobs
m	Number of nurses
k	Number of vehicles
J	Set of jobs, $J = \{1, \ldots, n\}$, associated with a qualification requirement q_i^J
M	Set of nurses, $M = \{1, \ldots, m\}$, associated with a qualification level q_j^M
K	Set of vehicles, $K = \{1, \ldots, k\}$
D	Set of delivery vertices, $D = \{v_1, \ldots, v_n\}$
P	Set of pickup vertices, $P = \{v_{1+n}, \ldots, v_{2n}\}$
e_i, l_i	Earliest/latest start time of J_i
A_i^M	Nurse's arrival time at J_i
A_i^K	Vehicle's arrival time at J_i
B_i	Nurse's service start time at J_i
Q_i	Vehicle's load when leaving J_i
w_i	Nurse's wait time at J_i
d_i	Service duration of J_i
t_{ij}^K	Driving duration of (i, j)
t_{ij}^M	Walking duration of (i, j)
H	Maximum working time
R	Maximum working time without a break of r time units
F	Maximum walking duration between two jobs
C	Maximum vehicles' capacity including the driver
L	Maximum detour between pickup and delivery
U	Maximum nurse's cumulative walking between each delivery and pickup
W	Maximum nurse's cumulative waiting between each delivery and pickup
E	Maximum allowed qualification deviation between job and nurse
S	Maximum number of downgradings allowed per nurse

Table 2
Objective and constraints.

Objective	
Nurses' working times without service durations	Nurses' working times are the difference of when each nurse last returns to the depot and first leaves it, without times spent on breaks. From the objective value, constant service durations are deducted. Consequently, it includes times spent on vehicles, walked and waited.
Drivers' working times	Durations which the vehicles are not in the depot are added to the objective value to represent drivers' working times.
Constraints	
Number of nurses	Limits the number of available nurses per qualification level.
Maximum walking duration	Limits the walking duration between two jobs.
Cumulative maximum walking duration	Limits the sum of walking durations between each delivery and pickup.
Maximum working time	Limits the working time of a nurse.
Maximum working time without a break	Nurses who work longer than this threshold have to take a break.
Breaks	Breaks are scheduled before or after a job and end at their start location. Before and after this break, no continuous working duration longer than the maximum working time without a break is allowed.
Time windows	Each job has to be started within its hard time window.
Maximum ride time	Limits nurses' detours between each pickup and delivery.
Qualification requirements and deviations	Jobs are performed by nurses at or to a certain amount above the job's qualification requirement.
Downgradings	A nurse can perform a predefined maximum number of jobs requiring lower qualifications.
Maximum waiting of nurses	The sum of waiting times is limited between each delivery and pickup of a nurse.
Depot constraint	A nurse starts and ends the working day at the depot and trips from/to the depot are performed with the transport service.
Number of vehicles	Limits the number of available homogeneous vehicles.
Load constraint	At any given time, the vehicle capacity cannot be exceeded.
Vehicle waiting	Vehicles can only wait at the depot.

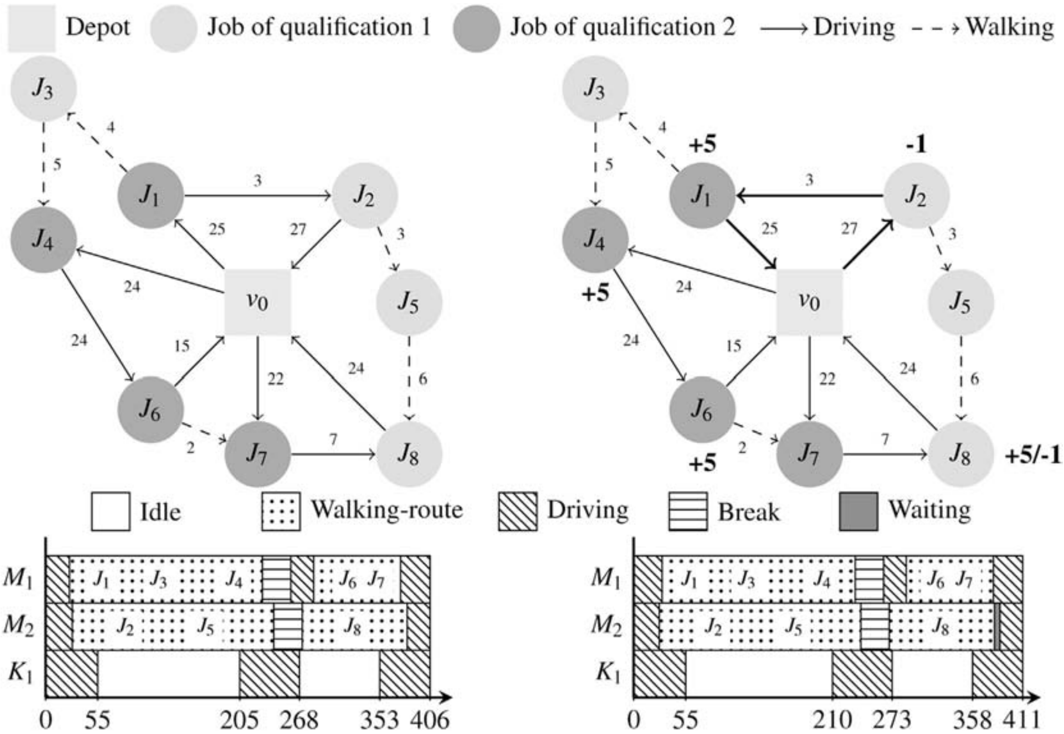

Fig. 1. A transport service with walking-routes (left); Interdependencies between tours (right).

approaches are not well-suited to deal with such problems as multiple vehicles' schedules are not considered.

4. Solution approach

We introduce a matheuristic consisting of two stages, creation of walking-routes and optimisation of the transport system. Fig. 2 gives an overview of the solution procedure. Stage 1 indicates where walking is possible and potentially beneficial. Therefore, a set of feasible walking-routes is created and promising ones are selected by set-partitioning. In Stage 2, starting from the initial set of walking-routes, multiple initial solutions to schedule and route nurses and vehicles are constructed by an extended biased-randomised savings heuristic. Starting from the best found, potentially infeasible, solution, a unified Tabu Search is implemented to restore feasibility and to optimise. This is combined with a walking-routes improvement operator to align the selected walking-routes with nurses' schedules and vehicles' tours.

4.1. Stage 1: selection of walking-routes

Stage 1 creates a set of feasible, non-dominated walking-routes *WR* and selects an initial set WR' containing each job exactly once. Walking takes in most cases longer than going with the transport service. Exceptions result from one-way streets or designated pedestrian areas. This gives driving a natural advantage over walking; however, if a vehicle is not available or costly to relocate, walking is beneficial. Additionally, driving may cause detours for other nurses on board and result in additional working times of drivers. Even deciding to drive where walking is faster might be necessary due to qualification constraints and working time regulations. Due to these trade-offs, *WR* has to provide flexibility to be able to select walking-routes, which fit the vehicle routing.

Algorithm 1 plots the creation of *WR*. For initialisation, n walking-routes, each containing a different single job, are added to *WR*. Afterwards, each walking-route in *WR* is tested for single jobs, which are not yet in this route and can be attached at the end. If adding is feasible, i.e. the extended walking-route complies to all

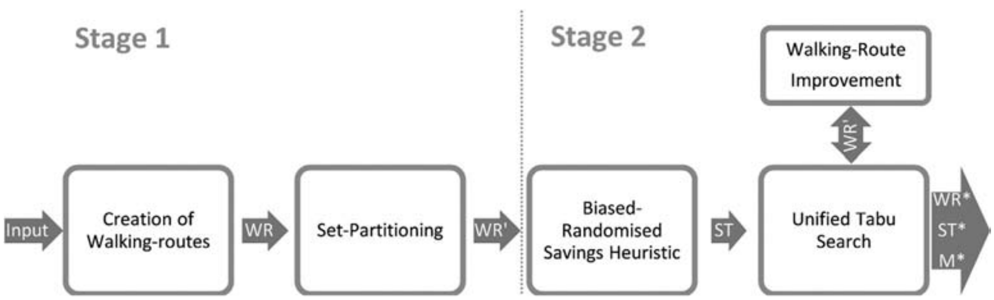

Fig. 2. Two-stage solution approach.

constraints, the walking-route is added to *WR*. The concept of forward slack time (Savelsbergh, 1992) is used to denote the resulting start time window of the walking-route. The procedure is repeated until no new walking-routes can be added.

Algorithm 1. *Construction of WR*

```
WR ← initialise(J);
i ← 1;
while i ≤ WR.size() do
    for j ∈ J do
        if J_j ∉ WR_i then
            WR'_i ← WR_i extended by J_j;
            if feasible(WR'_i) and !dominated(WR'_i) then
                add WR'_i to WR;
            end
        end
    end
    i++;
end
return WR
```

A dominance criterion is modelled to compare new walking-routes to all walking-routes in WR. If start and end jobs are the same and all other jobs are identical in any sequence, the one with a longer duration and tighter time window is removed. If equal, the new walking-route is deleted. However, walking-routes with longer durations, but wider time windows are kept as such walking-routes might enable additional jobs to be added later. Moreover, having wider time windows can be beneficial as more flexibility is given to the vehicle route optimisation.

Example 3. *Fig. 3 illustrates examples for stored and rejected walking-routes. Time windows of jobs and walking-routes are indicated in the squared brackets. To simplify,* $d_i := 1$ min *at each job is assumed. Comparing* WR_1 *and* WR_2*, both walking-routes contain the same jobs and the same start and end location. Due to a higher duration compared to* WR_1*,* WR_2 *is removed. In contrast, when comparing* WR_3 *and* WR_4*,* WR_4 *is kept due to its wider time window.*

From *WR*, an initial set of walking-routes WR' containing each job exactly once is constructed. Optimising the duration of the selected walking-routes would result in each walking-route only consisting of one job. As a result, a set-partitioning model selects WR' minimising both walking-routes' durations d_{WR_i} and driving distances from the depot to delivery and pickup vertices (1). Constraints (2) guarantee that each job is selected exactly once and (3) enforce that the decision variables y_i are binary.

$$\text{Minimise}: \sum_{i \in WR} y_i \left(d_{WR_i} + t^K_{0,WR_{i_D}} + t^K_{WR_{i_P},0} \right) \quad (1)$$

$$\text{Subject to}: \sum_{i \in WR: j \in WR_i} y_i = 1 \quad \forall j \in J \quad (2)$$

$$\text{Subject to}: \; y_i \in \{0,1\} \quad \forall i \in WR \quad (3)$$

After the set-partitioning problem is solved, the problem size is reduced to the number of selected walking-routes n'. The first job of each selected walking-route is added to $D = \{v_1, ..., v_{n'}\}$ and the last job to $P = \{v_{1+n'}, ..., v_{2n'}\}$. Which WR' is best used for Stage 2 depends on the instance characteristics; however, the proposed set-partitioning model finds a WR' which is suited for different conditions as it explicitly deals with the trade-off between walking and driving.

4.2. Stage 2: optimizing the transport system

Stage 2 routes the vehicles and schedules each walking-route to a nurse. The latter is done by enforcing a first-in-first-out (FIFO) rule. If multiple nurses can be assigned to a job, the one who entered the vehicle first is assigned if qualifications, downgradings, wait times, breaks and maximum working time regulations are held in compliance. This requires checking all walking-routes before the delivery of the nurse as well as all subsequent walking-routes. Enforcing this FIFO rule is practical from a maximum ride time perspective, because delivering the nurse who entered the vehicle first results in the shortest maximum ride times.

Starting from WR', an initial solution is constructed. We tested three different constructive heuristics for our problem based on a time-oriented nearest neighbour heuristic (Solomon, 1987), a sequential savings heuristic (Clarke and Wright, 1964) and a parallel savings heuristic (Clarke and Wright, 1964), whereas the latter clearly outperforms the other approaches. From a myopic point of view, lowest total costs are reached if a picked up nurse is delivered to a nearby feasible walking-route. The parallel savings heuristic finds such pairs.

4.2.1. Parallel savings heuristic

The heuristic starts with a set of tours ST', where each tour contains only one walking-route with an individually assigned nurse. Two tours are merged if a total objective value reduction is achieved starting from the merger with the highest savings value. However, our approach differs substantially from the savings heuristic of Clarke and Wright (1964) due to the special problem characteristics. Savings values have to consider the total cost of a tour $c(ST'_i)$, which includes the time spent by all nurses on board the vehicle as well as by the driver. Therefore, the savings value is derived from the arcs travelled by the merged tour multiplied by the vehicle's load compared to the costs of the separate tours as shown in Equation (4).

$$\text{Savings}_{ST'_l,ST'_h} = \sum_{(i,j) \in ST'_l} \left(t^K_{i,j} Q_i \right) + \sum_{(i,j) \in ST'_h} \left(t^K_{i,j} Q_i \right) - \sum_{(i,j) \in ST'_{l,h}} \left(t^K_{i,j} Q'_i \right) \quad (4)$$

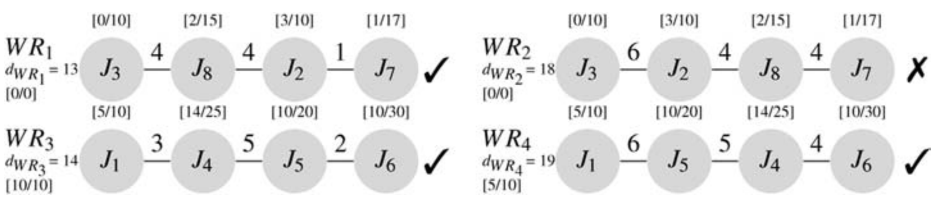

Fig. 3. Dominance criterion of walking-routes.

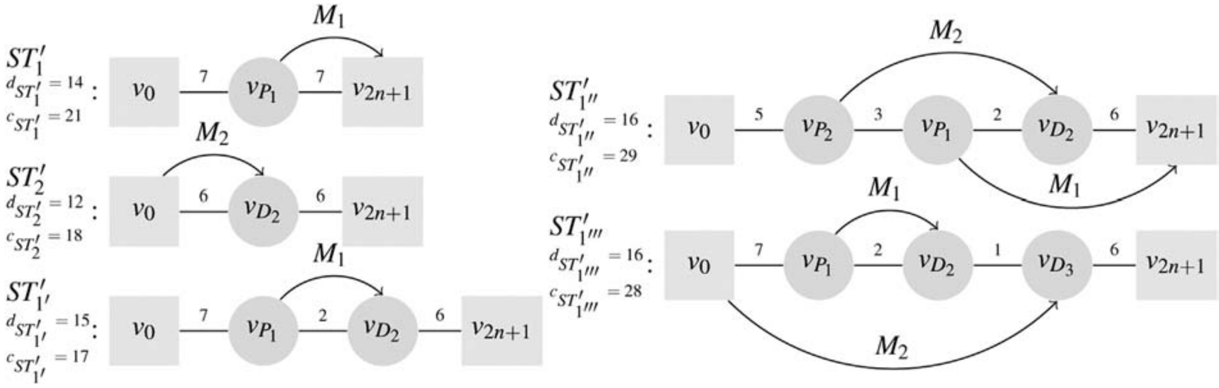

Fig. 4. Calculating and updating tour costs.

Example 4. *Figure 4 shows the savings values calculation where arrows indicate when nurses are on board. Merging v_{P_1} with v_{D_2} leads to a savings value of 22 ($c_{ST'_1} + c_{ST'_2} - c_{ST'_{1'}}$) as M_1 is picked up and directly delivered to the next job. After performing this merger, savings values are updated. For instance, adding v_{P_2} in the front requires reassigning nurses, while attaching v_{D_2} at the end requires an additional nurse from the depot.*

A merger impacts all related savings values and can lead to a change in the nurses' schedules considering the FIFO rule. Moreover, merging tours require shifts in the start times of all related tours due to interdependencies between delivery and pickup times. In the best case scenario, this affects only two tours, i.e. the ones of the merged tours' pickups and deliveries. In most cases, however, if the related tours contain additional jobs that require updating their related pickups or deliveries, it propagates into multiple tours. As a consequence, the buffer by which the start time of a tour can be postponed always depends on the tightest constraint node in all related tours. This also leads to infeasible cycles where moves in start times are not possible.

Example 5. *Fig. 5 illustrates infeasible cycles on an example where $d_{WR'_7} \coloneqq 35$min and $d_{WR'_3} \coloneqq 30$min. By checking the buffer of ST'_2, attaching v_{P_7} is possible. It requires postponing ST'_1; however, a move in its start time requires moving the start time of ST'_2. This again requires moving the start time of ST'_1, which results in an infinite loop.*

Working time, ride time and qualification compliance are checked at each calculation of savings values. In case of infeasibility, the merger is rejected. Required breaks, if feasible, are scheduled before pickups when evaluating mergers and require an update of all related start times and buffers as the time-lag between delivery and pickup is increased. Additionally, if walking-routes are served by different nurses after a merger, previously scheduled breaks have to be updated. Feasibility of breaks concerning the maximum continuous working time and waiting of nurses are not included in the calculation of savings values to speed-up construction; however, both factors are considered in the solution evaluation explained in Section 4.2.2.

The savings heuristic often returns solutions that require more vehicles and nurses than available. If an entire schedule of a surplus nurse can be performed by an overqualified vacant nurse, the nurses are exchanged. Two methods are introduced to further decrease the number of required nurses. Tours with negative savings values are merged if the number of surplus nurses can be reduced. Therefore, the savings values are divided by the number of reduced nurses. Additionally, schedules of two nurses can be combined into one if all constraints are fulfilled. In this case, an additional wait time at the depot might occur, which is limited by W. These two options are evaluated and the least costly one is executed. This is repeated until the number of given nurses of each qualification level is sufficient or no further options exist.

To schedule tours to vehicles, a simple insertion heuristic is used. Each constructed tour is indicated with a duration and time window. Starting with the tour having the tightest time window, all positions to insert the tour on each vehicle are checked until a feasible one is found. Shifting the start time is limited by the buffer and requires a shift in all related tours. If no feasible position exists, the tour is assigned to the vehicle with the least number of tours at the position where the smallest time conflict occurs. After all tours are assigned, ST' is evaluated.

4.2.2. Solution evaluation

Four penalty factors are added to the evaluation function $f(ST') = c(ST') + \alpha q(ST') + \gamma w(ST') + \tau t(ST') + \eta h(ST')$ to allow infeasible solutions during the search procedure. Costs $c(ST')$ include travel and wait times. Violations of capacity, time windows and ride times are denoted by $q(ST')$, $w(ST')$ and $t(ST')$ respectively. $h(ST')$ states how many nurses more than available are needed to serve ST'. Nurses' schedules have to comply with working time and break regulations. To test feasibility, nurses' schedules are first set ignoring start and wait times and only assignments between two

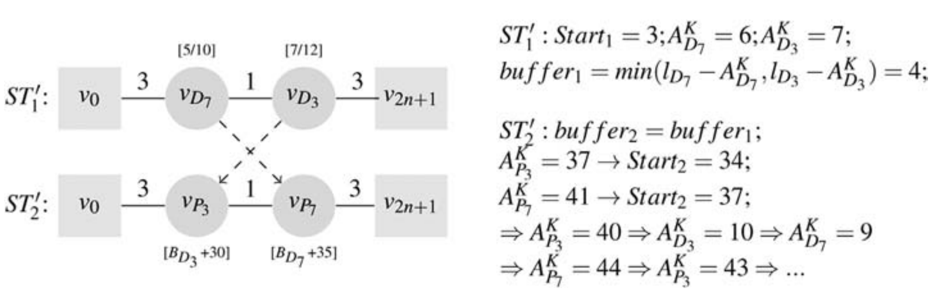

Fig. 5. Infeasible cycles.

nodes are checked, i.e. from depot or pickup to delivery. After all assignments, the complete schedule of each nurse is tested. If H or S is violated, nurses' schedules are split at the positions which lead to the least increases in $f(ST')$. Splitting indicates not delivering a previously picked up nurse, but instead delivering a new one from the depot. If a split is not possible, the penalty term $h(ST')$ is increased by one. This occurs if a walking-route's duration plus the time for delivery and pickup violates H.

Example 6. Fig. 6 *indicates splitting. The schedule of* M_1 *consists of three walking-routes leading to a working time violation, while* M_2 *is vacant. The split is performed at the cheapest position, assumingly at* WR'_1. M_1 *is not delivered to* v_{D_1}, *but instead returned to the depot.* M_2 *arrives from the depot at* v_{D_1} *and continues the further schedule previously assigned to* M_1. *Due to the nurses' additional time spent on the transport service,* $c(ST'_1)$ *increases.*

Breaks are placed within or after a walking-route and scheduled within $[\min(H, H'_i) - R, R]$ of the nurse's schedule, whereas H'_i indicates the working time in case of maximum waiting at each walking-route. This guarantees feasibility of the break position after optimisation of wait times as it considers the maximum potential working time under the current schedule. If no position complies with this rule, the nurse's schedule is split. If a split is not possible, i.e. breaks are required within walking-routes, but tight time windows do not allow, $h(ST')$ is increased by one.

Start times of ST' are optimised by solving a linear program. As wait times and time window violations contribute to $f(ST')$, the optimal start times of each vehicle's tour have to be calculated to fully evaluate a solution. Input is a solution ST' with a fixed order of tours per vehicle $ST'_{h,j}$. The objective function (5) sets each vehicle's tour's start time $A^K_{ST'_{h,j}}$ so that wait times w_i are minimised. If no feasible solution exists, the time window violation terms χ_i and φ_i are minimised to find the best infeasible solution. Therefore, the penalty terms are multiplied by the length of the planning horizon T (e.g. 1440 min). χ_i (φ_i) indicates that the vehicle arrives too early (too late). Constraints (6) limit the wait time per walking-route. (7) guarantee time window compliance of deliveries, whereas t'_i indicates the cumulative time it takes to reach i after starting from the depot based on the tour where i is included. (8) set the time-lag between delivery and pickup of the walking-route to its duration d_{WR_i}. By considering wait times after deliveries w_i and before pickups $w_{i+n'}$, these constraints ensure that vehicles and nurses are synchronised or that the relevant penalties are set accordingly. Additionally, if a break is scheduled at this walking-route, the pickup is further delayed by r_i. Otherwise, r_i equals zero. Note that breaks are not decision variables, but fixed prior to the run of the optimisation model. This is crucial to speed up computation time and to circumvent the need for binary variables. Furthermore, (9) enforce maximum working time compliance and ensure that no additional breaks are required after wait times are added to the nurses' schedules. Therefore, Z_j states the buffer between H (if a break is scheduled) or R (if no break is scheduled) and the current working time of the nurse including wait times within walking-routes $w_{WR'_i}$. Moreover, (10) ensure that multiple tours of one vehicle are not performed at the same time; (11) that vehicles' start times are within the planning horizon and (12) the non-negativity of the decision variables.

$$\text{Minimise}: \sum_{i=1}^{2n'} w_i + T\sum_{i=1}^{2n'}(\chi_i + \varphi_i) \tag{5}$$

$$\text{Subject to}: \quad w_i + w_{i+n'} + w_{WR'_i} \le W \quad \forall i \in D \tag{6}$$

$$e_i \le A^K_{ST'_{h,j}: i \in ST'_{h,j}} + t'_i + w_i + \chi_i + \varphi_i \le l_i \quad \forall i \in D \tag{7}$$

$$\begin{aligned} &A^K_{ST'_{h,j}: i \in ST'_{h,j}} + t'_i + w_i + \chi_i + \varphi_i + d_{WR'_i} + w_{i+n'} + r_i \\ &= A^K_{ST'_{h,j}: i+n' \in ST'_{h,j}} + t'_{i+n'} + \chi_{i+n'} + \varphi_{i+n'} \quad \forall i \in D \end{aligned} \tag{8}$$

$$\sum_{i \in M_j} (w_i + w_{i+n'}) \le Z_j \quad \forall j \in M \tag{9}$$

$$A^K_{ST'_{h,j-1}} + d_{ST'_{h,j-1}} \le A^K_{ST'_{h,j}} \quad \forall h \in K, \forall j \in ST'_h \setminus 0 \tag{10}$$

$$0 \le A^K_{ST'_{h,j}} \le T \quad \forall h \in K, \forall j \in ST'_h \tag{11}$$

$$w_i, \chi_i, \varphi_i \ge 0 \quad \forall i \in D \cup P \tag{12}$$

With the optimised tour start times and resulting wait times, schedules are finalised and wait times and time window violations are added to $f(ST')$. In case no solution is found by the linear program, ST' is rejected. Like in splitting, this occurs if a walking-route's duration plus the travel times for delivery and pickup violates H.

4.2.3. Biased-randomisation

In the savings heuristic, the first mergers have a strong impact. Time buffers are reduced after each merger, highly constraining feasible delivery and pickup times. Two mechanisms are introduced to deal with this problem characteristic. By implementing a biased-randomisation (Juan et al., 2013), multiple runs of the savings heuristic are performed in parallel. Hereby, savings values are ranked and a geometric distribution picks the next merger. The parameter β indicates the steepness of the distribution, whereas if β equals 0, the selection is randomly uniform. If β equals 1, the best ranked candidate is always picked. To further diversify, equally good candidates are sorted randomly as otherwise the same candidate is always ranked first and is selected with a higher

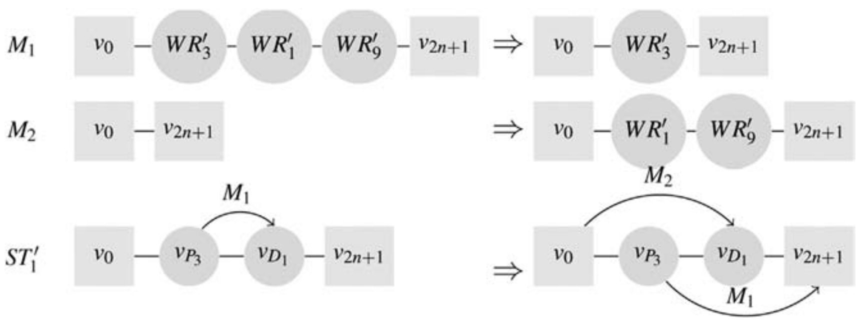

Fig. 6. Splitting nurses' schedules.

probability than equally good mergers. The heuristic stops after a specified number of runs and returns the best, potentially infeasible, solution *ST* as well as the best feasible solution, denoted by ST^*. Algorithm 2 plots the modified biased-randomised savings heuristic.

Algorithm 2. *Modified biased-randomised savings heuristic*

```
f(ST) ← ∞; f(ST*) ← ∞; WR' ← SetPartitioning(WR);
while !terminate() do in parallel
    ST', M ← initialise(WR');
    while !savingslist.empty() do
        randomise() and sort();
        i, j ← biasedrandomise(β);
        merge(ST'_i, ST'_j) and updateaffectedST'(ST'_i, ST'_j);
        recalculatesavings(ST'_i, ST'_j);
    end
    mergeNurses(ST', M) and assignTourstoVehicles(ST');
    f(ST') ← evaluate(ST', M);
    if f(ST') < f(ST) then
        f(ST) ← f(ST') and ST ← ST';
    end
    if f(ST') < f(ST*) and feasible()
        f(ST*) ← f(ST') and ST* ← ST';
    end
end
return ST, ST*
```

4.2.4. Tabu search

Starting from *ST*, feasibility and optimisation are achieved based on a modified unified Tabu Search (Cordeau and Laporte, 2003) which shows good results for DARPs. Two neighbourhood operators, *PDmove* and *DPmove*, are used to modify a solution. *PDmove* places a delivery on a dummy vehicle only containing this job to find the best position for the corresponding pickup. This position is then fixed and the delivery is reinserted into the solution at its best position. In contrast, *DPmove* places a pickup on the dummy vehicle. The operators enable moving both interdependent nodes with respect to the time-lag and also perform intra-tour moves. To speed up computation times, *PDmove* (*DPmove*) is executed on even (uneven) iterations and several moves of the same type are evaluated in parallel. Additionally, after X_1 iterations without an improvement of ST^* or when ST^* is improved, all vehicles' tours are sequentially checked in random order if inserting or removing a return to the depot at any position improves the solution. If so, *ST* is updated.

Evaluating a solution, as explained in Section 4.2.2, is a time-intensive operation. As a result, $f(ST')$ is calculated in steps. After each step, $f(ST')$ is compared to the total evaluation function value of ST°, which denotes the best solution found so far at this iteration. As each step increases $f(ST')$, evaluation is aborted in case of a higher intermediary evaluation value to save run time. First, vehicle travel times, times spent by nurses walking and on board of vehicles as well as load and ride time violations are recalculated for the tours where a change occurred. Other tours do not change in this respect. Next, start and wait times are optimised. Last, surplus nurses are added to $f(ST')$.

To diversify, as proposed by Cordeau and Maischberger (2012), a penalty is added to all non-improving moves based on the relative number of times this move has been added to *ST* in respect to the total number of performed iterations λ. In our algorithm, this penalty depends on how often a delivery or pickup at a job has been added to a certain tour ρ_{i,ST'_j}. To account for single stop tours, which are frequently added and removed, the number of times a new single stop tour of a certain job is created is stored and new tours are initialised with these values. The penalty term is further multiplied by the weight ζ as shown in Equation (13).

$$g(ST') = f(ST')\left(1 + \zeta\frac{\rho_{i,ST'_j}}{\lambda}\right) \tag{13}$$

In each iteration, the best neighbourhood solution ST° is selected and acts as the current solution *ST* for the next iteration. The delivery or pickup, which was placed on the dummy vehicle, is added to the tabu list. As a result, moving this node to any position is forbidden for θ iterations; however, if moving improves ST^*, relocation is allowed. α, γ, τ and η are either divided by $1 + \delta$ if *ST* is feasible, or multiplied by the same value in case of violations to dynamically adjust the penalty weights.

Depending on the vehicle routing, the optimal set of walking-routes differs. To enable a modification of WR', after X_2 iterations without an improvement of ST^* or if ST^* is improved, a walking-route improvement operator is executed. All walking-routes in WR' are sequentially tested in random order for three modifications. First, if all jobs of two walking-routes can be merged in any sequence into one walking-route. Second, if a walking-route can be split in any sequence into two walking-routes and third, if the sequence of a selected walking-route can be exchanged. Due to the pre-processing in Stage 1, modification occurs with all potential candidates in *WR*, which are already evaluated and tested for feasibility. Note that a split adds a delivery and a pickup to the problem, while a merger removes them. Fig. 7 shows examples for walking-route modifications.

After walking-routes are changed, *PDmove* is run to optimise the tour positions of the modified pickups and deliveries. If an operator improves *ST*, the best modification of this walking-route is saved and acts as the new *ST* for the following operator or walking-route. This guides the search to fit WR' with the vehicle routing and instance characteristics. If only few vehicles are available, more walking is enforced; however, if the number of vehicles is sufficient, walking only occurs if beneficial.

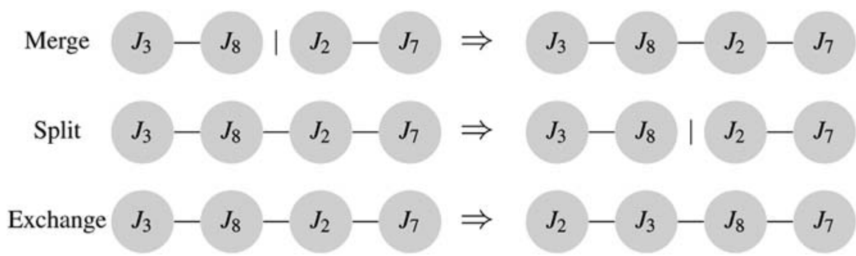

Fig. 7. Walking-route modifications.

The Tabu Search is stopped after a predefined time-limit or a maximum number of iterations and returns walking-routes, vehicles' tours and nurses' schedules of the best found feasible solution.

5. Computational experiments

The described matheuristic is coded in C++ with Microsoft Visual Studio 2012. FICO Xpress-BCL is used to solve the set-partitioning problem and the start time optimisation. Parallelisation is implemented with OpenMP. Computational results were gathered on an Intel Core i7-3930K, 32 GB RAM, with MS-Windows 7 as operating system and 6 threads operating in parallel. All instances and detailed solution files are available at https://www.wiso.boku.ac.at/en/production-and-logistics/research/instances/.

5.1. Instances

Due to the novelty of the concept in both academia and practice, no benchmark instances are available. Our solution procedure is tested with 30 instances based on real-world data provided by the Austrian Red Cross. Nurses have to visit clients to perform services of three qualification requirements varying from housekeeping assistance to medical treatments. Planning horizon is a day. Two geographic distributions of jobs are investigated, an urban and a sub-urban area, indicated in the instance names by “U” and “S” respectively. Duration matrices for walking and driving are calculated with ArcGIS Network Analyst and are based on OpenStreetMap data and a walking speed of 3.6 km/h. All durations are given in minutes and rounded to the next integer value. The mean walking duration between jobs is 29.51 (58.04) minutes for the urban (sub-urban) area. “n” indicates the number of jobs, “k” the given vehicles and “m” the given nurses separated by the different qualification levels starting with the lowest. Three different instance sizes are investigated, namely, 75,100 and 125 jobs. For the smaller instances, jobs where randomly removed from the full list of 125 until the target n was reached. Five different distributions of time windows, service times and qualification requirements were generated for each size and area. These were set based on the probabilities summarised in Table 3 originating from statistical analyses of approximately 2000 real-world visits.

Each vehicle has a C of 6, i.e. it can transport at maximum five nurses. Each nurse is allowed to perform one job at most one level below his/her qualification level ($S := 1; E := 1$). H is 600 min, R equals 360 min and breaks (r) last 30 min W is set to 15 min, F to 10 min, U to 20 min and L is limited by 15 min.

5.2. Parameter setting

To construct initial solutions, each thread executes 75 runs of the biased-randomised savings heuristic with $\beta := 0.45$, which showed the highest average improvement of all β in increments of 0.01 over all instances compared to a non-randomised run. The penalty factors α, γ, τ and η are initialised with 1. Based on Cordeau and Maischberger (2012), δ and ζ are independently set by a uniform distribution between [0, 1] to vary the aggressiveness of intensification and diversification. In accordance to Cordeau and Laporte (2003), θ is set randomly between $[0, 7.5 log_{10} n']$. After 25 iterations without an improvement of ST^*, these values are changed. Adding or removing depot trips (X_1) as well as walking-route improvements (X_2) are performed every $\lceil\sqrt{2n'}\rceil$ iterations without an improvement of ST^* or if ST^* is improved. Each instance is run 10 times to account for the random components in the solution procedures with a run time of 3600 s.

Table 4
Computational results. Bold values indicate the lowest (best) values.

Instance	TS-SPBS		TS-GT		Min ± (%)[a]
	Min (min)	Mean (min)	Min (min)	Mean (min)	
U1-n75-k2-m12-8-4	**521**	538.2	551	574.3	−5.44
U2-n75-k2-m12-8-4	**532**	543.3	560	571.9	−5.00
U3-n75-k2-m12-8-4	**526**	539.4	551	570.1	−4.54
U4-n75-k2-m12-8-4	**539**	546.0	552	568.4	−2.36
U5-n75-k2-m12-8-4	**571**	582.5	593	607.0	−3.71
U1-n100-k2-m16-10-6	**702**	708.8	732	770.5	−4.10
U2-n100-k2-m16-10-6	**707**	717.8	734	771.0	−3.68
U3-n100-k2-m16-10-6	**700**	710.6	743	768.1	−5.79
U4-n100-k2-m16-10-6	**690**	698.4	725	744.3	−4.83
U5-n100-k2-m16-10-6	**736**	742.8	755	794.1	−2.52
U1-n125-k2-m20-12-8	**817**	828.1	885	910.0	−7.68
U2-n125-k2-m20-12-8	**834**	846.8	897	920.1	−7.02
U3-n125-k2-m20-12-8	**838**	846.7	896	945.5	−6.47
U4-n125-k2-m20-12-8	**817**	830.1	857	913.1	−4.67
U5-n125-k2-m20-12-8	**791**	804.7	876	920.9	−9.70
S1-n75-k2-m12-8-4	826	832.4	**825**	854.8	0.12
S2-n75-k2-m12-8-4	**755**	771.0	767	791.1	−1.56
S3-n75-k2-m12-8-4	**793**	806.7	799	827.9	−0.75
S4-n75-k2-m12-8-4	**792**	804.7	822	854.8	−3.65
S5-n75-k2-m12-8-4	**821**	839.9	857	872.7	−4.20
S1-n100-k2-m16-10-6	**1027**	1038.4	1080	1102.3	−4.91
S2-n100-k2-m16-10-6	**998**	1011.7	1064	1089.1	−6.20
S3-n100-k2-m16-10-6	**1039**	1055.2	1109	1132.3	−6.31
S4-n100-k2-m16-10-6	**983**	998.1	1045	1067.7	−5.93
S5-n100-k2-m16-10-6	**1096**	1110.1	1171	1205.9	−6.40
S1-n125-k2-m20-12-8	**1224**	1233.3	1304	1346.3	−6.13
S2-n125-k2-m20-12-8	**1185**	1209.7	1253	1300.0	−5.43
S3-n125-k2-m20-12-8	**1201**	1243.5	1321	1362.4	−9.08
S4-n125-k2-m20-12-8	**1225**	1244.5	1274	1324.5	−3.85
S5-n125-k2-m20-12-8	**1213**	1231.7	1326	1358.0	−8.52

[a] TSSPBS_Min − TSGT_Min/TSGT_Min × 100.

5.3. Results

We compare two versions of the solution procedure. *TS-SPBS* uses set-partitioning and the modified biased-randomised savings heuristic as described in Section 4. In contrast, *TS-GT* starts solely with single stop walking-routes. The initial solution is constructed by adding all deliveries and pickups on one vehicle into one giant tour sorted by e_i. As a result, walking-route selection is completely given to the walking-route improvement operators within the Tabu Search allowing for a broader search procedure, while *TS-SPBS* starts more locally in a promising area of the solution space. The Tabu Search is identical in both versions. Table 4 summarises the

Table 3
Distribution of time windows, qualification requirements and service durations.

$[e_i, l_i]$	[360,630]	[630,900]	[900,1170]	[360,1170]										
Probability	0.25	0.35	0.25	0.15										
q_i^J	1						2					3		
Probability	0.70						0.20					0.10		
d_i	30	45	60	75	90	120	30	45	60	75	90	30	45	60
Probability	0.10	0.30	0.30	0.10	0.10	0.10	0.05	0.25	0.30	0.25	0.15	0.55	0.35	0.10

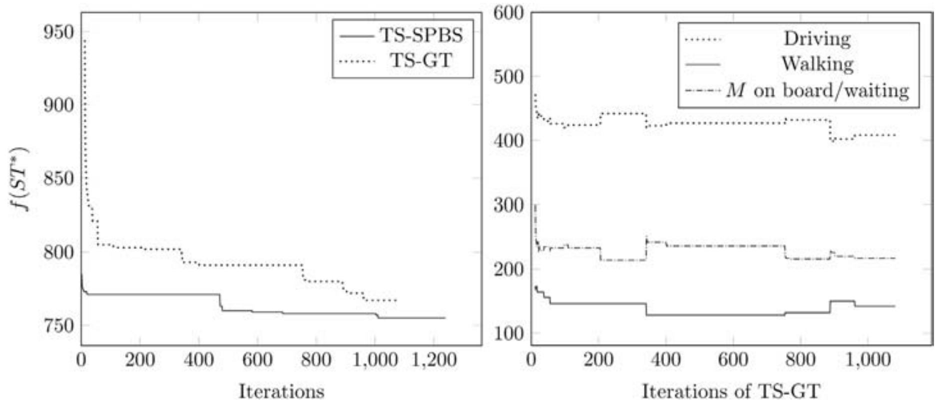

Fig. 8. Solution development for S2-n75-k2-m12-8-4.

computational results. The size of *WR* differs substantially per instance ranging from 225 to 70,500.

The results show the advantage of TS-SPBS. TS-GT performs worse on instances with a large size of *WR*, as the algorithm requires more walking-route improvements to find a suitable *WR*'. Fig. 8 plots the development of ST^* over run time for one sample instance and separates $f(ST^*)$ into the duration driven by the transport service, walked and spent by nurses on board vehicles plus wait times. Major improvements are achieved in the first iterations, providing feasible solutions after short run times. Note that even increasing the distance driven often results in improvements of ST^* if it reduces time spent on board by nurses. This is an interesting finding as improving the working time over all nurses and drivers does not necessarily lead to reductions in the distance driven. Nevertheless, our solution procedure can be modified easily by adjusting the evaluation function to consider various objectives of decision-makers.

Due to detours, additional wait times and as walking is often slower than driving, total working times of nurses increase compared to planning approaches where nurses operate separate vehicles and time spent looking for parking spaces is ignored. Our results, however, clearly indicate a huge advantage in facilitating walking, especially if jobs are clustered as in urban areas. Furthermore, the concept leads to major decreases in the number of required vehicles. Table 5 states the average number of nurses scheduled in ST^*, which further approximates required vehicles under current business practices, the resulting percentage reduction of vehicles by the proposed concept, the average number of pickups and the percentage of the objective value which is driven, walked and spent on board or waited by nurses.

Additionally, Fig. 9 plots the benefits of facilitating walking for one urban and one sub-urban instance. Substantial improvements are reached by allowing little walking, while enforcing long

Table 5
Average vehicle reduction, pickups, driving and walking in best found solutions.

	Avg.# of scheduled nurses	Avg. vehicle reduction of the concept (%)[a]	Avg.# of pickups	Avg. driving (%)[b]	Avg. walking (%)[c]	Avg. time nurses on board/waiting (%)[d]
U–N75–K2	15.20	−86.84	37.60	45.59	27.18	27.22
U–N100–K2	23.20	−91.38	45.00	44.13	28.49	27.38
U–N125–K2	26.40	−92.42	53.00	43.79	28.80	27.41
S–N75–K2	18.20	−89.01	50.60	55.24	14.33	30.43
S–N100–K2	24.80	−91.94	63.40	54.30	15.28	30.42
S–N125–K2	28.00	−92.86	74.80	53.14	17.34	29.51

[a] $(K/\text{Avg.\# of Nurses in}ST^* - 1) \times 100$.
[b] $\sum \text{Driving}/\sum f(ST^*) \times 100$.
[c] $\sum \text{Walking}/\sum f(ST^*) \times 100$.
[d] $\sum(\text{Ride Times of Nurses} + \text{Waiting})/\sum f(ST^*) \times 100$.

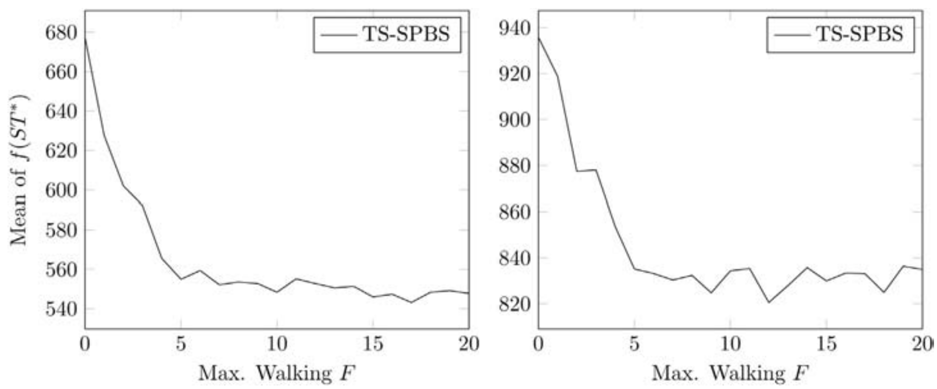

Fig. 9. Sensitivity of five runs with 500 iterations each to the maximum walking duration for U1-n75-k2-m12-8-4 (left) and S1-n75-k2-m12-8-4 (right).

walking durations do not lead to any further benefits. Increases in the objective value are due to the stochastic components of the algorithm.

For more sustainable concepts in practice, it is crucial that both pooling strategies as well as the option to walk are included in solution procedures. Our results indicate the huge potential benefit in doing so. By reducing the number of vehicles, fixed costs are decreased and service is less impacted by the availability of parking spaces. Particularly with increasing demand for home services, urbanisation and stricter environmental regulations, novel sustainable concepts have to be developed and analysed to guarantee future service quality of this crucial industry.

6. Conclusion

Recent challenges faced by home service providers require innovative transport concepts to provide high service levels, whilst being cost-effective and complying with environmental regulations. We developed a matheuristic for the daily planning of real-world home service transport systems, which deliver and pickup staff members to and from clients and facilitate walking. By considering various real-world requirements, the introduced solution procedure is capable of analysing this novel concept and therefore supports decision-makers in investigating the impact of its implementation. Results show that the number of required vehicles can be decreased substantially. Professional drivers relieve staff members of driving and parking pressures allowing them to relax aboard and prepare for their next jobs. Additionally, arrival times at clients are less impacted by failure to find parking spots.

Future work includes real-world case studies to evaluate the various trade-offs and environmental impacts of the concept under different objective functions. Execution times are certainly major limitations of the solution procedure as a linear program has to be solved at each solution evaluation due to interdependencies. Efficient neighbourhood reductions to limit the number of solution evaluations can improve this critical limitation. Additionally, real-world systems are prone to uncertainties and require robust solutions and efficient rescheduling algorithms. Therefore, results from the matheuristic can act as an input for solution procedures, which generate real-time solutions considering stochastic effects.

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Evaluation of a trip sharing concept for home health care services

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Abstract

Routing and scheduling of home health care (HHC) services usually focus on the case where each nurse operates a separate vehicle. However, with increasing urbanisation, limited availability of parking spaces and stricter environmental regulations, service providers are starting to investigate trip sharing concepts as a potential alternative. This paper numerically investigates operating transport systems which deliver and pick up nurses to and from clients combined with the additional option of walking. Different geographic distributions are investigated to identify beneficial settings for successful implementations under different objectives of decision makers. Although this paper focusses on HHC services, results are further of interest to various home service industries facing similar challenges. Facilitating walking and trip sharing reduces the number of required vehicles, resulting in a significant decrease in fixed costs. Travel durations are prone to increase compared to classical planning approaches; however, time spent for parking is rarely considered. Substituting walking and driving enables decision makers to either reduce driving durations or travel times of nurses. Furthermore, the evaluation shows that trip sharing performs best if long service durations exist, long delays for parking occur and in areas where clients are both geographically distributed randomly and in clusters.

Keywords: Trip Sharing, Home Health Care, Dial-a-Ride Problem,

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1. Introduction

Recent trends indicate a shift from long-term care provided in hospitals or nursing homes to services performed at clients' homes (Rosenfeld and Russell, 2012). While the majority of tasks are nursing services and counselling, demand for short-term care is particularly expected to increase (Dorin et al., 2014). As a result, home health care (HHC) providers face increased organisational efforts, whilst being additionally exposed to various risks affecting service quality as well as client and employee satisfaction (Rest et al., 2012). Decision support systems to schedule and route nurses help HHC providers to decrease administrative efforts and enable better fulfilment of clients' requests. Furthermore, by optimising travel durations and finding efficient nurses' schedules, operational expenses are potentially reduced. Operating structures, staff employment and patient utilisation of services are among others major determinants of the financial performance of HHC providers (Fukui et al., 2014). Solution procedures to route and schedule nurses; however, aim to solve operational tasks and are rarely used to investigate strategic questions such as staffing decisions, fleet management or mode of transport choices. As a consequence, current practices are little questioned, hindering the implementation of new innovative transport concepts.

This work investigates the impact of including trip sharing in the context of HHC operations. Expanding on the trip sharing concept and solution procedure presented in Fikar and Hirsch (2014), we compare trip sharing to each nurse operating a separate vehicle, investigate the performance in different geographic distributions of clients as well as under other determining factors and analyse different objectives of decision makers to investigate sustainability issues and to derive policy implications. Although the study focusses on HHC services, results of this work are further of interest to other home service industries facing similar challenges. Consequently, the contribution of this paper is twofold, extensively comparing the impact of trip sharing concepts with the current practice of each nurse operating a separate vehicle and providing decision makers with beneficial settings for an introduction of trip sharing concepts.

The remainder of this paper is organised as follows: Section 2 gives background information and reviews related literature. Section 3 describes the analysed optimisation problems while Section 4 introduces the solution procedures and experimental design. Results of the evaluation are presented and discussed in Section 5 and concluding remarks in Section 6.

2. Background

Trip sharing (also referred to as ride sharing), where multiple travellers share one vehicle for their individual trips, is used in various sectors by both public and private organisations and currently highly encouraged by governmental and intergovernmental agencies world-wide (ADB, 2010; EC, 2011; US-DOT, 2013). An extensive overview of its challenges and future potentials is provided by Furuhata et al. (2013), who list design, arrangement and trust issues as major obstacles for agencies performing trip sharing. Nevertheless, particularly in developing countries, shared taxis and shared trips are highly popular. For instance, Dissanayake and Morikawa (2008) indicate that 30 % of household trips in Bangkok are shared. Most systems deal with the transport of customers; however, little work is found on organised trip sharing provided by employers, with the exception of commuter carpools to and from work, which have been studied widely (e.g. Wartick, 1980; Teal, 1987; Ferguson, 1997; Vanoutrive et al., 2012). Profound theoretic numerical evaluations of trip sharing concepts for staff members travelling to perform services at customer's premises throughout the working day are, as a consequence, of high interest. This is especially of importance for HHC services due to their high complexity of operations and social importance in addition to current challenges resulting from increased urbanisation, limited availability of parking spaces and stricter environmental regulations.

2.1. Routing and scheduling of HHC services

HHC routing and scheduling with separate cars for each nurse is predominantly used in practice (e.g. Begur et al., 1997; Cheng and Rich, 1998; Trautsamwieser et al., 2011; Rasmussen et al., 2012; Trautsamwieser and Hirsch, 2014) and is closely related to the vehicle routing problem with time windows (VRPTW). For details on the VRPTW, refer to Bräysy and Gendreau (2005a,b) and Kallehauge et al. (2005). Congestion and time spent for parking are mostly ignored. Nurses either use their private cars or vehicles provided by the HHC provider resulting in high fixed costs as well as a high demand of parking spots. Due to long average service times at clients, these vehicles are additionally little utilised, especially in urban areas where travel distances are short.

Only little work on HHC routing with public transport is found in literature (e.g. Hiermann et al., 2015; Rest and Hirsch, 2015). A solution procedure to operate private transport systems to deliver and pick up nurses to and from clients and to facilitate the additional option of walking short distances is introduced in Fikar and Hirsch (2014). The problem is modelled as an extended many-to-many multi-trip dial-a-ride problem (DARP) and results show a high potential of considering walking and trip sharing in solution procedures. Travel times of nurses, however, are prone to increase both when using public transport or private transport systems due to detours, i.e. public transport does not travel on the shortest path, the transport service has to first pick up or deliver other nurses, and as walking is usually slower than driving. Additionally, wait times for the services may occur. This shows trade-offs between the cost of increased travel times of nurses and the expense of operating and maintaining a vehicle fleet. Social effects on service quality as well as on employee and patient satisfaction are often broadly discussed when investigating alternative concepts, e.g. determining trade-offs between cost-efficient and patient-centred planning is a common point of discussion (Kieft et al., 2014). Other impacts such as the resulting demand for parking spots and the contribution to congestion and air pollution are less investigated.

2.2. Sustainability of HHC transport concepts

Sustainability is frequently classified in three dimensions, economic, social and environmental sustainability (Adams, 2006). Related indicators are used to evaluate and monitor the sustainability of a business practice or policy. Services within Europe, which are performed directly at customers' homes or on their premises, for the most part generate social benefits (Halme et al., 2006). To measure the overall performance, Halme et al. (2006) derive 18 sustainability indicators. Within their category "Care & Supervision", under which HHC is included, social and economic sustainability perform equally well while environmental sustainability is lagging behind.

Economic factors. Costs concerning the working time of nurses spent travelling to clients, fixed and variable costs of operating a vehicle fleet and disruption costs in case of delays or failure to reach clients are the main economic factors of HHC transport systems. In particular, driving times are often underestimated by service providers and, therefore, require special attention (Holm and Angelsen, 2014). Furthermore, demand for parking spaces results in high opportunity costs for dedicated land, high operation and maintenance costs as well as tax and capital expenses (Shoup, 1997), while time spent looking for parking spaces leads to major increases in nurses' travel times. For instance, 70 million hours are estimated to be spent finding a parking spot by the French population within one year resulting in annual costs of about €700 million (Lefauconnier and Gantelet, 2006). Concepts based on road transport are further impacted by congestion, which increases not only driving durations, but also the distance driven as well as overtime and labour expenses (Figliozzi, 2010).

Social factors. HHC transport systems are of great importance to patients, employees and local communities. When investigating demands of patients, provider consistency, i.e. the patient is visited by the same nurse at the same time of the day, is often one of the most important factors (Woodward et al., 2004). Inconsistency of arrival times, therefore, lowers patient satisfaction. Additionally, fairness is a critical issue, which applies to both patients and employees. Each patient deserves the same quality of service, which respects their specific requirements within a preferred time window. Critical factors to employees include coverage constraints, assignments to primary skills, rest times, requests and time-related constraints (Martin et al., 2013). Furthermore, comfort is often a main argument for driving with separate vehicles (Knuth, 2012). Nevertheless, more and more nurses do not own driver permits or are reluctant to drive. This is especially critical to nurses from rural areas who are not familiar with driving in urban areas. Innovative transport concepts enable such nurses to be employed in the HHC industry and reduce driving stress. Additionally, HHC services impact the traffic conditions in local communities. In particular, substantial demand for parking spaces occurs due to long idle times of the vehicles. This either affects HHC providers in case of private parking spaces (e.g. to park the vehicles over night), or the public, if public parking spaces close to clients are occupied by HHC vehicles. Therefore, parking permits are often granted, which allow preferential parking for HHC vehicles. While efficient urban transport concepts can assist to decrease costs of urban HHC systems (Taniguchi et al., 2014), reducing the number of HHC vehicles by facilitating walking, public transport or trip sharing can potentially benefit the local community.

Environmental factors. Motorised transport results, among other things, in global, regional and local atmospheric pollution and causes waste, congestion and accidents (Piecyk et al., 2012). In HHC operations, average travel distances between two clients are rather short in both urban and sub-urban settings (Fikar and Hirsch, 2014). This results in short vehicle driving durations and high idle times. Consequently, high amounts of start, soak and idle emissions and low average speed occur, which, as shown by Hatzopoulou and Miller (2010), increase air pollution. Beside the distance travelled, fleet composition is an important factor (Lemp and Kockelman, 2008). HHC vehicles are either nurses' privately-owned cars or vehicles owned by the service providers. In both cases, these are often inefficient and aged vehicles. The implementation of a transport service can, therefore, incorporate the acquisition of more environmentally friendly vehicles to increase environmental sustainability. Furthermore, trip sharing and walking as well as other alternative modes of transport, like biking and the usage of public transport, can potentially decrease the distances driven.

3. Problem Description

Routing and scheduling of HHC services lead to challenging combinatorial optimisation problems, both for routing with separate cars and with trip sharing concepts. In daily HHC operations, providers have nurses available to serve client requests. Given a complete graph $G = (V, A)$, the vertex set $V = \{v_0, v_1, ..., v_{n+1}\}$ consists of clients $\{v_1, ..., v_n\}$ and the depot $\{v_0, v_{n+1}\}$, where all tours of vehicles and nurses start and end. Arcs $(i, j) \in A$ are associated with driving durations $t^d_{i,j}$. All clients have to be visited within a time window and, depending on the needs of clients, different nurses can be assigned. Therefore, nurses have qualification levels and clients have qualification requirements. A nurse is only allowed to serve a client if his/her qualification level is higher or equal than the requirement. Frequently, downgrading of nurses is allowed, i.e. a nurse can serve a client requiring a lower qualification level; however, this is often limited to a certain number of clients and a certain discrepancy between level and requirement to ensure employee satisfaction. To perform the service, the nurse is contracted to stay a certain time at the client's home. Over the entire day, nurses' schedules are subject to working as well as break regulations, which include maximum working times and if and when breaks of a certain duration have to be scheduled. Note that, depending on the number of clients and nurses, not all nurses

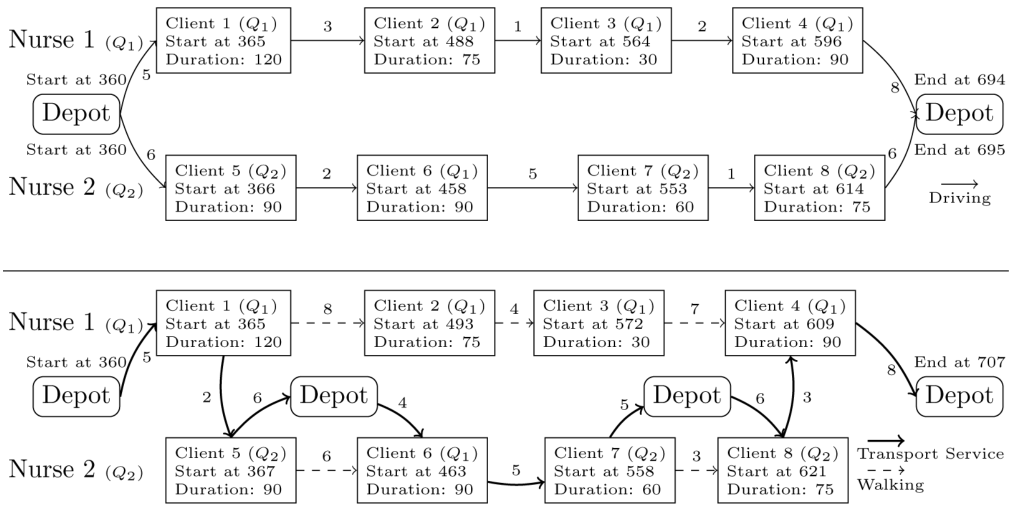

Figure 1: Nurses' schedules with separate vehicles (top) and a transport service (bottom). All time values are in minutes (e.g. 360 = 6am) and two qualification requirements $Q = \{1, 2\}$ are given.

have to work on a specific day. The objective is to minimise travel times of nurses consisting of drive and wait times to achieve efficient and cost-effective operations. For a detailed description and mathematical model of a daily HHC problem, refer to Trautsamwieser et al. (2011).

To analyse trip sharing concepts and to allow walking, arcs $(i, j) \in A$ are further associated with walking durations $t^w_{i,j}$ and each client in the vertex set V can act both as a pickup and a delivery location. The service provider has capacitated vehicles available to transport nurses between clients. If not utilised, the vehicle returns to the depot and waits for the next service. Detours and maximum wait times of nurses are bounded by maximum durations to ensure nurses' satisfaction. Furthermore, a maximum walking duration between two clients and for a whole walking-route is given. To consider the additional costs of the transport system, working times of drivers spent driving are added to the objective function. For a detailed description of the problem considering trip sharing and the additional option of walking, refer to Fikar and Hirsch (2014).

Figure 1 gives a simplified example of the two different concepts ignoring time windows and breaks in order to keep it readable. On the top, each nurse uses a separate car to visit clients. Nurse 2 visits client 6 with a lower required qualification, i.e. the nurse downgrades. In the bottom part, walking is enabled and nurses share a vehicle at the start and end of the working day. As a consequence, both nurses start and end at the same time. If idle, the transport service returns and waits at the depot. Due to the detours resulting from trip sharing and as walking is slower than driving, travel times of the nurses increase; however, instead of two vehicles, one for each nurse, only one vehicle is required.

4. Methods

Due to the combinatorial complexity of the underlying optimisation problems, we developed a matheuristic and an event-driven biased-randomised heuristic to analyse the different concepts. These solution procedures generate nurses' schedules and vehicle routes which are evaluated to perform the comparison. Each instance is run ten times due to random components in the solution procedures and the best result of all ten runs is reported. The following subsections briefly review these solution procedures.

4.1. Routing with separate cars

We implemented an event-driven randomised heuristic to derive nurses' schedules and vehicle routes for concepts where each nurse uses a separate vehicle. The basic idea is to generate and evaluate a wide range of different promising solutions within a short time-frame. To speed up computation, this is done in parallel on multiple threads of the operating system. In the solution construction, all decisions are made chronologically starting from the beginning of the working day. Nurses are assigned randomly to certain clients to start their working days, whereas a solution guidance procedure bias the activation times of new nurses in future construction runs. Whenever a nurse requires a new routing or scheduling decision, an event is called deciding which client a nurse is scheduled to go to next. Therefore, marginal costs, which consider the distance of this nurse to the client as well as the distance of the closest other nurse to the same client, are considered. All potential clients are then added to a list and sorted by the respective value. Biased-randomisation using a geometric distribution (Juan et al., 2013) selects one client, whereas less costly clients are given a higher probability. Therefore, the parameter β in the range of 0 to 1 indicates the bias of the selection, whereas a low β value indicates higher randomness in the selection. This enables a high number of different solutions within multiple runs. For our test runs, β is uniformly randomly selected for each construction between 0.5 and

1. Feasibility checks concerning time windows, qualification requirements as well as break times and working time regulations are performed constantly during the runs. In case of a violation, the current solution is neglected and the algorithm continues with the construction of a new solution. The algorithm stops after one minute of run time.

4.2. Routing trip sharing transport systems

To route and schedule trip sharing concepts facilitating walking, the algorithm has to decide when one walks and when one uses the transport service. Furthermore, it has to guarantee synchronisation of nurses and vehicles. For instance, a nurse who starts a service at 1pm and requires one hour for completion has to be picked up starting from 2pm. Each minute late results in waiting for the nurse, which leads to additional costs. A matheuristic was developed in Fikar and Hirsch (2014) combining exact solution procedures with a metaheuristic. We extended this solution procedure to consider different objective functions. Walking-routes are created by a set partitioning procedure and based on this set of walking-routes, multiple initial solutions are constructed. The best one is then further improved by a Tabu Search metaheuristic. Wait times are minimised by running a linear program to optimise start times of vehicles. Furthermore, at certain points during the run, walking-routes are modified to better align walking and vehicle routes. Therefore, a change in the sequence of clients within a walking-route is tested as well as splitting and merging routes. Due to the time-consuming exact components, the algorithm runs for one hour for each instance. Parameters are set in accordance to the test settings in Fikar and Hirsch (2014).

4.3. Experimental design

To compare routing with separate cars to the trip sharing concept, we use ten instances, each serving 100 clients, provided in Fikar and Hirsch (2014), available online at Fikar and Hirsch (n.d.). These instances are derived from real-world geographic locations of clients and consider road networks of the respective areas. Therefore, a walking speed of 3.6 km/h is assumed. Five instances are located in an urban area and five in a sub-urban area, indicated in the instance names with “U” and “S” respectively. The geographic position of clients is changed for each instance. Parking delays are included by increasing the driving durations for all trips to client locations by p when using separate cars. Nurses (service requests) can have three different qualification levels (requirements). In the first qualification level, which represents the lowest one, 16 nurses are available, 10 in the second and 6 in the third. Within a day, each nurse is allowed to serve a maximum of one client one level below the nurse's qualification level. Maximum working time per day is ten hours. If a nurse works longer than six hours, a break of 30 minutes has to be scheduled. This break does not count to the working time and has to be timed so that the nurse does not work longer than six hours consecutively. To analyse the trip sharing concept, two vehicles with a capacity of six including the driver are available. Additionally, maximum walking distances are constrained by 10 minutes between two clients and by 20 minutes between two trips on the transport service. Wait times between delivery and pickup as well as additional ride times per trip due to detours are limited to 15 minutes. These parameters were set according to the assumptions of a major HHC provider in Austria. For each area, the same five settings of time windows, qualifications and service durations are applied. These originated from statistical distributions of real-world operations and are summarised in Table 1.

Table 1: Qualifications, time windows and service durations in the instances of Fikar and Hirsch (2014). Time windows are indicated in minutes (e.g. 360 = 6am)

	Time Window	Qualification 1				Qualification 2				Qualification 3			
	Earliest start	360	630	900	360	360	630	900	360	360	630	900	360
Instance	Latest start	630	900	1170	1170	630	900	1170	1170	630	900	1170	1170
1	# of clients	12	26	19	10	7	3	6	3	3	6	2	3
2		25	25	11	7	6	8	5	6	1	1	4	1
3		22	22	17	7	5	8	4	5	2	6	1	1
4		19	27	21	7	5	8	2	4	-	4	2	1
5		22	14	17	12	4	7	10	2	6	2	3	1
1	Avg. duration	61.3	71	66.3	49.5	47.1	65	50	65	50	42.5	45	35
2	in minutes	57.6	63	65.5	60	70	50.6	51	37.5	45	30	45	30
3		53.2	55.2	58.2	62.1	39	50.6	60	57	45	35	30	30
4		63.2	61.1	60.7	60	51	48.8	60	56.3	-	37.5	37.5	30
5		66.1	64.3	70.6	63.8	52.5	60	58.5	60	37.5	37.5	35	60

To further analyse the impact of the geographic distribution of clients, we adopt the Solomon instances of group one with 100 clients on vehicle routing problems (Solomon, 1987). These focus on short scheduling horizons as present in daily HHC operations and were acquired from Solomon (n.d.). Three categories of client distributions are represented. Clusters of clients are present in "C"-instances, a setting often found in commuter towns outside of a city as well as in rural areas. In instances indicated by "R", clients are distributed randomly over the test region, similar to urban city centres. Instances “RC” include a combination of randomly distributed clients and clusters as often seen in suburbs. Figure 2 plots each type of instances. To

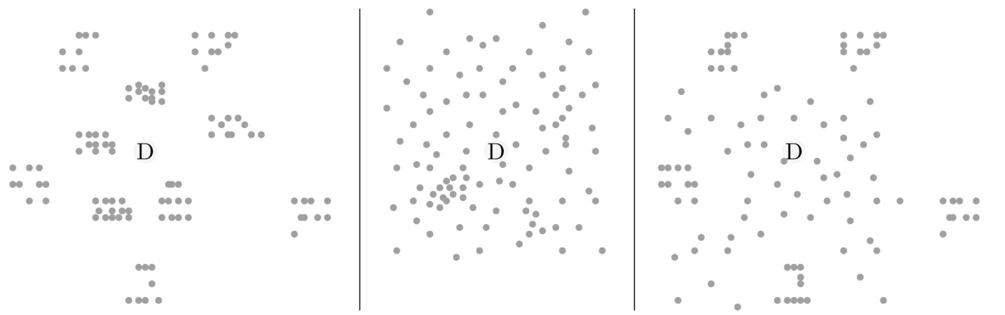

Figure 2: Geographic distribution of clients. Plots of each type, C (left), R (middle) and RC (right). “D” indicates the depot, dots the locations of clients.

adjust them to HHC operations, we only take the client locations from the instances. As coordinates are given, we further take the Euclidean distances as walking duration and divide them by a factor of 10 to calculate driving durations. All durations were rounded up to the next integer value. As the different Solomon instances for each category do not differ in coordinates, we only calculate one geographic distribution per category. For each geographic distribution, two different test settings are investigated. First, the five different time window, service duration and qualification requirement settings from Table 1 are utilised. These instances are denoted with R-HHC, C-HHC and RC-HHC. Second, to indicate the impact of time windows, qualification requirements and service durations, we further perform the test runs considering only one qualification, no time windows and a fixed service duration of one hour. These instances are denoted as R’-HHC, C’-HHC and RC’-HHC.

To investigate the impact of different objectives of decision makers and resulting trade-offs, we further run the U and S instances with different objective functions. These either only reduce the drive time (1) or the travel times of nurses (2), which consist of durations walked, waited and spent on board a vehicle, of a solution S and are compared to optimising the sum of drive and travel times (3) as done in the other experiments.

$$\text{minimise} \quad f(S) = S_{Drive} \tag{1}$$

$$\text{minimise} \quad f(S) = S_{Walk} + S_{Wait} + S_{Onboard} \tag{2}$$

$$\text{minimise} \quad f(S) = S_{Drive} + S_{Walk} + S_{Wait} + S_{Onboard} \tag{3}$$

Additionally, we investigate a fourth option (4) by adding a weight $\alpha \in [0, 1]$ to the objective function. This allows the decision maker to either put a weight on drive times, which are multiplied by α, or on nurses' travel times, which are evaluated with $1 - \alpha$.

$$\text{minimise} \quad f(S) \quad = \alpha S_{Drive} + (1 - \alpha)(S_{Walk} + S_{Wait} + S_{Onboard}) \qquad (4)$$

The experiments give implications on the impact of the studied factors; however, the following research limitations and assumptions have to be considered. This work is based on organisational frameworks and the national regulative in Austria, which may vary from settings in different regions. Additionally, the comparison is based on a static problem setting. The impact of uncertainties and stochasticies is little studied in literature for routing with separate vehicles and no work on stochastic routing and scheduling with the trip sharing concept exists. Nevertheless, potential relevant stochastic factors, which may be independent or interdependent, that might impact the performance are manifold including stochastic travel times, service delays as well as impacts related to driver behaviours.

5. Results and discussion

In this section, computational results are first compared to classical concepts where each nurse operates a separate vehicle. In the next step, prerequisites for a successful implementation of these concepts are analysed by investigating different geographic distributions of customers. Concluding, the importance of the objective of the decision maker is analysed. All test runs were gathered on an Intel Core i7-4930K, 64GB RAM, with Windows 7 as operating system and 6 threads operating in parallel.

5.1. Impact of trip sharing

Table 2 compares the trip sharing concept, denoted in the following part as *TripSharing*, with operations where each nurse uses a separate vehicle, denoted as *allCar*. Therefore, travel time considers time spent by nurses on board a vehicle, walked or waited. The results show that *TripSharing* leads to a drastic increase in travel times of up to 76 % in urban and 57 % in sub-urban areas. This is the case as additional detours occur if a nurse is waiting for another nurse to be delivered and picked up, wait times for the transport service occur and as walking is slower than driving (exceptions

Table 2: Comparison of *TripSharing* and *allCars* on urban and sub-urban real-world based instances.

	Travel time nurses			Driver	# of Vehicles
	allCars	TripSharing	+/-	TripSharing	+/-
U1-N100	233	401	72.1 %	301	-86.7 %
U2-N100	230	404	75.7 %	303	-84.6 %
U3-N100	226	387	71.2 %	313	-83.3 %
U4-N100	230	382	66.1 %	308	-85.7 %
U5-N100	247	401	62.4 %	335	-88.2 %
S1-N100	325	477	46.8 %	550	-87.5 %
S2-N100	310	484	56.1 %	514	-86.7 %
S3-N100	304	452	48.7 %	587	-87.5 %
S4-N100	308	483	56.8 %	500	-85.7 %
S5-N100	343	462	34.7 %	634	-88.9 %

occur for one-way streets and designated pedestrian areas). Nevertheless, the results show that *TripSharing* leads to a major decrease of about 87 % in the number of required vehicles. From a strategic point of view, the number of vehicles which should be purchased is of high importance when analysing trip sharing concepts. Longer service times at clients' homes lead to lower vehicle utilisations in *allCars* as less distance is travelled on a working day. As a consequence, the potential reduction in vehicles of *TripSharing* is higher in such situations. Concerning the number of required vehicles for *TripSharing*, the number of clients to serve, average distances between homes and the amount of potential walking is of high importance. As a consequence, HHC providers can save a significant amount of expenses spent on leasing, vehicle-related taxes, insurances, maintenance and parking if the vehicles are owned by the provider. These strategic long-term savings have to be weighted by the decision maker with the daily increases in variable costs for additional time spent to travel to clients, the impact on fuel consumptions and the costs for hiring drivers for the transport services. If nurses are using their private cars, mileage reimbursements are avoided, which again have to be compared against the additional costs of the transport systems.

One benefit of implementing a transport service is that is does not require parking spots at client locations while the service is performed. Therefore, substantial time to look for a parking spot, to park and to walk from the potentially distant parking spot to the client can be saved. Planning algorithms often do not consider this complication of real-world operations. Table 3 shows the impact of parking delays on the travel time of nurses. In

Table 3: Impact of time spent for parking (p) on *allCars* compared to *TripSharing*.

	$p = 1$		$p = 2$		$p = 3$	
	+/- Driven	Travel time nurses	+/- Driven	Travel time nurses	+/- Driven	Travel time nurses
U1-N100	12.0 %	-16.0 %	45.2 %	9.0 %	78.1 %	33.7 %
U2-N100	8.3 %	-18.8 %	41.9 %	6.4 %	75.2 %	31.4 %
U3-N100	4.8 %	-15.2 %	36.4 %	10.3 %	69.6 %	37.2 %
U4-N100	7.8 %	-13.1 %	39.9 %	12.8 %	71.8 %	38.5 %
U5-N100	3.6 %	-13.5 %	33.7 %	11.7 %	64.8 %	37.7 %
S1-N100	-22.9 %	-11.1 %	-4.5 %	10.1 %	14.2 %	31.7 %
S2-N100	-22.0 %	-17.1 %	0.0 %	6.2 %	18.3 %	25.6 %
S3-N100	-31.3 %	-10.8 %	-14.0 %	11.7 %	2.7 %	33.4 %
S4-N100	-19.6 %	-16.8 %	0.8 %	4.3 %	20.4 %	24.6 %
S5-N100	-29.5 %	-3.2 %	-13.9 %	18.2 %	1.9 %	39.8 %

urban areas, *TripSharing* leads to a reduction in the total duration driven if a parking delay of only one minute is considered; however, travel times of nurses are still increased. Travel times of nurses in both urban and sub-urban instances are reduced starting with a parking delay of two minutes, while driving durations in sub-urban instances are still higher in three instances. With a parking delay of three minutes, *TripSharing* outperforms *allCars* in each of the test settings considering both travel times and driving durations. This shows the potential of trip sharing in settings where parking problems are present.

5.2. Geographic distribution of clients

Understanding how *TripSharing* performs in different geographic distributions of clients enables providers to find areas for implementation and indicates strengths and weaknesses of the compared concepts. The average percentages of the objective value, which are driven, walked, spent by nurses on board a vehicle and waited are given in Table 4 for the different geographic distributions. Walking is especially beneficial in settings where clients are clustered. Having multiple clients close to each other allows the nurse to walk to the subsequent clients without requiring the transport service. This further helps other nurses, as more transport services are available, resulting in lower wait times and fewer detours.

Table 5 compares *TripSharing* with *allCars*. Long delays occur if nurses are required to travel between clusters. In randomly distributed areas, nurses can walk in case the transport service is not available; however, walking is

Table 4: Average percentage of the *TripSharing* objective value spent for driving, walking, on board a vehicle and waiting.

	Driver	Nurse		
	% driven	% walked	% on board	% waited
C-HHC	44.8 %	27.9 %	26.9 %	0.5 %
R-HHC	55.7 %	17.8 %	25.4 %	1.1 %
RC-HHC	54.0 %	17.8 %	27.0 %	1.2 %

Table 5: Comparison of *TripSharing* with *allCars* in different geographic distributions of clients.

	Travel time nurses			Driver	# of Vehicles
	allCars	TripSharing	+/-	TripSharing	+/-
C1-HHC	281	422	50.2 %	369	-87.5 %
C2-HHC	256	408	59.4 %	325	-87.5 %
C3-HHC	263	414	57.4 %	323	-83.3 %
C4-HHC	263	410	55.9 %	329	-84.6 %
C5-HHC	277	463	67.2 %	371	-88.9 %
R1-HHC	236	390	65.3 %	461	-88.9 %
R2-HHC	245	377	53.9 %	477	-85.7 %
R3-HHC	223	382	71.3 %	479	-83.3 %
R4-HHC	233	371	59.2 %	485	-87.5 %
R5-HHC	252	379	50.4 %	487	-88.2 %
RC1-HHC	290	448	54.5 %	468	-87.5 %
RC2-HHC	297	391	31.7 %	512	-87.5 %
RC3-HHC	278	412	48.2 %	508	-87.5 %
RC4-HHC	275	440	60.0 %	453	-86.7 %
RC5-HHC	292	422	44.5 %	536	-88.2 %

costly as average distances are long. The combination of clusters and randomly distributed clients leads to the best results for *TripSharing* concerning nurses' travel times as disadvantages of both are mitigated. Nurses can efficiently walk within clusters; however, if a nurse completed all assignments within a cluster and requesting a vehicle is costly, the nurse usually still has potential clients within walking distance. Additionally, Table 6 presents the results if no time windows, only one qualification level and a fixed service duration is assumed. The experiments show that time windows, qualification levels and different service durations have a substantial impact on the performance of *TripSharing* as they limit potential walking options and further complicate synchronisation of nurses and vehicles for pickups. More flexibility in the timing decision allows for better sharing of trips. This results in

Table 6: Comparison of *TripSharing* with *allCars* ignoring time windows, qualifications and with a fixed service duration.

	Travel time nurses			Driver	# of Vehicles
	allCars	TripSharing	+/-	TripSharing	+/-
C'-HHC	165	343	107.9 %	169	-83.3 %
R'-HHC	163	328	101.2 %	368	-83.3 %
RC'-HHC	183	392	114.2 %	298	-83.3 %

lower driving durations and more efficient routes. Nevertheless, *allCars* also profits from this flexibility, increasing the gap between the two concepts.

5.3. Objective of the decision maker

Due to detours, *TripSharing* may lead to an increase in the total distance driven. Nevertheless, if trips are shared well, driving distances may even decrease as certain paths are shared by multiple nurses. Therefore, the decision maker has to specify an objective to deal with this trade-off. While reducing drive times of vehicles results in environmentally sustainable solutions, decreasing the travel time of nurses, depending on the cost structure of the HHC provider, potentially results in more financial sustainable solutions. Tables 7 & 8 show the impact of both only reducing drive times and only reducing travel times of nurses compared to optimising the sum of drive and travel times as done in the previous sections.

Table 7: Comparison of minimising drive durations ($\alpha = 1$) and optimising both travel times of nurses and driver ($\alpha = 0.5$).

	+/- Driver	+/- Walk	+/- Nurse on board/waiting	Total travel time nurses
U1-N100	-44.9 %	81.5 %	175.9 %	131.4 %
U2-N100	-45.9 %	60.8 %	219.8 %	136.2 %
U3-N100	-49.8 %	80.8 %	206.4 %	133.7 %
U4-N100	-45.8 %	90.8 %	200.0 %	132.4 %
U5-N100	-46.9 %	75.4 %	228.4 %	149.4 %
S1-N100	-36.0 %	50.0 %	262.7 %	234.9 %
S2-N100	-37.4 %	72.8 %	214.9 %	220.2 %
S3-N100	-37.0 %	66.0 %	315.1 %	272.8 %
S4-N100	-32.6 %	41.3 %	275.9 %	235.6 %
S5-N100	-37.7 %	105.7 %	256.5 %	270.8 %

The results clearly indicate that substantial reductions in the driving distances of close to 50 % are achievable by sharing trips and facilitating

Table 8: Comparison of minimising nurse travel times ($\alpha = 0$) and optimising both travel times of nurses and driver ($\alpha = 0.5$).

	+/- Driver	+/- Walk	+/- Nurse on board/waiting	Total travel time nurses
U1-N100	164.8 %	-90.0 %	7.1 %	-38.7 %
U2-N100	154.1 %	-87.6 %	23.0 %	-35.9 %
U3-N100	120.1 %	-83.3 %	8.0 %	-40.9 %
U4-N100	132.5 %	-86.2 %	19.5 %	-37.9 %
U5-N100	133.1 %	-89.9 %	17.5 %	-37.9 %
S1-N100	80.2 %	-86.8 %	3.5 %	-18.0 %
S2-N100	91.3 %	-89.4 %	-1.0 %	-17.7 %
S3-N100	66.6 %	-87.6 %	4.4 %	-17.5 %
S4-N100	97.6 %	-92.0 %	12.1 %	-17.2 %
S5-N100	69.2 %	-87.8 %	-4.8 %	-12.2 %

walking; however, it highly impacts nurses' travel times. If the main focus is to reduce travel times, driving duration nearly doubles. Figure 3 plots these different objectives by increasing the weight α in increments of 0.1. If α is 0, drive times of the vehicles are completely ignored, if 1, travel times of nurses are not considered. The results show that the sum of driving durations and

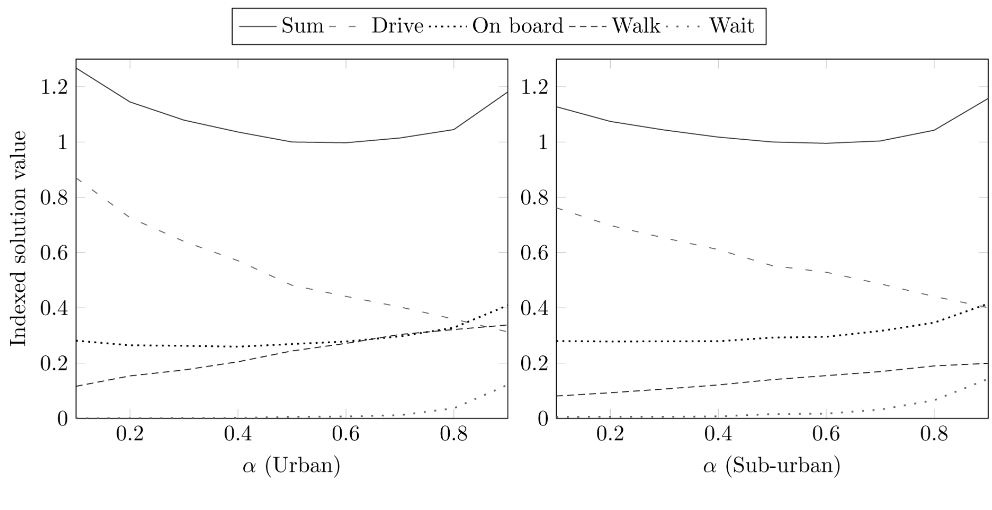

Figure 3: Trade-offs between driving and nurses' travel times. Average results with $\alpha = \{0.1, 0.2, ..., 0.9\}$ for U1-N100 to U5-N100 (left) and S1-N100 to S5-N100 (right). All values are indexed to the sum of durations with $\alpha = 0.5$.

travel times of nurses show a convex behaviour. Slightly deviating from the minimum only leads to minor changes in the sum of durations. This allows the decision maker to substitute between reducing the duration driven and the time travelled by nurses. Additionally, the results indicate that these small changes mostly affect the duration walked or driven. This allows direct substitution between these two modes of transport and the resulting costs for either driver or nurses, while the duration spent on board is more stable. Nevertheless, if reducing the duration driven is of high focus, travel times start to dramatically increase as major wait times occur. In sub-urban areas, substitution between different modes is more difficult to achieve due to longer distances between clients, leading to flatter functions.

6. Conclusions

We analysed sustainability factors of HHC transport concepts, compared a trip sharing concept facilitating walking to current practices and, furthermore, analysed the concept's performance in different geographic client distributions and under different objectives of decision makers. Trip sharing in HHC services performs best in areas where long service times and challenges to find parking spots occur, leading to substantial reductions in both travel times of nurses and the number of required vehicles. Furthermore, areas where clients are both geographically clustered and randomly distributed show greater potential for the implementation of such concepts according to our evaluation. Nevertheless, additional drivers have to be compensated and driving durations are prone to increase compared to the usage of separate vehicles due to detours; however, substituting walking and driving enables decision makers to derive plans based on their preferences. Even though this analysis focusses on HHC services, results potentially can be transferred to different home service industries where similar challenges and long service times occur.

Additionally, implementing trip sharing concepts potentially improves employee satisfaction by lowering driving stress and can lead to environmentally friendlier operations if driving durations are reduced and walking is facilitated. Local communities and patients may profit from fewer spaces occupied by HHC vehicles. Nevertheless, trade-offs between the costs of operating a large fleet of individually operated vehicles and the additional costs of operating a trip sharing transport system need to be considered closely. For instance, daily operations are potentially prone to disruptions and delays, which may have a major impact on the benefits of these concepts. Therefore, decision makers have to carefully analyse their services and operational area as well as resulting risks and impacts on patient and staff satisfaction before introducing trip sharing concepts.

Although we have extensively investigated trip sharing using both real-world based and theoretic data, future work and field tests are required to comprehensively analyse the impact on real-world implementations. Most work on HHC routing and scheduling ignores stochasticities and uncertainties. Potential challenges are cancellations, additional client requests or disruptions of daily schedules due to delays in travel or service times. This offers a wide range of research questions, which need to be explored to better understand potential disruption risks due to trip sharing. Additionally, extending our work by performing cost-utility analyses or facilitating sustainability indicators is of high interest for HHC services as well as other related industries. To closer investigate the environmental impact of such concepts, studies on emissions of different vehicles and trip sharing policies are of importance. Furthermore, the impact of trip sharing on patient and nurse satisfaction has to be closely analysed. Studies surveying both groups would benefit future implementations in HHC operations.

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A discrete-event driven metaheuristic for dynamic home service routing with synchronised trip sharing

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Abstract: It is common practice in the home service industry that each staff member operates a separate vehicle to visit customers. Facilitating trip sharing and walking policies allows reducing the number of required vehicles, however, often does not succeed due to operational difficulties in routing and planning. In particular, coordinating arrival times of staff members and vehicles at pickup locations introduces major complexity. Previous work in this field focusses on static problem settings where all data is known in advance. Real world-operations, however, are dynamic as cancellations or new requests can happen at any time. This requires decisions to be made in real-time. To assist planners, we propose a flexible discrete-event driven metaheuristic to deal with dynamic routing and scheduling scenarios using combined trip sharing and walking. The computational experiments show that our approach generates solutions in a fast and efficient way, thus, facilitating real-world operations and enabling rescheduling and rerouting. [Received 23 May 2015; Revised 14 October 2015; Accepted 8 December 2015]

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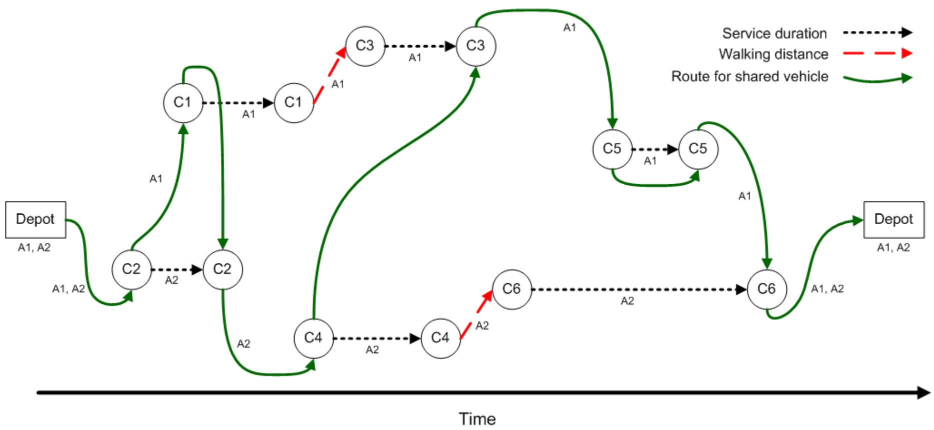
1 Introduction

Vehicle routing problems with synchronisation constraints are an emerging topic with various real world applications where future work is required (Drexl, 2012). The service industry constitutes one of these real-world applications. For home service providers who perform jobs at customers' premises, transport is a major cost factor as staff members spend substantial time travelling to clients. For instance, within home health care (HHC) operations, Holm and Angelsen (2014) show that up to 26% of total working time accounts to driving, time which is often underestimated by the service providers. Halme et al. (2006) classify home services, also denoted as household services, in seven categories: consulting and information, care and supervision, leisure services, maintenance and repairs, mobility and delivery services, safety and security services, as well as supply and disposal. While some of these services only require short stops of the staff members at the customers' homes, others, such as care, supervision and maintenance, result in long stays. As it is common practice that each staff member operates a separate vehicle, vehicle utilisation is low.

Consequently, facing increased cost pressures and stricter environmental regulations, a high interest to change to environmentally friendly modes of transport or to share trips occurs in the industry, both of which are strongly supported by various agencies world-wide (e.g., ADB, 2010; EC, 2011; US-DOT, 2013). Daily operation planning with such concepts, however, is complex, especially as multiple vehicles or staff members have to be synchronised to share vehicles or to meet at certain locations. To solve a resulting scheduling and routing problem, Fikar and Hirsch (2015) analyse a transport system which facilitates trip sharing and walking in a static setting. It considers various real-world requirements such as working time and break regulations, time windows and qualification-based assignment constraints. Resulting benefits include a major reduction in the size of the required vehicle fleets. Nevertheless, despite these advances, analysing the problem in a static setting is not sufficient to enable real-world implementations. Real-world operations are highly dynamic, due to frequent cancellations and the occurrence of new requests. As a result, solutions procedures to solve dynamic trip sharing problems are of high importance.

Figure 1 provides a time-based view of a simplified example including two staff members (A1 and A2) initially located at a base depot and one shared vehicle operated by a professional driver. There are six customers (C1 to C6) requiring time-consuming jobs to be provided by one of the staff members. To reach customers, the staff members have to be delivered and picked up by a shared vehicle at the correct times. In the simplified example, staff member A1 takes care of odd-numbered customers while A2 is in charge of even-numbered customers. Starting from the depot with both A1 and A2 on board, the vehicle delivers A2 to C2 and then proceeds to C1 to deliver A1. If two customers are located close to each other (e.g., C1 and C3), the staff member walks instead of using the shared vehicle. Otherwise, the vehicle picks up the staff members to deliver them to the next customers. At the end of the day, both staff members are picked up by the vehicle and brought back to the depot. In a dynamic situation like this, where vehicles and staff members need to be perfectly synchronised, unexpected events such as delays, cancellations, or new requests lead to major issues that require real-time modifications of the original routing and scheduling plans.

Figure 1 A simplified example with two staff members and one shared vehicle (see online version for colours)



Therefore, real-life applications considering dynamic scenarios require new optimisation approaches capable of rescheduling and rerouting requests in a fast and efficient way. To respond to such needs, we present a flexible discrete-event driven metaheuristic for dynamic trip sharing problems with synchronisation constraints. The algorithm is designed to efficiently solve home service transport problems facilitating trip sharing and walking in dynamic environments. Moreover, the solution procedure can be easily adapted to provide real-time solutions to other dynamic multi-modal vehicle routing problems with synchronisation constraints. The paper is structured as follows. Section 2 gives an overview of related literature. Section 3 describes the problem being considered. The methodological approach to solve the problem is described in Section 4. Section 5 includes some computational experiments that allow testing the efficiency of our approach on benchmark instances. Finally, concluding remarks are presented in Section 6.

2 Literature review

Most prior work focuses on static problem settings in certain industries and is closely related to the vehicle routing problem with time windows (VRPTW). For details on the VRPTW, refer to Bräysy and Gendreau (2005a, 2005b) and Kallehauge et al. (2005). Xu and Chiu (2001) investigate technicians in the telecommunication industry performing maintenance and repair services or installing new services at customers' homes. Different types of services, time windows and urgency levels of specific tasks are considered. To solve the problem, the authors propose a greedy heuristic, a local search algorithm and a greedy randomised adaptive search procedure (GRASP). Cappanera et al. (2011) investigate a home service problem originating from after-sales services, which is referred to as skill vehicle routing problem. Available technicians have to be routed and scheduled to perform jobs requiring at least a certain qualification level. Travel costs that are dependent on the skill level of the technician are considered and overqualified technicians can perform jobs with a lower qualification requirement. Tricoire et al. (2013) investigate the multi-period field service routing problem (MPFSRP) dealing with technicians visiting customers for maintenance activities or commercial operations. They propose a branch and price solution method and several heuristics. A wide range of work is found in the context of HHC operations. Begur et al. (1997) aim to balance workload of nurses by developing a range of construction and improvement heuristics. Eveborn et al. (2006) develop a repeated matching algorithm to plan HHC services in Sweden. Reduced time spent for planning activities and an improved quality of routes and services are reported as a result of a real-world implementation. A branch and price algorithm considering various soft preference constraints and temporal dependencies is introduced by Rasmussen et al. (2012). Nevertheless, none of the previous work explicitly implements the option of walking short distances or trip sharing concepts, which are fundamental characteristics of our model.

Working time regulations and complex operational constraints are often neglected or relaxed, however, these have recently gained importance in the literature. In the context of HHC, break regulations and maximum working times are, for instance, used by Trautsamwieser et al. (2011), Trautsamwieser and Hirsch (2014), Fikar and Hirsch (2015) and Rest and Hirsch (2015). Drexl (2012) gives an overview of vehicle routing problems with synchronisation. Bredström and Rönnqvist (2008) focus on temporal synchronisation and precedence and propose an optimisation-based heuristic. The authors list HHC services as one real-world application. Mankowska et al. (2014) investigate similar settings where two nurses are required to treat patients, either simultaneously or in a certain order. A heuristic based on a sophisticated solution representation is introduced in their work.

A review of dynamic ride-sharing optimisation is given in Agatz et al. (2012), stating, among others, the high need for fast solution approaches to solve real-life instance sizes. Fleischmann et al. (2004) introduce a dynamic routing system which is combined with on-line traffic information. Therefore, the authors distinguish between four types of events: new order requests, pickup of an order, the completion of an order and significant changes in the expected travel times. Different assignment rules, assignment algorithms and insertion algorithms are compared to reduce costs and delays. Pillac et al. (2012) implement an event-driven optimisation framework for dynamic vehicle routing problems. The authors take advantage of multi-core processors to allow fast response. An adaptive variable neighbourhood search improves solutions constructed by a randomised heuristic. Petrakis et al. (2012) investigate different off-line and on-line mobile field force management solutions to schedule staff for maintenance and repair of mobile-phone base stations. Their results show that travel times are often lower in on-line solutions and that deadline penalties are considerably reduced. Nevertheless, none of these approaches for dynamic routing problems consider synchronisation issues and trip sharing, which are a key aspect of our model.

Other optimisation works in the carpooling area also focus on reducing vehicle fleets. Baldacci et al. (2004) develop an exact method based on Lagrangian column generation for companies organising carpooling for their employees' commute to work. In the context of home services, Fikar and Hirsch (2015) analyse implementing a transport system facilitating trip pooling and walking under various real-world constraints in a static setting. The authors propose a matheuristic to solve the corresponding routing and scheduling problem, however, long execution times are reported. Hence, their approach can only be employed in static environments, i.e., it cannot be used in a dynamic environment with service cancellations, new service orders or unexpected delays. The methodology introduced in our paper precisely allows one to overcome these limitations since it is designed to provide real-time solutions to routing and scheduling synchronisation problems under dynamic environments. This is essential to enable real-world implementations.

3 Problem description

In this section, we introduce dynamic home service trip sharing problems including walking. The problem considered is defined as an extended many-to-many multi-trip dial-a-ride problem (DARP) and takes into consideration the static version presented in Fikar and Hirsch (2015). A complete graph $G = (N, E)$ is considered. $N = \{0, 1, 2, ..., n\}$ is a set of nodes representing a depot (node 0) and n customers needing to be served (nodes 1 to n), while $E = \{(i, j)/i, j \in N, i < j\}$ represents the set of edges connecting these nodes. Each customer has to be visited and served by exactly one agent from a set $A = \{1, 2, ..., m\}$ of m agents with different qualification levels (typically, $m \ll n$, so that each agent serves different customers). Agents can move from one node to another either by walking or riding on a vehicle. In the latter case, they can use a shared transport vehicle from a set $V = \{1, 2, ..., k\}$ of k vehicles, each with its own driver (typically, $k \ll m$, so each vehicle is used by several agents). Initially, all agents, vehicles and drivers are located at the depot, where they have to return at the end of their workday. c_e represents the time necessary to traverse edge e by transport service, while w_e represents the time necessary to traverse the same edge by walking. Due to synchronisation issues among agents and vehicles, wait times after finishing a job at a customer may occur for an agent being picked up by a vehicle. Similarly, a driver may have to wait at a given customer to pick up an agent. We denote by a_i^l the wait time of agent l at customer i ($\forall l \in \{1, 2, ..., m\}$ and $i \in \{1, 2, ..., n\}$) and by d_i^h the wait time of driver h at customer i ($\forall h \in \{1, 2, ..., k\}$ and $i \in \{1, 2, ..., n\}$). The objective is to find a routing and scheduling, both for agents and vehicles, that, while completing all requested jobs, minimises the total unproductive time. In other words, the sum of all wait times and travel times is minimised. This objective function is formulated as follows:

$$\text{Min} \sum_{i=1}^{n} \left(\sum_{l=1}^{m} a_i^l + \sum_{h=1}^{k} d_i^h \right) + \sum_{e \in E} \left(\sum_{l=1}^{m} \left(c_e x_e^l + w_e y_e^l \right) + \sum_{h=1}^{k} c_e z_e^h \right) \tag{1}$$

The following binary decision variables are used: $x_e^l = 1$ if agent l has to traverse edge e by car and 0 otherwise ($\forall l \in \{1, 2, ..., m\}$ and $e \in E$); $y_e^l = 1$ if agent l has to traverse edge e by walking and 0 otherwise ($\forall l \in \{1, 2, ..., m\}$ and $e \in E$); and $z_e^h = 1$ if vehicle h has to traverse edge e and 0 otherwise ($\forall h \in \{1, 2, ..., k\}$ and $e \in E$). Additionally, the problem is subject to the following constraints:

- *Customer-related constraints*: A job at a customer has to start within a time window $[s_i, s_i^*]$, where s_i states the earliest allowed start time and s_i^* the latest allowed start time. The job at customer i requires t_i time units to be completed. Each customer requesting a job has to be visited by exactly one agent who has to comply with the required qualification level for that particular job. During the day of operation, cancellations and new requests might occur, both resulting in rescheduling and rerouting.

- *Agent-related constraints*: All agents start and end their working day at the depot and can only work at maximum one shift per day. Agents might have different qualification levels. Thus, whenever an agent is assigned to a customer, the agent's qualification level must allow him or her to perform the required job. Moreover, we add the additional requirement that no agent can be assigned to a job for which he/she is overqualified by more than one level, i.e., downgrading an agent by more than one level is forbidden. In total, only one downgrading is allowed per agent per day. Working schedules have to comply with working time and break regulations, i.e., there is an upper bound for the continuous time an agent can work without taking a mandatory break. For instance, in the real-world-based benchmarks used during our numerical experiments, staff members are allowed to work for a maximum period of six hours without taking a break of 30 minutes, while the total time an agent can work per day cannot exceed ten hours plus the break. Additionally, constraints limiting ride, walk and wait times are included to consider employee satisfaction. For instance, maximum ride times are based on the detour which agents in a shared vehicle have to take compared to the shortest path to complete their routes. More details on the specific values for the instance set are provided in the experimental section.

- *Vehicle-related constraints*: Multiple agents can be transported on a vehicle simultaneously as a long as the capacity of the vehicle is not exceeded. Drivers cannot serve any customer and their only task is to drive the vehicle to deliver or pick up agents to/from customers' locations. To simplify the model, Fikar and Hirsch (2015) always force the vehicle to return to the depot if idle and then wait there for the next agent request. This might be quite inefficient and environmentally unfriendly since the next agent request might imply travelling back to a location in the vicinity of the previous customer. As a result, our approach allows the vehicle to wait en-route as an alternative to returning to the depot. Therefore, wait times en-route are considered in the objective function. Idle times at the depot, however, are not added to the objective value as drivers perform administrative support tasks there.

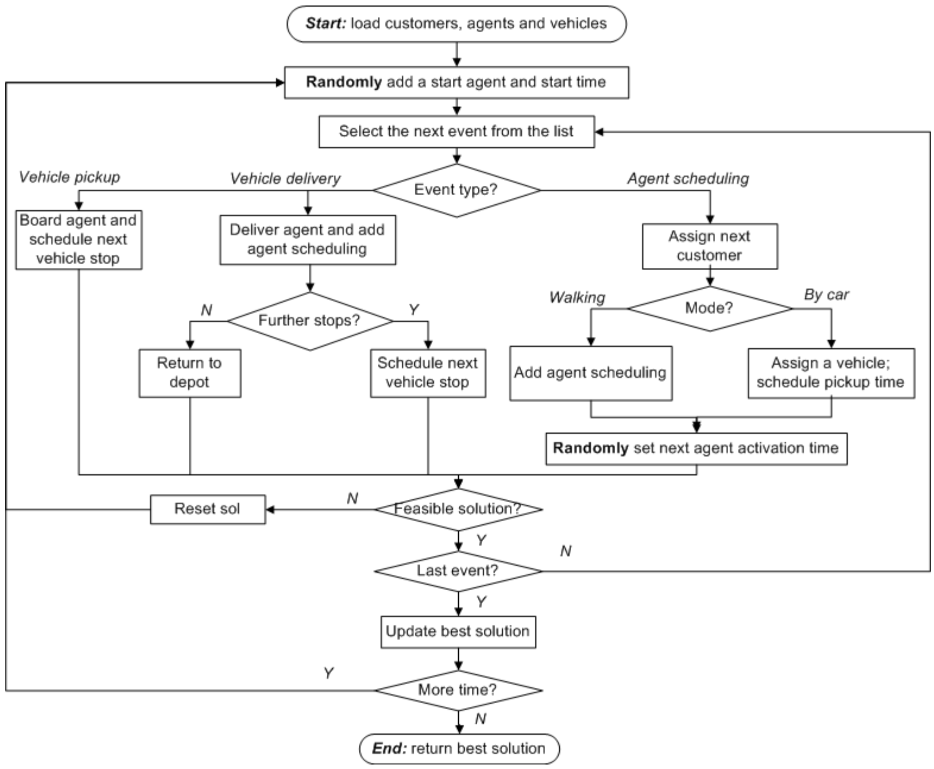
4 Solution algorithm

In order to deal with dynamic environments in an efficient way, a discrete-event driven metaheuristic was developed, which iteratively generates promising solutions based on the occurrence of events over time. These events can be either related to agents, i.e., a decision about the next job to perform is required, or to vehicles, i.e., an agent pickup or an agent delivery. Multiple promising solutions are generated by varying start times, walking routes and staff member movements through the use of biased-randomisation techniques. As described in Juan et al. (2011, 2013), the main idea behind these techniques is to introduce randomness in the constructive procedure in such a way that more promising candidates receive higher probabilities of being selected. The first sub-section provides an overview of the approach, while the remaining sub-sections explore some conceptual and implementation details that contribute to increase the efficiency of the algorithm.

4.1 Metaheuristic overview

Figure 2 shows an overview of the proposed discrete-event driven metaheuristic. To improve readability, 'random' denotes the use of biased-randomisation techniques. At the start, all customers who are known in advance are added to the problem and a timer is set to the current time. This timer is increased in the following steps based on the occurrence of events and is not allowed to decrease during a single run. Furthermore, all agents and vehicles are initialised with their current locations. Agents who have not yet started working are placed at the depot and their working time only starts when they leave the depot. To start the algorithm, a random start agent is added to the list of events at a random start time. This event list is constantly sorted in chronological order according to the event times and is iteratively processed until no events are left. At each iteration, the next event is selected, which can belong to one of the following types: vehicle pickup, vehicle delivery or agent scheduling.

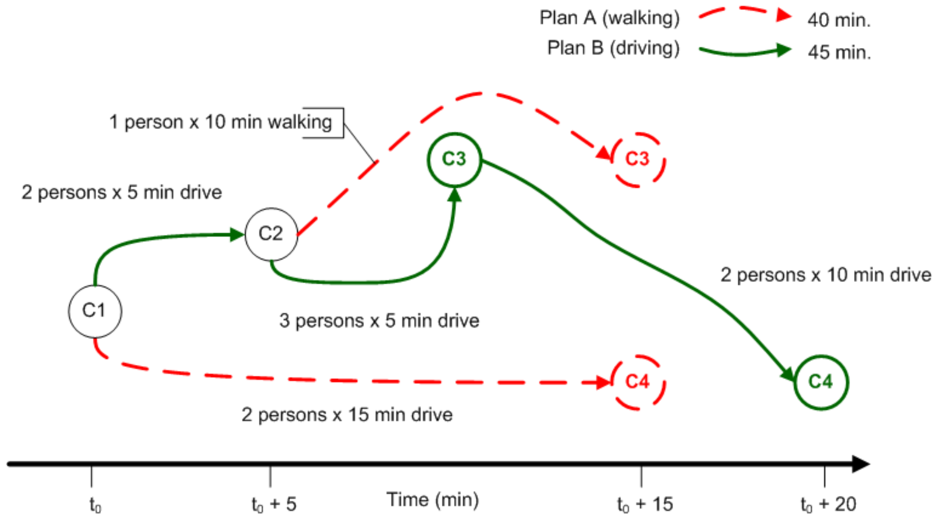
Figure 2 A schematic overview of the discrete-event driven metaheuristic



In the case of a pickup event, the agent is placed on board and the vehicle is moved to the next scheduled stop. Therefore, a related vehicle event is added. If the event is a delivery, the agent is delivered and an agent scheduling event is added at the start time of the job, i.e., either right after the delivery or at the earliest allowed start time. The vehicle either moves back to the depot or to the next stop, depending if further stops are assigned to this vehicle. In the case of a next stop, a related vehicle event is added to indicate the delivery or pickup. During an agent scheduling event, the next destination of an agent is decided. Therefore, the agent is assigned to an urgent feasible job located in relatively close proximity, where 'feasible job' refers to a customer's request complying with the agent's qualification level, working time regulations, customer time window constraints, etc. Furthermore, the different transport options to reach the subsequent stop are analysed and the best one is selected. If the agent walks to the job, a new agent scheduling event is added at the job start time. If he/she goes by car, a vehicle is selected and a pickup event for this vehicle is added. Additionally, after each agent scheduling event, a procedure based on a random activation time decides if a new agent should be activated at the depot. In such a case, an agent scheduling event is added at the selected start time of this agent.

By making all decisions in chronological order, complex and time-consuming back-rolling issues are avoided, i.e., the need to undo and correct earlier scheduled timing decisions. Decisions not yet executed, however, can be adjusted in order to incorporate updated information regarding the position of vehicles and agents, e.g., by changing vehicle routes or pickup and delivery times. During all stages of the algorithm, feasibility checks are performed. In the case of infeasibility, the incumbent solution is aborted and a new solution is initiated from scratch. The solution procedure is run in parallel on multiple threads of the computer system and after a maximum computational time, it stops and returns the best-found solution.

Figure 3 Comparing walking vs. using the transport service (see online version for colours)



4.2 *Event management details*

This section discusses details of the generation and management of different events.

- *Activation of agents:* Agents have to be activated before being able to visit customers. Activating all agents at the start of the day would lead to a bottleneck effect at later hours and long wait times. Therefore, the solution procedure requires an efficient way to decide at which time a new agent should be activated. For each job not yet scheduled to a certain agent, the distance from the current location of each feasible agent to the job and the resulting wait times are calculated. All feasible agents and their corresponding costs are added to a list. The list is then sorted by costs and a random agent among the least costly ones is selected. During the solution-construction process, if no available feasible agent can reach a given customer before the end of the customer's time window, the solution is marked as infeasible. If the selected agent has not started his/her working day and, as a consequence, is still at the depot, he/she gets assigned a random activation time. In order to bias the algorithm towards feasible solutions, various skewed probability distributions to select start times were tested. Similarly, as done in the work of Juan et al. (2014), a decreasing triangular distribution in which the mode equals the lower limit provided reasonably good results as it gives a bias to earlier start times. Over all open jobs, the most urgent agent, i.e., the agent with the earliest event time, is selected and added to the event list in case the agent is not yet activated. Note that the activation time of agents in this step only indicates if a new agent has to be activated, however, the final start time of the agent can still be adjusted later to improve synchronisation with the vehicle routes.

- *Determining next agent destinations:* Whenever an agent starts a job or is activated, all potential and feasible next jobs for the agent are evaluated for their total impact on the objective function. If an agent walks, only costs for the walk time and potential wait times have to be considered. If an agent requests a vehicle, additional costs for the driver, wait times to be picked up and detours/delays for other agents on board may occur. As a consequence, for each potential next job, all available vehicles as well as the option of walking are evaluated. All feasible positions in the current vehicle routes are tested and the one with the least cost is returned. If walking is feasible and equally or less costly than using a vehicle, walking is preferred as this contributes to free up vehicle capacity for future use. Figure 3 illustrates these ideas for a simplified example without time windows in which moving agent A1 from C2 to C3, either by transport service or by walking, is evaluated. Only one vehicle is available, which has a second agent A2 on board. This agent has to be transported to customer C4. If by transport service, the vehicle has to take a detour to pick up agent A1 at C2 and deliver him/her at C3 before continuing the trip to C4. This results in a total cost of 45 minutes including the driver's time. However, if A1 chooses to walk to C3, only a cost of 40 minutes occurs. Furthermore, the transport choice has an effect on the times in which the vehicle and agents will be available again for a new job. For instance, if agent A1 walks, the vehicle will be free 15 minutes after leaving C1, however, if he/she requests the transport service, it will not be free again until 20 minutes after leaving C1. Precisely this time dependencies makes it challenging to employ inter- or intra-route local search processes since any change on a given solution may severely affect synchronisation, potentially resulting in infeasibility issues.

  Additionally, by simply extending the evaluation options, the presented approach allows one to easily add other modes of transport, e.g., underground or public buses. This enables the algorithm to solve real-world multi-modal transport problems with heterogeneous fleets.

  Nevertheless, selecting the next location of an agent solely based on the shortest distance to all potential customer locations can lead to sub-optimal decisions. Depending on the position of other agents, going to a customer further away may be beneficial if no other agent is located in this area. As a result, the cost for an agent to go to each potential next job is compared to the closest other agent in the system who can reach the same job feasibly. To reduce computational times, the direct drive time from the agent location to the customer location is taken, i.e., potential detours and wait times resulting from trip sharing are ignored. To further consider if an agent is moving to or away from the depot, the difference between the time to the depot from the new job and from the old job is added to the evaluation. Each potential job is evaluated with these costs and the one with the least cost is selected. Similarly, to further determine if an agent should end the working day or continue service, the costs of going back to the depot are compared to the costs of going to the next selected job and the cheaper option is executed. If the selected option requires the transport service, the next stops of the vehicle are updated. Otherwise, the agent is scheduled to walk to the customer and an agent scheduling event is added at the start time of the job. If required, a break is scheduled before or after performing a job.

- *Vehicle-related tasks:* Each time one of the vehicles arrives at a location or is scheduled to leave the depot, a vehicle event is called. First, the associated operation is performed. In the case of a delivery, the agent is delivered to the job and a new agent scheduling event is added to the event list. If the delivery location is the depot, no event is added, but the agent ends the working day and is marked inactive. Furthermore, at each delivery, feasibility checks concerning the maximum working time, break regulations and time window violations are performed. In the case of a pickup, the agent is placed on the vehicle.

  After the operation is performed, the vehicle is checked in order to set the next location. If no further stops are scheduled, the vehicle returns to the depot. Otherwise, the next scheduled stop is selected. At what time a vehicle leaves the depot is optimised based on the concept of forward slack time as introduced by Savelsbergh (1992) to reduce unnecessary wait times. Hereby, the time the vehicle leaves the depot is delayed to the point where wait times are minimised. To include wait times of agents, the time at which the agents finish their current jobs are used as pickup times. In the case of agents who are picked up from the depot, the scheduled event times are taken. Based on the defined start time of the job, the vehicle either waits or goes directly to the location. If the vehicle is not at the depot and required to wait, costs of waiting en-route or making a detour to return to the depot are compared. Figure 4 gives an example of a situation in which returning to the depot leads to a lower objective value. If the vehicle goes directly from customer C1 to C2 (a five-minute trip), it has to wait for 25 minutes en-route before it can pick up the agent at C2. In contrast, if the vehicle returns to the depot (a three-minute trip), it can be idle there for 20 minutes before departing to C2 (a seven-minute trip). As idle times at the depot are not considered in the objective function, the objective value is reduced by 20 minutes due to the depot return.

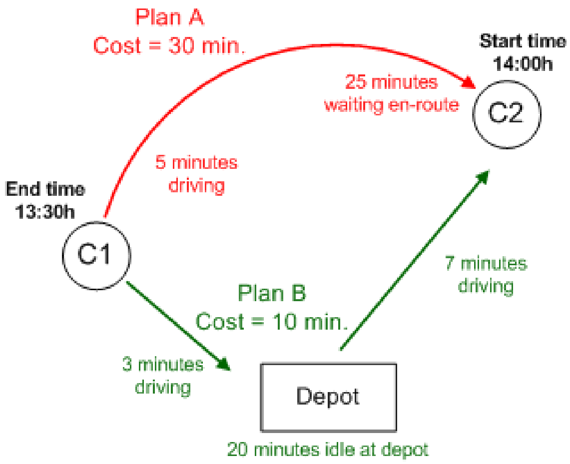
  Whenever the vehicle changes its location, a new event with the arrival time at the next stop is added to the event list. The algorithm then continues with the next event. If no further event exists, the feasibility and completeness of the solution are checked.

4.3 Further improvements: clustering

To further improve the computational time of each single solution construction and to diversify the generated solutions, we introduce a savings-based and biased-randomised clustering procedure, which is based on the ideas presented in Juan et al. (2011, 2013). It allows one to enforce walking between closely-located customers. Walking instead of driving saves the vehicle trip to the pickup location as well as the trip to the next location. The exact costs of this movement, however, depend on the previous and following vehicle stops. While going to a pickup location leads to nearly no extra costs if the pickup is along the current route, high costs occur if the stop is far off. As a consequence, the exact impact of walking cannot be calculated as it is dependent on the vehicle routing. Instead, as shown in equation (2), how much longer (s_e) it takes to walk (w_e) compared to driving (c_e) is calculated in order to rank an edge e.

$$s_e = c_e - w_e \tag{2}$$

Figure 4 A vehicle returning to the depot to save wait time (see online version for colours)



All feasible mergers are added to a list, sorted and processed. A lexicographic order is employed which first sorts candidates by s_e in ascending order, and, if equal, ranks mergers of jobs with different qualifications last. If still equal, the merger resulting in a higher reduction of the time window is ranked last. The next merger to process is selected by a geometric distribution. Therefore, the parameter $\beta \in (0, 1)$ indicates the bias of the selection. As $\beta \to 0$, the selection is more and more uniformly distributed, while as $\beta \to 1$, the selection is more and more greedy towards the best candidate. Feasibility concerning time windows, job durations, downgradings and walking distances are checked before each merger. After merging jobs, time windows, pickup locations as well as walking and job durations have to be updated. Note that in the case of a merger, the pickup location of the clustered job no longer equals the delivery location. After the entire list is processed, the set of clustered jobs is returned to the discrete-event driven metaheuristic.

To vary the clusters, a random maximum walking distance between two jobs in the range from 0 to the maximum allowed walking distance between two jobs is selected. Furthermore, each run randomly selects how many mergers with downgradings can be performed per qualification level. After each run, the best found objective value for each maximum walking distance within a cluster is updated and the following cluster generation prefers more promising maximum walking distances based on a biased-randomised selection. For each generated cluster, a defined number of solutions is generated. The best result of the cluster is compared to the overall best found solution. Inspired by simulated annealing (Kirkpatrick et al., 1983), the acceptance criterion in equation (3) is used to decide if a cluster is kept for the following iteration or discarded.

Keep cluster if:

$$rand \leq 1 - [\log_{10}(S^*_{currentCluster}/S^*_{all}) \cdot solutions_{currentCluster}] \tag{3}$$

$rand \in [0, 1]$ is a random number generated from a uniform distribution. S^* indicates the best found solution either in the current cluster $S^*_{currentCluster}$ or in all tested clusters so far S^*_{all} and $solutions_{currentCluster}$, the number of generated solutions for the current cluster. As a result, non-promising or highly investigated clusters have a higher probability of being discarded. This steers the solution procedure to analyse a wide range of clusters, while spending additional time in promising ones.

5 Computational experiments

The discrete-event driven metaheuristic described in the previous section was implemented in Java. In order to test its efficiency, computational experiments on already published benchmarks were run. These instances originate from a static problem setting where all information is known in advance, however, our procedure further enables one to solve dynamic instances. All tests in this section were run on an Intel Core i7-4930K, 64 GB RAM, with MS-Windows 7 as operating system.

5.1 Test instances

To the best of our knowledge, the only test instances in literature for this problem are those proposed in Fikar and Hirsch (2015), which are publicly available at: http://www.wiso.boku.ac.at/en/production-and-logistics/research/instances/. As described by the authors, these instances are based on real-life cases originated from urban and sub-urban HHC operations. The instance set contains 30 instances, half of them located in an urban area (‘U’ instances) and the other half in a sub-urban area (‘S’ instances). For each area, five instances for each 75, 100 and 125 jobs to perform (denoted by ‘N’) are given. These jobs are further indicated by a time window, a qualification requirement and a duration. Distance matrices for both walking and driving indicate the distances between customer locations and a depot. The number of available vehicles is indicated by ‘K’ and each vehicle has a capacity of six passengers (including the driver). The number of available agents (nurses in this case) is stated by ‘M’. Each agent can work a maximum of ten hours per day and has to take a 30-minute break if he/she works longer than six hours. Therefore, the break has to be timed so that the agent never works longer than six hours consecutively. Furthermore, additional constraints apply as follows: an agent can walk from one customer to the next only if the walking time does not exceed ten minutes, the accumulated walking time between two trips on the transport service cannot exceed 20 minutes and the accumulated wait time as well a ride time spent for detours is limited by 15 minutes.

5.2 Parameter settings

As described in Section 4.2, the presented approach makes use of a decreasing triangular distribution with no additional parameters to select the start times of new agents. In the cluster-selection process detailed in Section 4.3, the biased-randomisation component makes use of a geometric distribution with parameter β. This parameter was set to 0.15 after performing a binary search algorithm with increments of 0.05 over all test instances. If not a single feasible solution has been found after eight runs, a cluster is discarded. Additionally, after eight feasible solutions are found, the acceptance criterion is called to decide if the current cluster is kept for eight more solutions or if a new cluster is generated.

5.3 Results and discussion

To benchmark the discrete-event driven metaheuristic, further denoted as *DER*, each of the 30 instances was run ten times and the best found solution as well as the average objective value over all runs is reported. A single run was limited to one minute and employed a different seed for the pseudo-random number generator so that the specific random behaviour of the algorithm changes from run to run. Using exactly the same experimental design, we also run all instances of the matheuristic *TS-SPBS* developed by Fikar and Hirsch (2015). *TS-SPBS* is a quite sophisticated algorithm combining set partitioning to generate walking routes with a Tabu Search metaheuristic. It also includes a modification operator to align walking and vehicle routes. *TS-SPBS* is able to provide high-quality solutions for the real-life-based instances that are considered in a static setting. However, in *TS-SPBS*, synchronisation and start-time optimisation is achieved by solving a linear program at each solution evaluation, which results in substantially high computational times. Thus, *TS-SPBS* is not suited for real-time decision-making under dynamic scenarios. Additionally, in order to deal with the complexity of the problem, the *TS-SPBS* matheuristic forces drivers to return to the depot as en-route waiting is not enabled. On the contrary, *DER* does allow en-route waiting and, as discussed, can also support real-time decision-making in dynamic settings.

Table 1 shows the best and average results obtained using both the *TS-SPBS* and the *DER* algorithms.

There are several findings to highlight from this table:

- While *DER* always finds a feasible solution in real time (average time of 0.010 s), the *TS-SPBS* algorithm does not find a single feasible solution in 12 out of 30 instances within a minute of run time. In particular, while the *DER* algorithm is able to find a feasible solution for the last sub-urban instance (number 30) in 0.029s, the *TS-SPBS* cannot find any feasible solution for this instance after ten runs of 60 s each. Since the *DER* algorithm has been able to generate feasible solutions in milliseconds in each instance, it is suitable for real-time decision-making under dynamic scenarios.
- Considering the best-cost and the average-cost solutions of the ten runs, *DER* performs better than *TS-SPBS* for sub-urban instances (numbers 16 to 30), while the opposite is true for urban instances (numbers 1 to 15). In the case of the *TS-SPBS* results, averages only consider the runs providing a feasible solution. Averages are quite similar, with 1.71% being the average gap for the best-cost solution and 0.74% the average gap for the average-cost solution between *DER* and *TS-SPBS*.

Table 1 Comparison of best and average solutions – ten runs per instance, 60 s each run

No.	Instance name	*TS-SPBS*[a]			*DER*			*Gap*[b]	
		Best (1)	*Avg (2)*	*All runs feasible?*	*Best (3)*	*Avg (4)*	*First feasible after*	*(1)–(3)*	*(2)–(4)*
1	U1-n75-k2-m12-8-4	*550*	*562.4*	Y	567	572.0	0.003 s	3.09%	1.71%
2	U2-n75-k2-m12-8-4	*550*	*560.8*	Y	562	567.1	0.003 s	2.18%	1.12%
3	U3-n75-k2-m12-8-4	*550*	*559.3*	Y	575	579.5	0.003 s	4.55%	3.61%
4	U4-n75-k2-m12-8-4	*546*	*555.9*	Y	561	565.7	0.003 s	2.75%	1.76%
5	U5-n75-k2-m12-8-4	*587*	*603.9*	Y	600	607.3	0.004 s	2.21%	0.56%
6	U1-n100-k2-m16-10-6	*716*	*730.3*	Y	720	744.9	0.006 s	0.56%	2.00%
7	U2-n100-k2-m16-10-6	*733*	*752.6*	Y	761	774.6	0.007 s	3.82%	2.92%
7	U3-n100-k2-m16-10-6	*719*	*737.0*	Y	757	763.5	0.006 s	5.29%	3.60%
9	U4-n100-k2-m16-10-6	*712*	*717.3*	Y	730	739.1	0.006 s	2.53%	3.04%
10	U5-n100-k2-m16-10-6	*761*	*773.7*	Y	782	793.5	0.006 s	2.76%	2.56%
11	U1-n125-k2-m20-12-8	*842*	*850.2*	Y	858	866.1	0.007 s	1.90%	1.87%
12	U2-n125-k2-m20-12-8	*878*	897.2[c]	N	885	*892.1*	0.008 s	0.80%	–0.57%
13	U3-n125-k2-m20-12-8	*867*	*880.4*	Y	890	895.8	0.012 s	2.65%	1.75%
14	U4-n125-k2-m20-12-8	*857*	*874.1*	Y	874	890.9	0.011 s	1.98%	1.92%
15	U5-n125-k2-m20-12-8	*820*	*834.0*	Y	874	878.1	0.012 s	6.59%	5.29%
16	S1-n75-k2-m12-8-4	*839*	*854.3*[c]	N	847	869.6	0.005 s	0.95%	1.80%
17	S2-n75-k2-m12-8-4	*773*	*795.0*	Y	803	811.2	0.005 s	3.88%	2.04%
18	S3-n75-k2-m12-8-4	*812*	824.4	Y	*812*	*820.6*	0.005 s	0.00%	–0.46%
19	S4-n75-k2-m12-8-4	839	848.6[c]	N	*826*	*835.9*	0.006 s	–1.55%	–1.49%
20	S5-n75-k2-m12-8-4	870	*881.2*[c]	N	*869*	881.5	0.006 s	–0.11%	0.04%
21	S1-n100-k2-m16-10-6	*1,052*	1,081.8	Y	1066	*1,077.5*	0.010 s	1.33%	–0.40%
22	S2-n100-k2-m16-10-6	*1,026*	1,083.7[c]	N	1,064	*1,075.6*	0.016 s	3.70%	–0.74%
23	S3-n100-k2-m16-10-6	*1,064*	1,113.7[c]	N	1,085	*1,093.0*	0.010 s	1.97%	–1.86%
24	S4-n100-k2-m16-10-6	*1,005*	*1,033.2*	Y	1,029	1,041.7	0.011 s	2.39%	0.82%
25	S5-n100-k2-m16-10-6	*1,149*	*1,149.0*[c]	N	1,185	1,195.2	0.016 s	3.13%	4.02%
26	S1-n125-k2-m20-12-8	1,327	*1,327.0*[c]	N	*1,323*	1,346.5	0.024 s	–0.30%	1.47%
27	S2-n125-k2-m20-12-8	1,285	1,301.5[c]	N	*1253*	*1,258.5*	0.012 s	–2.49%	–3.30%
28	S3-n125-k2-m20-12-8	1,342	1,410.3[c]	N	*1282*	*1,291.1*	0.021 s	–4.47%	–8.45%
29	S4-n125-k2-m20-12-8	1,317	1,363.3[c]	N	*1285*	*1,294.4*	0.021 s	–2.43%	–5.06%
30	S5-n125-k2-m20-12-8	*N/A*	*N/A*	N	*1288*	*1,297.8*	0.029 s	N/A	N/A
			Feasibility issues:	12/30		Averages:	0.010 s	1.71%[c]	0.74%[c]

Notes: [a]Fikar and Hirsch (2015), [b](DER-TS-SPBS)/TS-SPBS, [c]mean of feasible runs

It is possible to identify several reasons to explain why each solution procedure performs better for a subset of instances (U or S):

- S-instances are more difficult to solve as agents are more utilised (due to longer driving distances) and less distances are walked, resulting in more complex synchronisation issues that slow down the *TS-SPBS* approach
- the set partitioning used to find promising walking-routes for U-instances in the *TS-SPBS* algorithm performs quite well, while the *DER* algorithm does not benefit from an exact method in the selection of the walking routes
- waiting en-route is better in S-instances than in U-instances, which benefits *DER* over the *TS-SPBS*.

6 Conclusions

Transport strategies that are both economically and environmentally sustainable, such as those combining trip sharing with walking, are highly needed in the home service industry. Unfortunately, the final implementation of these multi-modal strategies is often hindered by the complexity of real-life operations. In particular, the need for synchronisation among agents and vehicles under dynamic scenarios raises operational challenges that are difficult to manage using traditional optimisation approaches or local search procedures. To support trip sharing concepts in the home service industry, we present an efficient and flexible metaheuristic that relies on discrete-event and biased-randomisation principles. When combined, these principles allow one to efficiently manage the complex synchronisation issues. Various real-world constraints and different industry characteristics are included and both driving as well as walking are enabled. The results show that the proposed discrete-event driven metaheuristic is able to produce high-quality solutions very quickly, thus, allowing real-time decision making even under dynamic scenarios.

In future work, we plan to consider random variables in the problem formulation (e.g., stochastic driving and job durations) and to extend our discrete-event metaheurisic to a simheuristic (Juan et al., 2015). By extending our approach in this way, we expect to be able to generate robust and low risk solutions under uncertain scenarios.

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Petrakis, I., Hass, C. and Bichler, M. (2012) 'On the impact of real-time information on field service scheduling', *Decision Support Systems*, Vol. 53, No. 2, pp.282–293.

Pillac, V., Guéret, C. and Medaglia, A.L. (2012) 'An event-driven optimization framework for dynamic vehicle routing', *Decision Support Systems*, Vol. 54, No. 1, pp.414–423.

Rasmussen, M.S., Justesen, T., Dohn, A. and Larsen, J. (2012) 'The home care crew scheduling problem: preference-based visit clustering and temporal dependencies', *European Journal of Operational Research*, Vol. 219, No. 3, pp.598–610.

Rest, K-D. and Hirsch, P. (2015) 'Daily scheduling of home health care services using time-dependent public transport', *Flexible Services and Manufacturing Journal*, in press, see DOI: 10.1007/s10696-015-9227-1.

Savelsbergh, M.W.P. (1992) 'The vehicle routing problem with time windows: minimizing route duration', *ORSA Journal on Computing*, Vol. 4, No. 2, pp.146–154.

Trautsamwieser, A. and Hirsch, P. (2014) 'A branch-price-and-cut approach for solving the medium-term home health care planning problem', *Networks*, Vol. 64, No. 3, pp.143–159.

Trautsamwieser, A., Gronalt, M. and Hirsch, P. (2011) 'Securing home health care in times of natural disasters', *OR Spectrum*, Vol. 33, No. 3, pp.787–813.

Tricoire, F., Bostel, N., Dejax, P. and Guez, P. (2013) 'Exact and hybrid methods for the multiperiod field service routing problem', *Central European Journal of Operations Research*, Vol. 21, No. 2, pp.359–377.

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Xu, J. and Chiu, S. (2001) 'Effective heuristic procedures for a field technician scheduling problem', *Journal of Heuristics*, Vol. 7, No. 5, pp.495–509.

Appendices

A Curriculum Vitae

CHRISTIAN FIKAR, MSc

Schiffmühlenstraße 87/2/11, 1220 Vienna, Austria | christian.fikar@gmail.com | +4367761469555

PERSONAL DETAILS

Date of Birth:	13th of December 1986
Place of Birth:	Vienna, Austria
Citizenship:	Austrian
Email:	christian.fikar@gmail.com
Phone:	+4367761469555

EDUCATION

University of Natural Resources and Life Sciences, Vienna (BOKU) Vienna, Austria since 02.2013

- 2013-*: ***Doctorate in Social and Economic Sciences***
  - Focusing on optimization and meta/matheuristics in the context of humanitarian logistics
  - Title of thesis: "Routing and scheduling of home services facilitating trip sharing and walking"
  - Awarded the Raiffeisen Science & Innovation Publication Award 2014 for the publication 'A matheuristic for routing real-world home service transport systems facilitating walking, Journal of Cleaner Production 105, 300-310'.
  - Dissertation submitted: Graduation expected in early 2016

Vienna University of Economics and Business Vienna, Austria from 02.2007-08.2012

- 2010-2012: ***Master of Science in Supply Chain Management***
  - Specialization: "Retail and Marketing" and "Transportation Geography and Modelling"
  - Language of instruction: English
  - Title of thesis: "Emission Constrained Dual Sourcing"
  - Honorary admission to the Center of Excellence (http://www.coe.at/) incl. successful completion
  - Academic degree: Master of Science (WU), degree awarded with distinction on 29.08.2012
- 2007-2010: ***Bachelor of Science in Business, Economics and Social Sciences (BESC) - Business Administration Major***
  - Specialization: "Production Management" and "Export Management"
  - Title of thesis: "Supply chain contracts with consideration of emission costs"
  - Academic degree: Bachelor of Science (WU), degree awarded on 15.07.2010

University of Wisconsin-Madison Madison, Wisconsin, USA from 09.2009-12.2009

- Exchange term at the Wisconsin School of Business
  - Completion of courses in supply chain management, logistics und international finance
  - Official transcript dated 06.01.2010

Bundeshandelsakademie Wien 22 Vienna, Austria from 2001-2006

- General qualification for university entrance with good standing at a business high school
  - Degree awarded 14.06.2006

CHRISTIAN FIKAR, MSc

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WORK EXPERIENCE

University of Natural Resources and Life Sciences, Vienna (BOKU) Vienna, Austria from 11.2012-01.2016

- Research assistant at the Institute of Production and Logistics (40h/week)
  - Development of meta- and matheurstics for home service trip sharing problems
  - Development of simulation-optimization based disaster relief last-mile distribution
  - Development of simulations to investigate transalpine freight transport vulnerabilities
  - Drafting of project proposals and coordination of multidisciplinary research activities
- Lecturer (Starting from Fall 2014)
  - Bachelor Courses: General Management, Business economics for equine sciences, Bachelor's Thesis Seminar (Language of instruction: German)

Vienna University of Economics and Business Vienna, Austria from 12.2015-01.2016

- Lecturer
  - Master Course: Advanced Operations Research (Language of instruction: English)

IN3 - Open University of Catalonia Barcelona, Spain in 03.2014 & 03.2015

- Two one-month stays as a Visiting Researcher at the IN3-Smart Logistics & Production group
  - Research collaboration, development of solution algorithms, drafting European project proposals

Vienna University of Economics and Business Vienna, Austria from 09.2011-07.2012

- Tutor/eAssistant at the Institute for Production Management (up to 19.5h/week)
  - Tutoring for international master students in the subjects of "Operations Management" and "Supply Management" (Language of instruction: English)
  - Assistance in projects, particularly the development of electronic teaching notes and case studies

Austrian Trade Delegation Taipei Taipei, Taiwan from 08.2010-09.2010

- 6-week internship and training program
  - Compilation of industry profiles in the fields of machinery and online distribution
  - Additional tasks to support Austrian companies conducting business in/with Taiwan

Lernquadrat Bildungsmanagement GmbH Vienna from 11.2008-06.2009 & 02.2010-12.2011

- Part-time employment as a tutor (varied hours)
  - Tutoring groups of up to six high school students in accounting and business administration

COMPULSORY SOCIAL SERVICE

Bundespolizeidirektion Wien Vienna, Austria from 09.2006-05.2007

- School crossing guard and office assistant at the police department of Donaustadt
  - Ensuring the safety of children in traffic by guarding pedestrian crosswalks near schools
  - Managing police archives for various traffic and civilian offenses

LANGUAGE SKILLS

- German: Native
- English: Fluent (married to a native speaker)
- French: Basic

CHRISTIAN FIKAR, MSc

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MISCELLANEOUS

- Advanced skills in MS Word, MS Excel, MS PowerPoint and LaTeX
- Programming experience in C++, JAVA and VBA
- Work experience in AnyLogic, FICO Xpress and ArcGIS 10
- Education as quality manager according to ISO 9001 (29.03.2005 – with honours)
- Language courses in Great Britain (1999), Ireland (2004) and France (2004)
- Participant in the UN Shadowing Programme 2015

PUBLICATIONS

Journal Articles

- Berariu, R, Fikar, C, Gronalt, M, Hirsch, P (2016) Training decision-makers in flood response with system dynamics. Disaster Prevention and Management, 25(2), in press, http://dx.doi.org/10.1108/DPM-06-2015-0140.
- Berariu, R, Fikar, C, Gronalt, M, Hirsch, P (2015) Understanding the impact of cascade effects of natural disasters on disaster relief operations. International Journal of Disaster Risk Reduction 12, 350–356, http://dx.doi.org/10.1016/j.ijdrr.2015.03.005.
- Fikar, C, Hirsch, P (2015) A matheuristic for routing real-world home service transport systems facilitating walking, Journal of Cleaner Production 105, 300-310. http://dx.doi.org/10.1016/j.jclepro.2014.07.013.
- Fikar, C, Juan, AA, Martinez, E, Hirsch, P (2015) A discrete-event metaheuristic for dynamic home service routing with synchronised trip sharing. European Journal of Industrial Engineering, in press.

Journal Articles under Review

- Fikar, C, Hirsch, P (2015) Evaluation of a trip sharing concept for home health care services. Submitted to Transportation Research Part A: Policy and Practice. 2nd Revision.
- Fikar, C, Gronalt, M, Hirsch, P (2015) A decision support system for coordinated disaster relief distribution. Initial Submission – Under Review.
- Fikar, C, Hirsch, P, Posset, M, Gronalt M (2015) Impact of transalpine rail network disruptions: A study of the Brenner Pass. Initial Submission – Under Review.

Conference Proceedings (Selection)

- Fikar, C, Gronalt, M, Goellner, J, Hirsch, P (2015) Simulation-optimisation based decision-support for coordinated disaster relief last-mile distribution. In: Bruzzone, Del Rio Vilas, Longo, Merkuryev, Piera (Eds.), Proceedings of the Int. Conf. on Harbor Maritime and Multimodal Logistics M&S, 2015, 15-22; ISBN: 978-88-97999-58-4.
- Gruler, A, Fikar, C, Juan, A, Hirsch, P, Contreras, C (2015) A Simheuristic for the Waste Collection Problem with Stochastic Demands in Smart Cities. In: Rabe, M; Clausen, U (Eds.), Simulation in Production and Logistics, Fraunhofer Verlag, 49-58, ISBN: 978-3-8396-0936-1.

Master Thesis

- Fikar, C (2012): Emission constrained dual sourcing. Master's thesis at the Institute for Production Management, 62; Vienna University of Economics and Business.

CHRISTIAN FIKAR, MSc

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REVIEWER FOR SCIENTIFIC JOURNALS

- 2015-*: International Transactions in Operational Research
- 2015-*: Central European Journal of Operations Research
- 2014-*: Journal of Cleaner Production

SCIENTIFIC MEMBERSHIPS

- Euro Working Group on Humanitarian Operations
- Euro Working Group on Vehicle Routing and Logistics Optimization
- OR2015 Emerging Scholars Program

RESEARCH PROJECTS

ALTCARE (FFG-iv2splus)

- Duties and Achievements:
    - Development of solution procedures for trip sharing concepts in home health care operations
    - Evaluation of the concepts and investigation of policy implications
    - Two published journal publications and one manuscript currently under review
    - Publication award: Raiffeisen Science & Innovation Publication Award 2014
- Project Members: University of Natural Resources, Vienna; Austrian Red Cross
- Duration: 11.2012-10.2014

LMK-MUSE (FFG-KIRAS)

- Duties and Achievements:
    - Key member in the organization and draft of the project proposal
    - Key researcher in the development of simulation-optimization methods
    - Two journal publications and one manuscript currently under review
    - Projects results planned to be used in training of decision makers
- Project Members: University of Natural Resources, Vienna; BMLVS; BMI; University of Vienna
- Duration: 11.2013-01.2016

RAGOUT (FFG-KIRAS)

- Duties and Achievements:
    - Development of supply chain vulnerability simulation for transalpine rail movements
    - One manuscript currently under review
- Project Members: University of Natural Resources, Vienna; BMLVS; Austrian Institute of Technology; University of Vienna; Red Cross Innsbruck
- Duration: 10.2014-12.2015