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A Survey on Workforce Scheduling and Routing Problems

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Abstract In the context of workforce scheduling, there are many scenarios in which personnel must carry out tasks at different locations hence requiring some form of transportation. Examples of these type of scenarios include nurses visiting patients at home, technicians carrying out repairs at customers' locations, security guards performing rounds at different premises, etc. We refer to these scenarios as *Workforce Scheduling and Routing Problems* (WSRP) as they usually involve the scheduling of personnel combined with some form of routing in order to ensure that employees arrive on time to the locations where tasks need to be performed. This kind of problems have been tackled in the literature for a number of years. This paper presents a survey which attempts to identify the common attributes of WSRP scenarios and the solution methods applied when tackling these problems. Our longer term aim is to achieve an in-depth understanding of how to model and solve workforce scheduling and routing problems and this survey represents the first step in this quest.

Keywords workforce scheduling, employee rostering, routing problems, mobile workforce

1 Introduction

In recent times, employees often need to be more flexible regarding the type of job performed and similarly, employers need to make compromises in order to retain their best employees (Eaton, 2003; Martínez-Sánchez et al, 2007). Moreover, in some cases workforce should perform tasks at different locations,

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e.g. nurses visiting patients at their home, technicians carrying out repairs at different companies, etc. Therefore, the scheduling of workforce with 'flexible' arrangements and 'mobility' is of great importance in many scenarios. Many types of personnel scheduling problems have been tackled in the literature (Baker, 1976; Miller, 1976; Golembiewski and Proehl Jr, 1978; Cheang et al, 2003; Ernst et al, 2004; Alfares, 2004). We are interested in those workforce scheduling problems in which personnel is considered *flexible* (in terms of tasks and working times) and *mobile* (travelling is required in order to do the job). By *mobility* we refer specifically to those cases in which moving from one location to another takes significant time and therefore reducing the travel time could potentially increase productivity. To some extent, this problem combines features from the general employee scheduling problem and also vehicle routing problems. The survey and discussion presented here represent the first step in our aim of formulating and tackling the problem of scheduling flexible and mobile workforce. In the rest of this paper, we refer to this as the workforce scheduling and routing problem (WSRP).

In section 2 we describe the WSRP and identify some of the main characteristics of this type of workforce scheduling problems. Section 3 outlines some workforce scheduling scenarios that have been investigated in the literature and that in our view present a case of WSRP. Examples include home care, scheduling of technicians, manpower allocation, etc. Subsection 3.6.3 is dedicated to the vehicle routing problem with time windows (VRPTW) (Desrochers et al, 1992; Kallehauge et al, 2005) since it is the base for the routing component of many of the problems discussed in this survey. Section 4 outlines different methods (optimisation, heuristics and hybrid approaches) used when tackling WSRP scenarios. Section 5 summarises our findings and outlines the next steps in our research into workforce scheduling and routing.

2 Workforce Scheduling and Routing Problems

2.1 Description of the problem

In this paper, we refer as Workforce Scheduling and Routing Problem (WSRP) to those scenarios involving the mobilisation of personnel in order to perform work related activities at different locations. In such scenarios, employees use diverse means of transportation, e.g. walking, car, public transport, bicycle, etc. Also, in these scenarios there are more than one activity to be performed in a day, e.g. nurses visiting patients at their homes to administer medication or provide treatment (Cheng and Rich, 1998), care workers aiding members of the community to perform difficult tasks (Eveborn et al, 2006), technicians carrying out repairs and installations (Cordeau et al, 2010), and security guards performing night rounds on several premises (Misir et al, 2011). The number of activities across the different locations is usually larger than the number of employees available, hence employees should travel between locations to perform the work. This results in a combination of employee scheduling and vehicle routing problems. The number of activities varies depending on the duration of the working shift, but assuming that each activity needs to be performed at a different location, a routing problem also arises. A route is a sequence of locations that need to be visited (Raff, 1983) but we exclude problems in which workers need to move across work stations within the same factory for example. Work activities which need to be performed in a specified time (time window) require scheduling in addition to routing. Tackling WSRP scenarios could potentially involve many objectives like: reducing employees travel time, guaranteeing tasks to be performed by qualified people only, reducing the cost of hiring casual staff, ensuring contracted employees are used efficiently, etc.

We assume employees should rather spend more time doing work than travelling, particularly in settings in which travelling time is counted as working time, hence reducing travel time is valuable (Fosgerau and Engelson, 2011; Jara-Díaz, 2000). In WSRP scenarios is often beneficial that employees perform activities at customer premises more efficiently. Like in many workforce scheduling problems, the set of skills that an employee has for performing a task is of great importance (Cordeau et al, 2010). Many papers in the literature assume that the workforce is homogeneous regarding skills but in many scenarios, a diverse set of skills is the predominant environment. We should note that scenarios like the pick-up and delivery of goods (parcels) is not considered here as a WSRP because no significant 'work' (in terms of time) is carried out at customers' premises. Although, one could argue that the action of delivering a parcel is a task, it does not take a significant amount of time once the worker gets to the destination. This type of pick-up and delivery problems are definitely routing problems but are not covered in our study of workforce scheduling and routing problems.

2.2 Main characteristics

In this subsection, we outline the main characteristics of any WSRP. Some of these characteristics are 'obvious' since they are in the nature of the problem while others were identified during our survey. We include the characteristics that appear the most in the literature and describe them in the subsections below. For a list of all the attributes considered and the papers included in this survey please refer to *Table 1*.

Time windows for performing a task/duty/job at a customer premises. It is assumed that employees can start the work as soon as they arrive to the location. Time windows can be very flexible or very tight and in accordance to contractual arrangements. In some cases, no time window is defined as employees work based on annualised hours. Also, in some cases employees can benefit from over-time payment, making compliance with the time window more of a soft constraint.

Transportation modality refers to employees using different means like: car, bicycle, walking or public transport. We assume that time and cost of transportation is not the same for each employee.

Start and end locations One location, when all employees start at the main office (Eveborn et al, 2006), up to many locations (perhaps as many as the number of employees) assuming each employee may start from their home. In some cases the company's policy might be that employees should start their working time at the main office but then returning home directly after the last job performed.

Skills and qualifications act as restrictive filters on who can perform a task and there are two main cases. *1)* In general, all workforce have the same ability (skills and qualifications) so anyone can perform the task, but this tends to be expensive for the organisation. *2)* Workforce with diverse levels of abilities, this is common in industries such as consulting and healthcare. Matching employees' skills to the tasks assigned has been tackled for complex organisations (Cordeau et al, 2010).

Service time corresponds to the duration of the task and it varies depending on the employee who performs it and the type of task. Most models in the literature assume a fixed duration. If service times are long enough so that they restrict each worker to perform only one job, then the problem reduces to task allocation since every route would consider only one job per employee.

Connected activities refers to dependencies among the activities to be performed. *Sequential*, when one activity must be performed before/after another. Activities are said to be *simultaneous* when they happen at the same time and require two or more employees to be present. *Temporal dependencies: synchronisation, overlap, minimum difference, maximum difference, min+max difference*, as defined by Rasmussen et al (2012).

Teaming may be necessary due to the nature of the work to be carried out (Li et al, 2005). If members of the team remain unchanged then the team can be treated as a single person and synchronising the arrival of team members is necessary. If members of the team change frequently then skill matching according to the job is required (Cordeau et al, 2010).

Clusterisation may be necessary for several reasons. One is employee preferences when expecting not to travel more than a number of miles. Another reason is when companies assign employees to perform work only in certain geographical areas. Clusters may also be created just to reduce the size of the problem and solve many smaller instances.

3 Workforce Scheduling and Routing Problems in the Literature

In this section we describe some of the problems tackled in the literature that can be considered as a type of workforce scheduling and routing problem (WSRP). The intention is to illustrate the variety and importance of WSRP scenarios in the real-world.

3.1 Home health care

Bertels and Fahle (2006) describe home health care (HHC) as visiting and nursing patients at their home. Patients preferences regarding the time of visit are respected as much as possible, as they cannot wait for the entire day.

Additionally, nurses have also *time window* limitations regarding the number of hours they work in a day or their starting and ending time. In HHC, *transportation modality* is present when nurses travel by car, public transport or even walking to visit more than one patient. The *start and end location* of nurses routes vary. They can depart from their homes or from a central health care office, and end their day once they return home or in some cases at the last patient visited. A diverse set of *skills and qualifications* is present in the set of nurses due to the large range of procedures required. Healthcare organisations often cannot afford to have nurses trained in all procedures. Then, the use of a highly qualified nurses should be restricted to tasks that demand those skills. Nursing activities vary in duration (*service time*) e.g. from a 10 min injection to a 45 min physical therapy. *Connected nursing activities* can be found when applying medicine e.g. the first dose is applied during the morning and 3 hours later another dose. Some activities require more than one nurse at the same time e.g. handling a person with epilepsy. In such cases, nurses can be *syncronised* to arrive at the location at the same time, or assign a *team of two nurses* who always performed these type of tasks. *Clusterisation* is used, by the organisation providing health care to avoid nurses having to travel too much.

Other characteristics of HHC which are not part of the main WSRP main ones include nurses preferences, shift types and other legal requirements. Also, it is desirable not to change much which nurses visit which patients. This is because patients and nurses develop a bond that is usually good to maintain. Cheng and Rich (1998) explore the use of casual nurses, i.e. those not in a contract with the organisation. Cheng's work does not consider different nurses' skills and qualifications but instead, proposes a matching method in which a pairing patient-nurse is either feasible or not for some reason. The objective in Cheng's work is to reduce the amount of overtime and part-time work employed.

3.2 Home care

Home care (also called domiciliary care) refers to the provision of community care service by local authorities to their constituents (Akjiratikarl et al, 2007). The aim is to schedule care workers across a region in order to provide care tasks within a *time window* while reducing travel time. This problem is related to the home health care problem described by Bertels and Fahle (2006) and Cheng and Rich (1998). The difference is that home health care involves helping people for a relatively short period of time to recover after hospitalisation. Home care however usually refers to helping elderly and/or disabled people to perform their daily activities such as shopping, bathing, cleaning, cooking, etc. (Eveborn et al, 2009). Once a person starts receiving home care support it is likely to remain receiving such care for a long time. Home carers usually *start* travelling from their homes to deliver support at their predefined destinations using their own transport arrangements (mixed *transportation modality*) and *return home at the end of the day*. In some cases reported in the literature, care workers do not start from their home but from a *home care office* as last minute changes to their schedules are possible and need to be agreed before starting the working day (Eveborn et al, 2009). In some cases, travel time is considered as work hours and hence the objective is to reduce the time used not providing care. Some assumptions are made such as given travel speed for a carer and travel distances to be euclidean. In other cases like the work by Dohn et al (2008), the objective is to maximise the quality level of care service provided. Reducing cost, although important, is not the main objective. Dohn et al (2008) study the problem as a variant of the VRP with time windows. Although not as much as in HHC, there are some *skills and qualification* required in home care when caring for others e.g. health and safety, handling people with dislexia, etc. *Service time* is standarised and it only varies due to the experience of the carer or difficulties with the person receiving care. *Connected activities* also exist in home care e.g. taking a shower before doing groceries. *Teaming* is not present since carers tend to be *syncronised* to perform difficult tasks e.g. assisting a heavy person. *Clusterisation* is based on municipalities borders to clearly defined which authority is responsible for part of the community e.g. council, borough, district etc.

Additional features of home care are: *prioritising visits*. Usually, there is not enough personnel to perform all the visits in a single day. Therefore, visits are rescheduled or even canceled in the worst case. Deciding who does not receive a visit is part of the problem. For example, it is more important to assist someone with his diabetes medication than to help another person doing groceries. The *shift patterns* are either given by contracts or expressed as preference by carers. Many organisations emphasise respecting *carers' preferences* to increase staff retention. Also, *tolerance on time windows* to perform care vary, e.g. critical medical activities having 5 minutes tolerance while support activities having 15 minutes to 2 hours tolerance.

3.3 Scheduling technicians

Some telecommunications companies require scheduling employees to perform a series of installation and maintenance jobs, e.g. Cordeau et al (2010). In the literature, this problem is referred to as technician and task scheduling problem (TTSP). In this sector, commitments on time to perform the jobs are enforced, resulting in strict *time windows*. Due to the equipment technicians carry, it is common to use *company vehicles* to travel from one customer location to the next one. Technicians *start and end locations* are the company premises, although in some cases technicians are allowed to take companys' cars home if the first job of the following day is at a location closer than the company's location. Technicians, depending on the sector, often are highly *skilled*. Nevertheless, their skills are related to their experience and training, as a result companies have levels of seniority among their workforce e.g. junior, senior, etc. Those seniority levels to some extend help estimating the *service time* required to complete the job e.g. although both junior and senior fibre optics technicians could recalibrate a connection, the later one does the job faster. Activities tend to be independent from each other with in the same day, but in a wider time frame there are some *connection* between them. In this scenario, *teams* are often formed with the aim of having a balance set of personnel with as many skills as possible. *Teaming* also helps technicians to learn from each other, hence improving their performance. Companies with many branches across different regions use *clusterisation* to assign jobs to each branch when the scheduling is done centrally for all branches.

3.4 Security personnel routing and rostering

In this problem, round of visits are performed by security personnel to several customer premises distributed at different locations over a 24 hours period (Misir et al, 2011). Many organisations outsource security guards duties only for when premises are closed while in other cases, security is outsourced at all times. Round visits must be performed at the contracted time often given as a *time window*. Security personnel often uses a combination of *private vehicles* to go from one location to the next and *walking* once they get to the facility but require to check several buildings. Security guards *start and return* to their own homes. In this scenario, the author mentions 16 types of *skills* that the company records among its workforce and some visits require enforcing those skills. The duration (*service time*) of each visit can vary but it should be between a time framework in which the visit must finish. Visits are independent from each other. Customers are divided into regions (*clusterisation*), so that security guards living nearby are assigned to each region reducing travelling time. In this industry, contract terms vary considerably and this originates many different constraints being added to the problem. Although not mentioned in the scenario, it is not unreasonable to think that teams of two or more guards can are used.

3.5 Manpower allocation

Manpower allocation (Lim et al, 2004) refers to assigning servicemen to a set of customer locations to perform service activities. The objectives in this problem are to minimise the number of servicemen used, minimise the total travel distance, minimise the waiting time at service points, maximise the number of tasks assigned, etc. The manpower allocation cases when employees have to perform tasks at different locations and hence requiring transportation can qualify as a WSRP. Manpower allocation with *time windows* is particularly relevant since customers explicitly defined when the workforce is required. There is no mention of *transportation modality* so we assume all workforce uses the same type of transport. Every serviceman *starts and finishes* his working day at the control centre. *Skills* among the workforce are assumed to be the same, making no difference on who performs the service. Nevertheless there are restrictions on the number of hours each employee can work. Waiting time, the time that servicemen have to wait at a customer location before the start of the time window, is included within the *service time* making it vary accordingly. Li et al (2005) add job *teaming* constraints, a team is assembled at every location and work cannot start unless all members of the team have arrived. More recently, a variation of the manpower allocation problem was used in the context of scheduling teams to do ground handling tasks in major airports (Dohn et al, 2009). In the work by Li et al (2005) teams are set at the beginning and do not change over the working day. Additional characteristics include teams having mandatory breaks within certain time windows, hence breaks are treated as just another visit.

3.6 Vehicle routing problem with time windows

The routing part in many of the problems considered here as examples of WSRP are based on the vehicle routing problem with time windows (VRPTW). In this problem the main objective is to minimise the total travel distance by a set of vehicles when performing visits to several customers spread across many locations. Every customer must be visited once by one vehicle. Each customer specifies a *time window* when the visit should take place. The delivery vehicle must arrive to the location within that specified time window. If the vehicle arrives before the time window starts, it must wait until the time window opens to perform the delivery (Desrochers et al, 1992; Kallehauge et al, 2005). Extensions of the VRPTW include other features such as multiple trips, multiple depots, capacity constraints, etc.

3.6.1 VRPTW with multiple depots and waiting costs

Here, the fleet of vehicles is distributed across multiple depots allowing vehicles to return to the closest depot once all the deliveries by that vehicle have been completed. This VRPTW variant (Desaulniers et al, 1998) is relevant to our study because its formulation is applicable to workforce scheduling and routing. Many papers in the literature dealing with WSRP scenarios use this VRPTW variant and associate every employee's *starting and ending point* to a depot. It is also possible for every employee to start at the same location (depot) but then each employee to end their working day at a different location (home).

3.6.2 Vehicle routing problems with multi-trips

This variant extends the classical vehicle routing problem to include multiple trips (Brandão and Mercer, 1998). It is important because it addresses the fact that an employee could perform more than one trip on a day to visit the same location. A trip in this context is a series of jobs before going back to the depot. In WSRP scenarios, an employee is assumed to have a mean of transportation either from the company or personal. Sometimes the employee might need to go back to the main office (depot) to replenish resources. The type of vehicles that can access a particular customer's location might be restricted as pointed by Brandão and Mercer (1997). Vehicles have different capacities which can be associated to model an heterogeneous workforce. Vehicles can also be hired for some time which is associated to hiring casual staff.

3.6.3 Synchronisation constraints in routing

Synchronisation, a type of *connected activity*, among workers when executing their tasks can be modelled in the same way as when vehicles need to arrive at the same customer location and at the same time (Bredström and Rönnqvist, 2007). Precedence constraints are another characteristic related to synchronisation (Bredström and Rönnqvist, 2008). Assuming a client can be visited more than once per day, it could be that the order of the visits matter. For example, before technicians install a satellite TV, it is important that the antenna is calibrated and then a demodulator set. These activities could be performed by different people at different times but the order matters and must be respected.

4 Solution Methods

In this section we summarise the range of solution approaches that have been used to tackle WSRP in the literature. We present them in three categories: optimisation techniques, heuristic algorithms and hybrid approaches. The purpose of this section is to identify the methods that have been applied to tackle different variants and components of WSRP scenarios. In *Table 1* row 44 associates each surveyed source with a domain problem mentioned in *Section 3* and row 45 presents the main technique used for its solution.

4.1 Optimisation techniques

Begur et al (1997) applied a mixed integer programming model combined with the nearest neighbor heuristic (Rosenkrantz et al, 1977) to solve a weekly nurse scheduling problem.

De Angelis (1998) used linear programming with clustering techniques. The scenario is split in two parts, a local one which addresses resource allocation within each district, and a global one focusing on all districts.

Desaulniers et al (1998) used an integer non-linear multi-commodity network flow model with time variables and solved it using column generation (Desrosiers and Lübbecke, 2005), embedded in a branch and bound algorithm. Minimum and exact waiting costs were taken into account.

Borsani et al (2006) used a mixed integer linear programming model based on assignment and scheduling models. The assignment model is used when new patients enter the system. The scheduling model is used to create weekly visits' plan taking as input the result of the assignment model.

Bredström and Rönnqvist (2007) used a set partitioning formulation. The model involves two types of variables, routing and scheduling variables. The formulation was tackled with a branch and price method (Barnhart et al, 1998).

Dohn et al (2008) also used a set partitioning problem with side constraints solved with branch and price. A series of shortest path problems are solved for the column generation and the master problem is solved with the set partitioning approach.

Dohn et al (2009) applied an integer programming formulation solved with branch and price. Dantzig-Wolfe decomposition was applied through feasible paths. The problem is divided into a generalised set covering problem and elementary shortest path.

Kergosien et al (2009) solved an integer programming model. After obtaining a first solution to the model, the second stage improves performance by adding cuts on the time windows. Activities requiring multiple people are split into several services.

Rasmussen et al (2012) also used a set partitioning problem with side constraints solved through a branch and price approach.

Salani and Vaca (2011) used a flow-based mixed integer program solved with branch and price.

From the above summary it can be noticed that a methodology that has been very useful to tackle WSRP is branch and price. Branch and price refers to using a branch and bound approach with column generation (Barnhart et al, 1998; Feillet, 2010). Column generation is not a recent technique it has been used successfully in other fields (Desaulniers et al, 2005). The advantage of using column generation is that the problem can be relaxed and solved with a reduced set of columns, which might not be an exhaustive enumeration of all possible routes for every employee, but at any time provides a solution if it exits. In the literature, the personnel scheduling constraints side of the problem is commonly solved by heuristics to generate columns. On the other hand, the routing component can be tackled via branching. Kallehauge et al (2005) showed that the problem formulation can be decomposed into a master problem and a pricing problem. The master problem is a set partitioning problem and the subproblem a series of shortest path problems with resources constraints (Irnich and Desaulniers, 2005; Feillet et al, 2004).

Models applied to VRPTW have also been aplied to WSRP, in particular multi-commodity network flow models with time windows and capacity constraints. When using branch and price, many authors have modelled the master problem as either a set partitioning problem or as a set covering problem. There is not much difference between these two. In the first one, each customer is in one route only, whereas in the second one, more than one route could visit the same customer location.

4.2 Heuristics algorithms

Blais et al (2003) employed a tabu search heuristic for the political district problem by Bozkaya et al (2003) which only uses two types of moves for the neighborhood single movements and swaps .

Akjiratikarl et al (2006, 2007) used an evolutionary approach, particle swarm optimisation (Kennedy and Eberhart, 1995), for a home care problem. An initial solution is generated using the earliest start time priority with minimum distance assignment formulation. Authors also used two local improvement procedures, a swap move to interchange activities among workers and an insertion procedure to move activities from one route to another one.

Lim et al (2004) applied two different approaches, tabu-embedded simulated annealing and squeaky wheel optimisation (Joslin and Clements, 1999). Three operators are used to generate local neighbourhoods shift, exchange and rearrange operators. The shift and exchange operators are similar to the insertion and swap procedures used by Akjiratikarl et al (2006).

Itabashi et al (2006) created a multi-agent system based on negotiation via text messages among agents representing employees. Both carers and patients have a personal device assistant. Patients submit requests to a centralised scheduling system which assigns them to a carer. The carer confirms the schedule which then is reflected in the overall schedule.

Cordeau et al (2010) utilised a constructive heuristic followed by an adaptive large neighbourhood search with five destroy and two repair heuristics (Ropke and Pisinger, 2006). The heuristic approach plans one day at a time in two stages. The first stage deals with team construction allocating single activities. In the second stage, the remaining activities are assigned to already defined teams.

Misir et al (2010) used three hyper-heuristics (Ross, 2005) with a simple learning mechanism that excludes the use of some heuristics for given phases of the search. Phases consists of a number of iterations and the best heuristics for each phase are stored in memory. Six low-level heuristics are used, two of them based on swap movements and four on removal and insertion in different routes. Three move acceptance mechanism are employed: improving or equal, improving and equal plus worsening subject to a threshold value and iteration limit, and an adaptive version by threshold changing.

Misir et al (2011) employed hyper-heuristics based on two different heuristics selection methods: simple random and adaptive dynamic heuristic set. First, visits are ordered and the assignment of these visits to available personnel is carried out. This is then followed by improvement heuristics that change visiting times. During the first stage, ten low-level heuristics are used. The moves to produce neighbouring solutions are swap, insertion and a move based on the idea of 'scramble' visit in the same route.

When employing heuristics including meta-heuristics and hyper-heuristics to solve the WSRP, there seems to be a tendency in the literature to use approaches based on swap (exchanges) and insertion operators. Depending on the method employ either memory is used to keep the best solutions so far or to remember which low-level heuristics are best applied in the stages of the search. Many solutions employ a constructive heuristic to generate a fast initial solution. There seems to be no solution method applied to different WSRP scenarios so far. Nevertheless, the operators used to generate neighbour solutions appear to be very similar in the different approaches.

4.3 Hybrid methods

Li et al (2005) combined the relaxation of an integer programming formulation of a network flow problem, to obtain lower bounds, with constructive heuristics embedded in a simulated annealing framework (Laarhoven and Aarts, 1987) for upper bounds. Two constructive heuristics were used, simple-append and block-insertion. Initial solutions are obtained with the first one. Neighbors are generated using block-transposition and block-reverse operators.

Bertels and Fahle (2006) created a hybrid model of a rostering and routing problem. It was solved using constraint programming and integer programming for sequencing visits. For improvements, simulated annealing, tabu search and combination of both, were used. The solution approach was to find a partition of jobs to nurses and to find an optimal sequencing of each partition.

Eveborn et al (2006, 2009) used a set partitioning model. Aditionally, repeated matching to find suitable pairs of routes and workers and splitting techniques for when improvements are seek.

Bredström and Rönnqvist (2008) mixed, integer linear programming model and heuristics. During the first stage CPLEX is applied and in the second stage, heuristics similar to the ones by Fischetti et al (2004) are used to iteratively improve the best known solution.

Landa-Silva et al (2011) used a hybrid-approach combining a clustering algorithm, constructive and local search heuristics, and exact assignments based on integer programming to cluster shipments, create subgroups, build initial loads, carrier assignments and improve loads.

Most hybrid approaches try to combine the most appropriate algorithms depending on which part of the WSRP is being tackled (clustering, routing, matching skills, etc). For the routing part, it seems that the most used approaches are mathematical programming and constraint programming. This might be due to the significant advances in optimisation methods achieved recently for vehicle routing problems. Nevertheless, good heuristics methods, particularly those which provide fast initial solutions have also been employed. When matching employees to activities, the use of heuristics approaches appears to dominate.

5 Conclusion

A workforce scheduling and routing problem (WSRP) refers to any environment in which a skilled diverse workforce should be scheduled to perform a series of activities distributed over geographically different locations. Activities should be performed at specific times or within a given *time window*. The time window for each activity is usually determined by the customer or recipient of the job. This survey aimed to identify problems tackled in the literature that can be seen as a WSRP scenario. The problems identified in this survey include but are not limited to: *home health care, home care, scheduling of technicians, security personnel routing and rostering, manpower allocation*. This survey also sought to identify the similarities between these problems in order to define the core characteristics that any WSRP would have. Those characteristics include: *time windows, transportation modalities, star and end* *locations, a diverse skilled workforce, activities' service time and relationship between them, and optionally, presence of teaming and clusterisation of locations* among perhaps others.

The second part of this survey sought to identify the solution methods that have been employed in the literature when tackling WSRP scenarios. Since the WSRP combines employee scheduling and vehicle routing with time windows, there seems to be a clear tendency for using exact approaches for the routing component of the problem, and using heuristics for the matching of employees to activities. Among other approaches for solving WSRP, we found: mixed integer linear programming (MILP), integer linear programming (ILP) and constraint programming (CP); using models such as set partitioning problem (SPP) and multi-commodity network flow problem; variety of meta-heuristics, tabu search (TS), particle swarm optimisation (PSO) and simulated annealing (SA).

The state of the art in WSRP, particularly in home health care and home care seems to be the use of a set partitioning problem with side constraints solved via branch and price. When clusterisation is used, it tends to be used in the initial stage of the solving procedure. The motivation for using clusterisation seems to be either to reduce the size of the problem (by creating many small problems) or to satisfy employee preferences regarding the geographic area for the location of their work. Although not present in all sources clusterisation is a current area of research, particularly in those problem which optimality could not be achieved (Rasmussen et al, 2012). In order to use the same approach for other WSRP domains, specific algorithms to generate columns based on the business rules and constraints of each domain seems to be a promising area. Our next steps are to develop such algorithms and aim to use them in a similar framework as Rasmussen et al.

As a result of this survey on workforce scheduling and routing problems, two issues seem to arise. The first one, it appears that authors who have used heuristics have not reused much previous work. We note this given the very diverse set of meta-heuristic and hyper-heuristics approaches applied. It seems not possible to identify heuristic solution methods that are popular and/or better in tackling WSRP scenarios. The second one, with the exception of the work by Akjiratikarl et al it appears that no different papers have used the same data set. This is because most papers tackle different specialised variants of the problem. Nevertheless, this opens the opportunity to develop a data set that represents well various WSRP scenarios and that serves to investigate different solutions approaches.

Table 1: Characteristics overview in WSRP

No	**Characteristics in WSRP**	Begur et al (1997)	Brandão and Mercer (1997)	Brandão and Mercer (1998)	Cheng and Rich (1998)	De Angelis (1998)	Desaulniers et al (1998)	Blais et al (2003)	Lim et al (2004)	Li et al (2005)	Akjiratikarl et al (2006)	Bertels and Fahle (2006)	Borsani et al (2006)	Eveborn et al (2006)	Itabashi et al (2006)	Akjiratikarl et al (2007)	Bredström and Rönnqvist (2007)	Dohn et al (2009)	Bredström and Rönnqvist (2008)	Dohn et al (2008)	Eveborn et al (2009)	Kergosien et al (2009)	Cordeau et al (2010)	Misir et al (2010)	Rasmussen et al (2012)	Misir et al (2011)	Landa-Silva et al (2011)	Salani and Vaca (2011)
1	Flexible time windows	⋆		⋆			⋆		⋆	⋆		⋆		⋆	⋆	⋆	⋆		⋆							⋆	⋆	
2	Specific time windows	⋆	⋆								⋆	⋆		⋆		⋆		⋆	⋆	⋆		⋆		⋆	⋆	⋆	⋆	⋆
3	Multi-trip planning		⋆	⋆			⋆				⋆				⋆	⋆												⋆
4	Loading and unloading time		⋆				⋆																				⋆	
5	Diverse fleet			⋆			⋆			⋆		⋆			⋆			⋆		⋆				⋆	⋆			
6	Homogeneous fleet								⋆								⋆									⋆		⋆
7	Maximum driving time		⋆	⋆																								
8	Multiple depot				⋆						⋆				⋆	⋆									⋆	⋆		
9	Start and return to the source	⋆	⋆	⋆			⋆		⋆	⋆	⋆					⋆	⋆	⋆										⋆
10	Start and end at different points													⋆	⋆						⋆			⋆	⋆	⋆	⋆	
11	Stack specification																									⋆		
12	Backward milage																									⋆		
13	Subcontracting		⋆	⋆									⋆	⋆									⋆				⋆	
14	Diverse capacity	⋆	⋆	⋆					⋆	⋆	⋆	⋆			⋆										⋆		⋆	⋆
15	Clustering required							⋆					⋆	⋆							⋆				⋆	⋆	⋆	
16	Initial feasible solution			⋆				⋆													⋆							
17	Vehicle fill in factor																											
18	Sites vehicles restrictions		⋆											⋆	⋆						⋆			⋆	⋆			
19	Real distances used	⋆	⋆						⋆	⋆															⋆			
20	Preference on visitors	⋆			⋆							⋆	⋆	⋆					⋆		⋆	⋆			⋆			
21	Diverse skill sets	⋆			⋆	⋆				⋆		⋆	⋆	⋆	⋆			⋆	⋆	⋆	⋆	⋆	⋆	⋆				
22	Flexible shifts	⋆									⋆	⋆			⋆									⋆				
23	Specific shifts								⋆	⋆	⋆	⋆				⋆		⋆		⋆	⋆	⋆						
24	Absence availability included					⋆					⋆	⋆	⋆				⋆		⋆	⋆				⋆				
25	Diverse contracts								⋆		⋆	⋆				⋆			⋆	⋆	⋆							

Table 1 – continued from previous page

No	Characteristics in WSRP	Begur et al (1997)	Brandão and Mercer (1997)	Brandão and Mercer (1998)	Cheng and Rich (1998)	De Angelis (1998)	Desaulniers et al (1998)	Blais et al (2003)	Lim et al (2004)	Li et al (2005)	Akjiratikarl et al (2006)	Bertels and Fahle (2006)	Borsani et al (2006)	Eveborn et al (2006)	Itabashi et al (2006)	Akjiratikarl et al (2007)	Bredström and Rönnqvist (2007)	Dohn et al (2009)	Bredström and Rönnqvist (2008)	Dohn et al (2008)	Eveborn et al (2009)	Kergosien et al (2009)	Cordeau et al (2010)	Misir et al (2010)	Rasmussen et al (2012)	Misir et al (2011)	Landa-Silva et al (2011)	Salani and Vaca (2011)
26	Location within limits							⋆			⋆		⋆			⋆			⋆							⋆		
27	Heterogeneous workforce	⋆			⋆					⋆	⋆	⋆			⋆	⋆		⋆		⋆	⋆		⋆	⋆		⋆		
28	Diverse task types	⋆								⋆	⋆	⋆		⋆	⋆	⋆		⋆		⋆	⋆	⋆	⋆	⋆				
29	Synchronisation of tasks												⋆	⋆			⋆	⋆	⋆	⋆		⋆	⋆	⋆	⋆			
30	Precedence constraints																		⋆	⋆		⋆	⋆	⋆	⋆			
31	Synchronisation of vehicles												⋆				⋆		⋆					⋆	⋆			
32	Vehicles availability																	⋆	⋆	⋆	⋆			⋆	⋆			
33	Multiple staff per vehicle																											
34	Break Scheduling				⋆									⋆														
35	Exhaust relationship carer-patient												⋆															
36	Specific number of workers								⋆									⋆										
37	Demand on patients needs					⋆					⋆					⋆				⋆	⋆							
38	Ensure non-synchronised activities																					⋆						
39	Overtime considered				⋆																							
40	Levels of planning																				⋆							
41	Teaming involved									⋆								⋆										
42	Jobs performed at different locations									⋆	⋆				⋆		⋆	⋆		⋆	⋆			⋆	⋆			
43	Demand can be splitted																											⋆
44	Domains: HC Home care HHC Home health care ST Scheduling technicians SP Security personnel MA Manpower allocation VRP Vehicle routing	HHC	VRP	VRP	HHC	HC	VRP	HC	MA	MA	HC	HHC	HC	HC	HC	HC	VRP	MA	VRP	HHC	HC	HHC	ST	HC	HHC	SP	VRP	VRP

Table 1 – continued from previous page

No	Characteristics in WSRP	Begur et al (1997)	Brandão and Mercer (1997)	Brandão and Mercer (1998)	Cheng and Rich (1998)	De Angelis (1998)	Desaulniers et al (1998)	Blais et al (2003)	Lim et al (2004)	Li et al (2005)	Akjiratikarl et al (2006)	Bertels and Fahle (2006)	Borsani et al (2006)	Eveborn et al (2006)	Itabashi et al (2006)	Akjiratikarl et al (2007)	Bredström and Rönnqvist (2007)	Dohn et al (2009)	Bredström and Rönnqvist (2008)	Dohn et al (2008)	Eveborn et al (2009)	Kergosien et al (2009)	Cordeau et al (2010)	Misir et al (2010)	Rasmussen et al (2012)	Misir et al (2011)	Landa-Silva et al (2011)	Salani and Vaca (2011)
45	Solution method employed: O. Optimisation 1. MILP 2. ILP 3. INLP 4. SPP 5. MCNFP H. Heuristics 6. TS 7. PSO 8. SA 9. SWO 10. Agents based 11. LNS, VLNS, ALNS 12. Hyper-heuristics C. Hybrid	O. MILP	H. TS	H. TS	C. MILP, Constructive	O. MILP	O. INLP	H. TS	H. TS, SA, SWO	C. ILP, Constructive, SA	H. PSO	C. MILP, SA, TS	O. MILP	C. ILP, SPP, Matching	H. Agents	H. PSO	O. ILP, SPP	O. ILP, SPP	C. MILP, heuristics	O. ILP, SPP	C. SPP, Repeat matching	O. ILP	H. LNS, VLNS, ALNS	H. Hyper-heuristics	O. ILP, SPP	H. Hyper-heuristics	H. LNS, Clustering	O. MCNFP

MILP Mixed integer linear programming, ILP Integer linear programming, INLP Integer non-linear programming, SPP Set partitioning problem, MCNFP Multi-commodity network flow problem, TS Tabu search, PSO Particle swarm optimisation, SA Simulated annealing, SWO Squeaky wheel optimisation, (V/A)LNS (Very/Adaptive) Large neighbourhood search

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