DYNAMIC VEHICLE ROUTING FOR DEMAND RESPONSIVE TRANSPORTATION SYSTEMS

by

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"Pasmo sempre quando acabo qualquer coisa. Pasmo e desolo-me. O meu instinto de perfeição deveria inibir-me de acabar; deveria inibir-me até de dar começo. Mas distraio-me e faço. O que consigo é um produto, em mim, não de uma aplicação de vontade, mas de uma cedência dela. Começo porque não tenho força para pensar; acabo porque não tenho alma para suspender. Este livro é a minha cobardia."

Fernando Pessoa, *O Livro do Desassossego*

ABSTRACT

Buses circulating with very low occupancy rates mean high costs for the operators, often leading to low frequencies and, as a consequence, to social exclusion, low perceived quality and degradation of the image of public transportation. Demand Responsive Transportation (DRT) services try to address these issues with routes and frequencies that may vary according to the actual observed demand.

The advantages of DRTs in terms of social cohesion, mobility, traffic, or environment, are fairly obvious. However, in terms of financial sustainability and quality level, the design of this type of services may be rather complicated. Moreover, in terms of operation, DRTs are very dynamic, requiring the adaptation of solutions in real-time, in a multiple criteria context.

The problems of designing and operating DRT services are closely related to the Vehicle Routing Problem (VRP), and in particular to the Dial-A-Ride Problem (DARP). Service design has a fundamental role in the success of DRT services and, therefore, decision-makers need to understand well how different ways of operating the service affect its performance.

In this work, a general modeling framework for planning and managing DRT services was developed, starting with a comprehensive analysis of European best practices. Based on this framework, a Decision Support System (DSS) was designed and implemented. This DSS integrates both a simulation model and a constructive multi-objective heuristic. Our approach aimed at finding a good overall design by running a simulation of several demand-offer scenarios. This simulation encompasses the multi-objective heuristic approach to deal with the combinatorial nature of the problem and with the multiple perspectives of the different stakeholders.

To assess the approach, we have simulated the operation of a night time DRT service, in the city of Porto, in Portugal. Passengers specify origins and destinations from a set of pre-defined possible stops, a pickup time, and a desired arrival time. Experiments with simple cases, inspired in real problems, have shown the potential of the approach for designing and managing quite different DRT services. From the simulation, a set of guidelines was obtained and planners can use the developed DSS to design DRT services, achieving adequate trade-offs between cost levels and quality of service.

KEYWORDS: Combinatorial Optimization. Simulation. Multiple-Objectives. Heuristics. Logistics and Transportation.

RESUMO

Os sistemas de transportes são um fator chave para a sustentabilidade económica e bem-estar social das comunidades. A eficiência económica do transporte público rodoviário tradicional assenta em níveis significativos de procura e padrões de mobilidade bem estabelecidos, sendo, portanto, mais adequado para zonas de média/alta densidade populacional. Oferecer um serviço de transporte público de qualidade em cenários de baixa procura, tais como zonas rurais dispersas ou em determinados períodos do dia nas áreas urbanas, é extremamente caro, levando, muitas vezes, a frequências baixas e, consequentemente, à perceção de um serviço de baixa qualidade e à degradação da imagem do serviço de transporte público. Os sistemas de transportes flexíveis (do inglês *Demand Responsive Transportation*, ou DRT) procuram endereçar este problema através de rotas e horários que podem variar de acordo com a procura efetiva observada. Dada esta flexibilidade adicional, o serviço de transporte fornecido pelos operadores torna-se mais eficiente, com rotas planeadas pouco antes do início do serviço, com melhores taxas de ocupação e veículos com características mais adequadas às necessidades de mobilidade dos utilizadores. Apesar das vantagens, em termos de sustentabilidade financeira e nível de qualidade de serviço o desenho deste tipo de serviços pode ser bastante difícil.

Os problemas de desenho e operação de sistemas de transportes flexíveis são bastante semelhantes ao problema clássico de roteamento de veículos (do inglês *Vehicle Routing Problem* ou VRP) e, especialmente, aos modelos de transporte-a-pedido (do inglês *Dial-A-Ride Problem* ou DARP). O desenho dos serviços DRT tem uma importância fulcral no sucesso dos mesmos e por isso é importante não só resolver o modelo inerente de forma eficiente, mas também que os agentes de decisão percebam perfeitamente como diferentes formas de operar um serviço afetam o seu desempenho.

Neste trabalho foi desenvolvida uma *framework* genérica para o planeamento e gestão de serviços DRT, partindo de uma análise aprofundada das melhores práticas na Europa. Com base nesta *framework* foi desenvolvido um Sistema de Apoio à Decisão, que inclui modelos de simulação e uma heurística construtiva multiobjectivo paralelizada para obter um conjunto de soluções eficientes de acordo com as múltiplas perspetivas dos diferentes intervenientes.

Para avaliar a abordagem proposta, simulamos 2 horas de operação de um serviço DRT noturno na cidade do Porto. Experiências com casos simples, inspirados em problemas reais, demonstraram o potencial da abordagem proposta no desenho e gestão de um conjunto bastante alargado e diferenciado de serviços DRT. Os agentes de decisão podem usar o Sistema de Apoio à Decisão para desenhar serviços DRT que atinjam os objetivos de custo e qualidade de serviço almejados.

PALAVRAS-CHAVE: Otimização Combinatória. Simulação. Heurística. Objetivos múltiplos; Logística e Transportes.

PUBLICATIONS AND COMMUNICATIONS

During this doctoral project several communications and publications were done, reflecting the progress of the work and our main achievements and contributions:

Book chapters

- "Roteamento de veículos dinâmico". In B. Prata (Ed.), "Logística Urbana: fundamentos e aplicações". Curitiba - Brasil: Editora CRV, 2012

Journal articles

- "A Decision Support System for the design and operation of Demand Responsive Transportation systems", submitted for publication, IEEE – IET Intelligent Transport Systems, January, 2013;
- "A new Heuristic Approach for Demand Responsive Transportation", submitted for publication, International Journal of Transportation, January, 2013
- "An integrated approach for the design of Demand Responsive Transportation services", submitted for publication, European Journal of Operational Research, November, 2012;

Awards

- Best Poster Award, 2nd Industrial Engineering and Management Symposium – IEMS 2011, Porto, January, 2011;
- Best PhD Paper Award, 7th Annual Meeting of the Portuguese Working Group on Transport Studies (GET), Nazaré, January 2010;

Invited talks

- Gomes, R., "DRT scheduling platform", E3 Forum – Education, Employment and Entrepreneurship, Lisbon, Portugal, June, 2012

Conferences

- "An integrated approach for the design of Demand Responsive Transportation services", EWGT 2013 - 16th Euro Working Group on Transportation, Porto, Portugal, September, 2013;
- "An integrated approach for the design and operation of Demand Responsive Transportation services", WCTR 2013 - World Conference on Transport Research, Rio de Janeiro, Brazil, July, 2013;

- "An integrated approach for the design of Demand Responsive Transportation services", TRISTAN VIII, San Pedro de Atacama, Chile, June, 2013;
- "Dynamic Vehicle Routing for Demand Responsive Transportation Services", 10th Annual Meeting of the Portuguese Working Group on Transport Studies (GET), Alcobaça, January, 2013;
- "Dynamic Vehicle Routing for Demand Responsive Transportation Services", 4th Industrial Engineering and Management Symposium, Porto, January, 2013;
- "Design and operation of Demand Responsive Transportation systems", 15th Euro Working Group on Transportation Meeting, Paris, France, September 2012;
- "An integrated approach for the design of Demand Responsive Transportation services", VeRoLog 2012 – 1st Conference of the EURO Working Group on Vehicle Routing and Logistics Optimization, Bologna, Italy, June 2012;
- "Dynamic Vehicle Routing for Demand Responsive Transportation Services", 9th Annual Meeting of the Portuguese Working Group on Transport Studies (GET), Tomar, January, 2012;
- "Dynamic Vehicle Routing for Demand Responsive Transportation Services", 3rd Industrial Engineering and Management Symposium, Porto, January, 2012;
- "Contributions for the design and operation of Demand Response Transport Systems", 25º ANPET - Congresso de Pesquisa e Ensino em Transportes, Brazil, November, 2011;
- "Dynamic Vehicle Routing for Demand Responsive Transportation Services", 8th Annual Meeting of the Portuguese Working Group on Transport Studies (GET), Esmoriz, January, 2011;
- "Dynamic Vehicle Routing for Demand Responsive Transportation Services", 2nd Industrial Engineering and Management Symposium, Porto, January, 2011;
- "A New Heuristic Approach for Demand Responsive Transportation Systems", XLII SBPO – 42nd Brazilian Symposium on Operations Research, Bento Gonçalves, Brazil, August, 2010;
- "Dynamic Vehicle Routing for Demand Responsive Transportation Services", 7th Annual Meeting of the Portuguese Working Group on Transport Studies (GET), Nazaré, January, 2010;
- "Dynamic Vehicle Routing for Demand Responsive Transportation Services", 1st Industrial Engineering and Management Symposium, Porto, January, 2010;
- "Dynamic Vehicle Routing for Demand Responsive Transportation Services", 13th Euro Working Group on Transportation Meeting, Padua, Italy, September, 2009;

- “Dynamic Vehicle Routing for Demand Responsive Transportation Services”, IO2009 - 14th Operations Research Portuguese Association conference, Lisboa, September, 2009;

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ACRONYMS

ADA	Americans with Disabilities Act
ADTSPTW	The A-priori Dynamic Traveling Salesman Problem with Time Windows
AIMSUN	Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks
AVL	Automatic Vehicle Location
CAD	Computer Aided Dispatching
CVRPPDTW	The Capacitated Vehicle Routing Problem with Pick-up and Deliveries and Time Windows
CVRPTW	The Capacitated Vehicle Routing Problem with Time Windows
DARP	The Dial-a-Ride Problem
DRT	Demand Responsive Transportation
DSS	Decision Support System
DTRP	The Dynamic Traveling Repairman Problem
DTSP	The Dynamic Traveling Salesman Problem
DTSPTW	The Dynamic Traveling Salesman Problem with Time Windows
DVRDRT	Dynamic Vehicle Routing for Demand Responsive Transportation
DVRDRT	Dynamic Vehicle Routing for Demand Responsive Transportation
DVRP	The Dynamic Vehicle Routing Problem
DVRPTW	The Dynamic Vehicle Routing Problem with Time Windows
EC	European Commission
EU	European Union
FAMS	Flexible Agency for Collective Mobility Services
FCFS	First Come First Serve
FEL	Future Event List
FIFO	First in, First out
GDP	Gross Domestic Product
GIS	Graphical Information Systems
GNP	Gross National Product

GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications, originally Groupe Spécial Mobile
ICT	Information and Communications Technology
IP	Idle Point
IPS	Integrated Payment Systems
ITS	Intelligent Transport Systems
IVR	Interactive Voice Response
KPI	Key Performance Indicators
MIT	Massachusetts Institute of Technology
NN	Nearest Neighbor
PDA	Personal Digital Assistant
PSS	Product-Service System
PVRP	The Probabilistic Vehicle Routing Problem
RAT	Requests Arrival Time
RTL	Request Time Limit
SMS	Short Message Service
SVRP	The Stochastic Vehicle Routing Problem
TDC	Travel Dispatch Center
TRAR	Trip Requests Arrival Rate
TSP	The Traveling Salesman Problem
TSPTW	The Traveling Salesman Problem with Time Windows
VRP	The Vehicle Routing Problem
VRPTW	The Vehicle Routing Problem with Time Windows

Chapter 1

OBJECTIVES AND SCOPE

1.1 Introduction

Public road transport systems are a key factor for the economic sustainability and social welfare of the communities. Their efficiency relies on solid demand levels and well-established mobility patterns and, so, providing quality public transportation is extremely expensive in low, variable and unpredictable demand scenarios, as it is the case of disperse rural areas or during some periods of the day in urban areas. Buses circulating with very low occupancy rates mean high costs for the operators, often leading to low frequencies and, as a consequence, social exclusion, low perceived quality and degradation of the image of public transportation. Demand Responsive Transportation (DRT) services try to address this problem by providing a kind of hybrid approach between a taxi and a bus, with routes and frequencies that may vary according to the actual observed demand. In a DRT system, vehicles follow routes and timetables scheduled by a travel dispatch center (TDC) to match the trip requests and to take as many users as possible in the same vehicle, while guaranteeing the quality standards in terms of pickup and delivery time and trip duration. Due to this added flexibility, the service provided by the operators becomes more efficient, with routes planned shortly before their start, with better occupancy rates and vehicles with characteristics better suited to users' requirements. The advantages of such a service in terms of social cohesion, mobility, traffic, or environment, are fairly obvious (Force 2003; Enoch *et al.* 2004; Laws *et al.* 2009). However, in terms of financial sustainability and quality level, the design of this type of services may be rather difficult. In fact, until now, there has not been a strong commercial case for DRT.

The problems of operating DRT services are closely related to the Vehicle Routing Problem (VRP) (Dantzig *et al.* 1959) and, in particular, to the Dial-A-Ride (DARP) (Cordeau *et al.* 2003a) models. In the DARP one is interested not only in minimizing the operating costs or the distance travelled by the vehicles, but also (and this is sometimes more important) in maximizing the quality of the service, expressed by indicators such as the average passenger waiting time or the on-board (ride) passenger time. Given the computational complexity of this type of problems (Lenstra *et al.* 1981), optimal solutions can take an unacceptable amount of time to be found, ruling out their usefulness in the context at hand. Besides, in a multiple criteria decision analysis the "optimal" solution is in general meaningless because it is impossible to satisfy all (usually conflicting) objectives simultaneously (Branke *et al.* 2008). It is also recognized that service design has a fundamental role in the success of DRT services (Brake *et al.* 2006). When designing a DRT service, it is not only important to be able to solve the underlying model in an efficient way, but also understand how different ways of operating the service affect customers and operators. Such effects are often studied by simulation.

In this thesis we present an innovative approach for Demand Responsive Transportation systems based on a Dynamic VRP model - Dynamic Vehicle Routing for Demand Responsive Transportation (DVRDRT) – where users can specify transportation requests at any time, from anywhere to anywhere. Vehicle Routing Problems for Demand Responsive Transportation extend the "classical" VRP model in a number of ways, being, therefore, more complex. It is clear that in the DRT context, vehicles have a limited capacity (and can be viewed as a variant of the Capacitated VRP), demands should be fulfilled in a certain time window (VRP with Time Windows) and there is still the uncertainty and variability associated with the number of stops along the route. Besides involving multi-objectives, this DRT application is also strongly dynamic (Larsen 2000), requiring the (re-)design of solutions in real-time. The goal is not only to minimize operating costs but also to maximize the service quality (Paquette *et al.* 2010), and to find a good overall service design by analyzing several European best practices and using appropriate simulation models. In this context, we have developed a general modeling framework for planning and managing transportation services of this type.

Many DRT service operators often make transportation reservations and dispatch vehicles using manual methods which are labor intensive and require highly skilled operators to be effective. Passengers are often dropped off to destinations in a first in, first out (FIFO) order (Nuworsoo 2011). This operation method can result in inefficient service as it can limit the number of passengers handled per time period, and result in additional operational costs due to the extra distance travelled. Recent works indicate that DRT operators that use computer-aided scheduling and dispatch systems show a significant reduction in operating cost per vehicle kilometer, mainly because this kind of systems help improve vehicle routing, thus increasing the number of shared trips and reducing the amount of extra or single trip kilometers travelled (Nuworsoo 2011). Similarly, (Goodwill *et al.* 2008) argue that with a well-coordinated reservation/scheduling/dispatch process and a good communication system, operators can better control the increasing costs of providing DRT services.

1.2 Research objectives

As demand declines, DRT efficiency can be achieved by delaying the decision about the route and vehicle as close as possible to the requested travel times and offering the same service to as many passengers as possible (Brake *et al.* 2006). Our approach for Demand Responsive Transportation systems based on a Dynamic VRP model aims at finding a good overall system design by the use of simulation and then use a Decision Support System (DSS) for providing a set of efficient solutions in real-time to user requests, hopefully close to the Pareto front, by an efficient, customizable multi-objective algorithmic approach to deal with the combinatorial nature of the problem and with the multiple perspectives of the different stakeholders.

One goal of this doctoral project was, in a first phase, to better understand and characterize a set of issues related to Demand Responsive Transportation (DRT) services, in particular by identifying their various types and features, and their scope for practical implementation. Having clearly identified the context and the problem, the next goal was to simulate how different ways of operating the service affect customers and operators, developing an appropriate simulation model for this kind of services. Finally, the last goal of the research was to create a "methodology" to support decision-making in the design and operation of DRT services. A generic solution strategy was developed for efficiently solving the problem. This strategy is based on state-of-the-art multi-objective heuristics to deal with the combinatorial nature of the problem and with the multiple perspectives of its different stakeholders, as an innovative approach to cope with these problems. With this approach the aim is to find a set of representative efficient solutions, hopefully close to the Pareto-optimal front. In order to promote the "involvement" of the experts in the planning process, a prototype of a Decision Support System was developed. This system integrates the multi-objective algorithmic approach previously developed, and was used in testing and assessing the approach. To assess the proposed methodology, a case study based on a real DRT implementation is tested and discussed.

To sum up, the key objectives for this PhD project were:

- to understand and characterize DRT services;
- to design a general modeling framework and a methodology to support the development process of DRT services;
- to develop a Decision Support System (DSS) to help design and operate DRT services, integrating
    - an appropriate simulation model to understand how different designs of the service affect customers and operators;
    - an efficient, customizable multi-objective algorithmic approach to deal with the combinatorial nature of the problem and with the multiple perspectives of its different stakeholders;
- to evaluate the proposed methodology using real world DRT case studies.

The present thesis work was partially developed within the CityMotion project, supported by the MIT -Portugal Program.

1.3 Methodology

In the first phase, it was important to understand the nature of the problem, why the problem is important and how this research could contribute. To do so, a literature and state-of-the-art analysis was carried out along with the classification and structuring of real services by means of a survey. The knowledge gathered during this phase allowed us to formulate the problem in terms of objectives, parameters and constraints and to devise a simulation model.

With the problem formulated, the next step was to create a mathematical model to express it. The mathematical model was the result of an abstraction process, from the complexity of the real system to the model, focusing on the main dominant variables and simplifying the interactions between them, without losing the essence of the real problem. We had to identify both static and dynamic structural elements of the problem and device mathematical formulas to represent their interrelationships. A generic solution strategy was developed for efficiently solving the problem, according to the combinatorial nature of the problem and with the multiple perspectives of its different stakeholders. Also included in this phase was the selection of appropriate data, using the model and the different inputs to the model reflecting actual problem conditions. The objective was to have data to operate and test the model.

The next phase was the model validation and analysis. In this phase, a Decision Support System (DSS) was developed embedding both the generic solution strategy developed in the previous phase and the simulation model. This DSS was used to evaluate the proposed methodology using real world DRT case studies. The interpretation of results is also included in this phase. These results work as a set of guidelines for practical implementation of DRT services.

1.4 Thesis outline

In this chapter the thesis context was presented in the scope of the Demand Responsive Transportation (DRT), emphasizing its importance for today's society. The problem and the motivation for the present work were also presented, and the main research objectives were stated. The chapter ends with the thesis outline.

Chapter 2 presents the main study object of this research, DRT systems. A brief historical context is presented for the United States of America, where these systems were born, and for Europe. The main DRT concepts are explained, mainly addressing strategic and operational aspects. DRT service operation and its required technological setup are described, as well as appropriate key performance indicators and more relevant issues. In this chapter we propose a framework for the analysis of DRT systems operation. This framework is used for undertaking a survey of several European real-life commercial DRT services. The chapter ends with the analysis of the survey results.

Service design is critical in the development of DRT services. After having presented DRT systems concepts, in Chapter 3 we address the design of DRT services, starting with a brief introduction on the subject. We then propose a DRT systems development process framework, providing a sequence of activities for system designers to follow. Usually the planning of journeys for DRT vehicles cannot take into account all of the real-life aspects, such as travel time variability and user delays at stop, for example. Such aspects are often studied by simulation. So the following section of Chapter 3 reviews the literature on simulation for DRT services, and a new simulation model for dynamic DRT services is proposed. The last section of this chapter presents DRT design patterns categorized by service type and service area: these design patterns allow the documentation of the best practices and solutions, effectively transmitting that knowledge.

Chapter 4 of the thesis addresses operational aspects on DRT services. As already mentioned, the problems of designing and operating DRT services are closely related to the Vehicle Routing Problem (VRP) (Dantzig *et al.* 1959), and in particular the Dial-A-Ride (DARP) (Cordeau *et al.* 2003a) models, so in the introduction of this chapter we address those classic problems and their relation with DRT services. The next section addresses mathematical modeling for the operation of a Demand Responsive Transportation service presenting a general modeling framework. Next we briefly present Vehicle Routing algorithms for both the static and the dynamic versions of DRT services. The chapter ends with the proposal of an efficient, customizable multi-objective algorithmic approach that deals with the combinatorial nature of the problem and with the multiple perspectives of its different stakeholders. After a brief discussion about benchmarking and the use of available real-dimension databases for assessing the proposed algorithmic approach, we present and analyze some computational results.

In order to "involve" the experts in the planning process, a prototype of a Decision Support System (DSS) has been developed. Chapter 5 details the development of the DSS, starting with the functional and non-functional requirements analysis, the logic architecture definition, the physical architecture proposal and dynamic views of the system. The chapter ends with the discussion of some of the most important implementation details and the presentation of the user interfaces of both the DSS and the remote transportation request clients.

In Chapter 6, the proposed integrated approach is tested by a) analyzing the behavior of a hypothetical DRT service in given real geographic area, making some assumptions regarding the demand structure; and b) by analyzing a real DRT service. Performance of the system is determined by observing what happens on the network, during simulation, with different conditions. The results of the simulation runs also give guidelines to help operators of public transport to design DRT services.

Chapter 7 ends the thesis with the conclusions and a set of suggestions for possible future research.

Chapter 2

CONTEXT

2.1 Introduction

Around 80% of the European citizens live in urban areas, which is where 85% of European Gross National Product (GNP) is generated (EC 2006b). It comes as no surprise that most public transportation systems are focused in these areas, where high population densities and jobs led to high frequency services with high occupation rates (Pucher *et al.* 1995). However, evermore big industries and enterprises are settling in peripheral zones where the land price is lower (Pucher *et al.* 1995). The lower land cost is also the reason why people are also moving to more peripheral zones, leading to an increasing number of inhabitants in these zones, as opposed to a decreasing number of inhabitants in the big cities (López 2006). These peripheral municipalities usually have lower population densities due to more green spaces and different house typologies (family houses vs. story buildings in big cities). The work patterns are also changing in response to globalization and flexibility trends. Working hours have become more flexible, work locations change more frequently, the number of part-time employees is increasing and technology allows new forms of work, such as teleworking, video conferencing and remote maintenance, inducing new mobility patterns (EC 2001). There are also more leisure related commutes (EC 2004). All these aspects are leading to more traffic partially due to the over-use of private vehicles for commuting (EC 2006a), more time lost during the commutes, thus increasing negative environmental effects, economic losses for both the cities and vehicle owners and higher road accident rates.

Traditional public transportation in low density areas faces several problems such as lack of coordination among different operators and municipal authorities, economic difficulties to operate frequent services with good occupancy rates and low quality. Providing quality public transportation is extremely expensive when demand is low, variable and unpredictable, such as in disperse rural areas or at some periods of the day in urban areas (e.g. during the night). The combination of low population density and geographical isolation means that conventional approaches to passenger transport, which are based on significant numbers of passengers travelling together, lose their viability in rural areas (EC 1999). If all trips are aggregated in space and time, it is possible to use a higher capacity vehicle to reduce the cost per seat. But, if the requests are not aggregated in time or the origins/destinations are spread across the service area, high capacity vehicles are not efficient because their occupancy rate is low and have a high cost per seat. In this case, to increase the efficiency it is necessary to decrease the frequency, lowering the quality of service. Public transports will only be used by those that do not have access to, or cannot use, private vehicles (López 2006). With limited financial resources and limited access to private vehicles, the economic and social exclusion in these low density areas becomes a serious problem.

To mitigate these problems, transportation systems that adapt to the observed demand were envisaged, using smaller vehicles, like mini buses or taxis, to be able to increase the frequency while assuring a high occupancy rate – these new transportation systems are usually called Demand Responsive Transportation (DRT) systems.

Figure 1, adapted from (López 2006), shows a set of factors contributing to DRT interest.

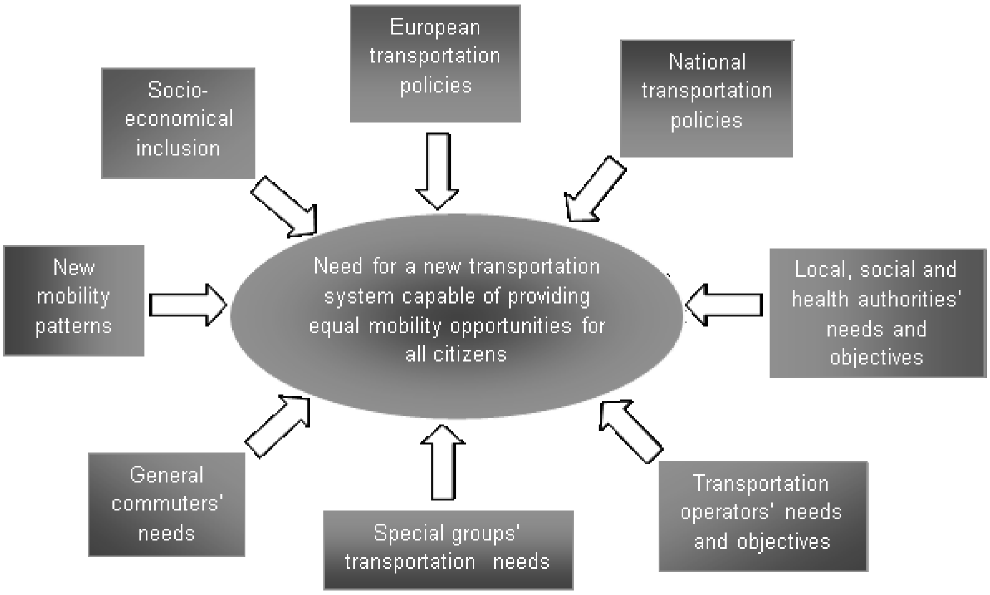


Figure 1 - Factors contributing for DRT systems (adapted from (López 2006))

Demand Responsive Transportation is an emerging term that covers services that are flexible in terms of route, vehicle allocation, vehicle operator, type of payment and passenger category. The flexibility of each of these elements can vary along a continuum of *demand responsiveness*, ranging from services where all variables are fixed a considerable time before operation (as in conventional public transport) to services whose characteristics are determined close to the time of operation (Brake *et al.* 2006). A good definition of a DRT system is "an intermediate form of public transport, somewhere between a regular service route (...) and the variably routed, highly personalized transport service offered by taxis. Services are routed according to the needs of the customers, generally only stopping where passengers request collection or dropping off" (Mageean 2003). Due to its characteristics, the DRT system is half-way between the taxi service and short to medium distance bus service, with a flexibility closer to the former and a trip price closer to the later. The DRT systems can also operate in a logic of feeding traditional systems in strategic points of the network, thus improving overall public transportation quality while also increasing the number of passengers.

Figure 2, adapted from (Nelson 2004), suggests the relation *flexibility versus cost* for different transport systems.

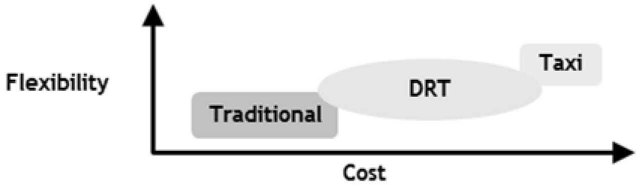


Figure 2 - *Flexibility versus Cost* for different transport systems (adapted from (Nelson 2004))

Due to this added flexibility, the service provided by the operators becomes more efficient, with routes planned shortly before their start, with better occupancy rates and vehicles with characteristics better suited to users' needs. The DRT concept is specially well suited in situations where operators, while having to reduce their costs, also need to provide transportation services in low demand scenarios, such as in disperse rural areas or at some periods of the day in urban areas, as requested by the public authorities in order to avoid social exclusion, for instance. It is then possible for the operator to have a fleet of vehicles of different capacities and, at each moment, use the one better suited to the observed demand in order to have the highest possible efficiency.

The DRT system operation leads to a reduction in service costs because fewer and smaller vehicles, less travelled distances and fewer drivers are required to provide the service. Improving the public transportation systems might induce a modal shift from private owned vehicles public transportation, lowering traffic levels and energy consumption, thus providing significant environmental benefits (a recent experiment has looked at the emissions of DRT services as compared to more conventional services (Diana *et al.* 2007) and concluded that, as DRT services have the possibility of using smaller vehicles, they perform better than fixed route services in almost all the scenarios tested). These are some of the main objectives of European transportation policies, alongside with equal mobility opportunities for all citizens (EC 2011). Enhanced mobility and access to services helps keeping people in areas that are losing population and DRT can also, to a certain extent, encourage tourism without cars (Brake *et al.* 2006).

Demand Responsive Transportation systems are not a new idea *per se*. The idea of the first "smart" public transport systems date back to late 1960s, with attempts to use (back to date) breakthrough technologies to provide new forms of transportation (mostly Dial-A-Ride services) with routes and schedules tailored, as much as possible in real-time, according to the observed demand. For instance, in 1969, with the CARS project, the Massachusetts Institute of Technology (MIT) did a series of DRT systems sustainability studies and the studied the technologies needed to operate them (Wilson *et al.* 1969). With the oil crisis during the 70's of last century many companies had to undertake major economic organizational changes, specially, the transportation related ones that had, on one hand, seek more efficiency and, on the other hand, new markets. The first DRT experiments in Europe date back to the 1980´s decade, with elderly and disabled groups in northern European countries (Finland, Sweden, Holland, Germany and the UK) (López 2010). In Europe, DRTs have a bigger social role than in United States of America. Table 1 from (Westerlund 2005) summarizes the DRT practices in Europe *circa* 2005.

But experience showed that, given the technologies available, the first DRT services were not cost effective. Recent years, however, provided the necessary frog leap in the technology (and cost reduction) necessary for DRT services regain both academic as well as industrial relevance, returning to its "smart" nature. In the United States of America, since the enactment of the Americans with Disabilities Act (ADA) in 1991, DRT has expanded from a national total of 42.4 million passenger trips per year to a total of 73.2 million passenger trips in 2000 (Palmer *et al.* 2004).

	Open DRT (for general public use)	**DRT for people with special needs**
Large scale DRT service providers (>1 M trips/year)	Netherlands (1)	Finland (1), Netherlands (1), Sweden (4), UK (3)
Many (>10) DRT schemes	Belgium, Finland, France, Germany, Italy, Netherlands, Sweden, UK	Denmark, Finland, France, Netherlands, Sweden, UK
Some individual DRT schemes	Austria, Denmark, Ireland, Switzerland	Belgium, Germany, Ireland, Italy, Norway, UK
Little or no DRT	Czech, Cyprus, Estonia, Hungary, Greece, Latvia, Lithuania, Luxembourg, Malta, Norway, Poland, Portugal, Romania, Spain, Slovakia, Slovenia	Austria, Czech, Cyprus, Estonia, Hungary, Greece, Latvia, Lithuania, Luxembourg, Malta, Poland, Portugal, Romania, Spain, Slovakia, Slovenia, Switzerland

Table 1 - DRT practice in Europe *circa* 2005 (from (Westerlund 2005))

It is in this context, that the concept of Intelligent Transport Systems (ITS) emerges. ITS applies advanced communication, information and electronics technology to solve transportation problems such as traffic congestion, safety, transport efficiency and environmental preservation, but its multidisciplinary nature increases the complexity of the problems because it requires knowledge transfer and cooperation among different research areas (Figueiredo *et al.* 2001). Nevertheless, technology allows improving dramatically the work of the DRT operators on the service model dimensions (route planning, scheduling, vehicle assignment) and also the interaction between commuters and transport operators in the different steps of the operational cycle (trip booking, trip parameters, negotiation, communication, service follow-up/location, reporting) (EC 1997). In addition, new ways of thinking about the provision of all types of what might be considered public transport has led to more flexible transport modes directly responding to end user needs.

More recently, innovative DRT solutions have been enabled by the development of ITS, allowing more flexible transport services, in terms of when the booking can be made and of the route taken by the vehicle (Brake *et al.* 2006). As demand declines within an area (such as rural and peripheral areas), efficiency is best achieved by delaying the decision about the route, the vehicle and transport provider as close as possible to the time of travel and by offering the same service to as many passengers as possible (Brake *et al.* 2006). The use of advanced ITS has a beneficial impact on both productivity and operating costs of DRT services (Palmer *et al.* 2004). An efficiency evaluation methodology for the related investments, focusing on public transportation system, has been proposed in (Khan 2009).

The main objectives of the introduction of a DRT system can be summarized as:

- comply with transportation requests set by the local authorities;
- improve the image of public transportation;
- public transportation patronage enhancement;
- better and more "real demand" suited service;
- cost optimization.

(Burri 2010) points to some advantages in DRT systems for users, operators and tendering authorities alike.

Advantages for users:

- high geographical availability;
- convenience and security (door-to-door service or chosen stops);
- personal service to the customer;
- good price/performance ratio;
- important element of the public transportation chain (as feeder or stand-alone system).

Advantages for the operators:

- extending the transportation chain by covering a wider geographical area as well as providing a better service availability in terms of longer operating hours;
- extending the scheduled transport in small-town areas;
- night bus services matching to individual needs;
- contribution to find out demand potential and mobility flows;
- less energy consumption when compared to scheduled transport services.

Advantages for the tendering authority:

- geographical expansion of public transport to not yet served areas;

- basic services in rural regions;
- sustaining the service availability of rural regions;
- increase of housing attractivity;
- better value of the invested money in public transportation;
- contribution to soft tourism.

Even though the idea is around 40 years old, it is puzzling that DRT is still an "immature" business. There is still a lack of common standards, interfaces, vehicle specifications and the terminology is, in many aspects, still open (Westerlund *et al.* 2007).

2.2 DRT systems concepts

There is a large spectrum of DRT systems, from the most "rigid", operating almost as traditional regular transportation systems, to the most flexible, operating almost as taxis. In fact, both extremes can be regarded as "special" types of DRT systems. Usually, more flexible systems are operated to satisfy special groups' needs (e.g., elderly or disabled) whereas less flexible solutions (without a door-to-door service) are operated for "general" users. DRT systems can also operate in different ways according to the geographic characteristics of a given service area. According to (Nelson 2004) the most important aspects of a DRT system are the following:

- the service concepts – essentially route and time concepts;
- the booking concepts;
- the network concepts;
- the vehicle allocation concepts.

Next, these aspects will be used for DRT classification purposes.

2.2.1 SERVICE CONCEPTS

The route of a service is a list of stops that will be served in a specific order. The timetable indicates the passing times of the vehicle at a given stop. For a conventional scheduled service these elements are fully defined in advance. For a taxi service, for instance, none of these elements is defined in advance. Between these two extremes, a wide range of different concepts is possible, even services where stops and passing times are determined during service operation. The type of service is mainly defined by the flexibility of the route (Westerlund *et al.* 2000).

(Nelson 2004) proposes a classification of route concepts for a generic DRT service with an increasing level of flexibility. These concepts are built up using the following types of stops (codes are added for better reference throughout the present document):

- a fixed stop (like conventional bus stops) – a predefined stop with a predefined passing time and which is always served (STP-1);
- a predefined stop with a predefined passing time which is only served on request (STP-2);
- a predefined stop which is only served on request (STP-3);
- a stop point anywhere in the region indicated by the address or the name of the place (non-predefined stops) (STP-4).

(López 2010) also presents a possible classification of DRT services according to the type of stops:

- regular stop points service;
- stop-to-door service;
- door-to-door service;
- hail-and-ride service, where the user physically signs its intention to use the service.

An important aspect for a DRT service is the definition of 'passing time'. Normally time-windows are accepted on the requested time, to give some time flexibility thus allowing additional stops to be served.

Based on combinations of stops and passing time, (Nelson 2004) defines several route-service scenarios (codes are added for better reference throughout the present document):

- Scenario 1 (R-SC1): Predefined route and partially fixed timetable

  In this concept the service is partially coincident with a conventional scheduled service. The complete route and the timetable are set in advance but it is possible to add additional stops along the predefined route, based on the demand. The passing times are also predefined.

- Scenario 2 (R-SC2): Deviations on a scheduled service to predefined routes

In this scenario there is a set of fixed stops and predefined passing times, but in addition the vehicle can deviate from the route to serve predefined stops on request. These predefined stops are located near the basic route, thus making the deviations short.

- Scenario 3 (R-SC3): Predefined stops in a corridor

  In this scenario there is one or two end points and a set of predefined stops located in a corridor. Some stops on the route have predefined passing times as a way to structure the service. This limits the flexibility but makes it feasible to serve more non-fixed predefined stops. It is also possible to exclude the end points, making the timetable fully demand oriented. The location of the stops in a corridor makes the organization of the DRT service easier.

- Scenario 4 (R-SC4): Predefined stops in an area

  In this scenario, the service covers an area with predefined stops. The structure of the service is defined by the demand. When no predefined passing time is determined for any stop, the service is closer to a taxi service. In most cases, a stop with a predefined passing time or a fixed stop is introduced, to make the organization of the service feasible – otherwise the vehicle would have to make a trip for each request.

- Scenario 5 (R-SC5): Points in an area

  This scenario corresponds to an evolution of scenario 4, with the served points in the area being be any points – e.g., house address or point-of-interest – instead of fixed stops.

These basic DRT scenarios can be combined to best match the demand patterns. For instance, one can have a service based partially on a fixed route and stops in the city center, and an area-wide service on request in the suburbs.

Another important aspect in terms of service is the type of users of the service (codes are added for better reference throughout the present document):

- special groups (USR-1);
- general public (USR-2).

As already mentioned, usually, more flexible systems are operated to satisfy special groups' needs (elderly or disabled) whereas less flexible are operated for "general" commuters.

2.2.2 BOOKING CONCEPTS

An important concept in DRT services is the booking of the trip. Typically, three phases can be distinguished in the booking process: 1) a customer request for a trip, with a particular origin and destination (stop or address) and arrival or departure times; 2) the proposal of a feasible service by the service operator; and 3) the booking confirmation (or refusal of the proposed service) by the customer:

- phase 1: the customer sends a request to the operator (or to the supporting system of the operator) - the request describes the characteristics of the trip the customer needs, e.g., a departure stop (or address), a destination stop (or address), a departure time or arrival time, the number of required seats and any special requirements (e.g., wheelchair accessibility);

- phase 2: the operator (or supporting system) presents one or more possibilities for the trip;

- phase 3: the customer confirms to the operator that he / she will use the service, based on the proposed trip.

Different variations of this basic workflow, and hence different types of service booking, can be defined depending on the time each phase is performed. (Nelson 2004) presents several booking scenarios (as before, codes are added for better reference):

- Scenario 1 (B-SC1): Non-pre-booked trips

  A customer would like to board a DRT service although he/she has not made a booking for the trip – this is known as hail-and-ride. It is up to the driver to decide whether the passenger is allowed to board the vehicle, possibly taking into account instructions received from the service operator. Also, a DRT service can be implemented where customers book their services via a computer terminal at the departure stop, just before boarding, by indicating the destination stop.

- Scenario 2 (B-SC2): Direct booking

  The customer issues a request to the operator, receives one or more detailed service proposals, decides and confirms the booking. The booking can occur before the departure time (i.e., a static service) or while the service is operating (i.e., a dynamic service).

- Scenario 3 (B-SC3): Wide time window - trip notification

  As an answer to his request, the customer will first receive a proposal from the operator, with rather wide time margins on departure and arrival times. Based on this information the customer will confirm the bookings. Only a short time before the departure time, will the operator inform the customer more precisely about the scheduled departure time. This allows the operator to optimize the organization of the service.

- Scenario 4 (B-SC4): Collecting requests – defining service

In this scenario the operator will first collect all requests of the customers and then compute an optimal route, taking into account some pre-defined optimization criteria. Once this process is finished, a new contact with the customer is made, informing him about the details of the service and he will decide whether to accept the service or not.

Naturally, to a certain extent, these booking scenarios can be combined.

The booking workflow can be implemented in a number of different technologies. In the first implementations of these systems, a human dispatcher was often involved as a direct interface between the customers and the booking component. Nowadays, technology systems, such as Interactive Voice Response (IVR) systems, Internet and Web Services, mobile phones and SMS, just to name a few, allow a higher degree of automation of the booking process. An IVR is a computer system that allows the user to select an option from a predefined menu, using the telephone keypad. More sophisticated IVR systems integrate speech recognition, so that the users can select options from the menu using their own voice (Gomes 2007). In a transportation context, IVR systems and smartphone applications allow users to schedule trips, check scheduled ride times, confirm services, and cancel trips, in an entirely automated and pervasive way which does not require interaction with human operators. Smartphones add the possibility of graphical feedback and more features such as map and route visualization.

Care must be taken, however, when selecting booking technologies: IVR and Smartphones do allow a higher degree of automation of the booking process, but sometimes the target users of the DRT service might not be prepared for new information technologies, specially Web sites and smartphones (IVR, in the end, is just an "old" phone call) and, consequently, the service booking must be as simple as possible (Vasconcelos *et al.* 2006).

2.2.3 NETWORK CONCEPTS

DRT Services can have different roles in the global public transport offer. (Nelson 2004) presents some possible roles (again codes are proposed for these roles):

- Stand-alone DRT service (N-SC1)

  Especially in rural environments, DRT services can be operated without any time or spatial relation with other services. For example, the opening hours of health services, or the location of the community can be the main elements for the definition of the service.

- DRT feeder service (N-SC2)

  The passengers use the DRT as a means to reach another transportation service. The main objective of such a feeder service is to complement a direct service between two important centers in order to avoid deviations in that direct service.

- DRT with multiple service roles (N-SC3)

  Combining the characteristics of the previous two roles, the DRT provides the inhabitants of a region, a transportation service to the most import nearby center where both services and travel interfaces are located. Therefore the DRT functions as a standalone and a feeder service. There is even the possibility of different roles according to different periods of the day of different areas (multitasking).

2.2.4 VEHICLE ALLOCATION CONCEPTS

An important choice in the definition of the DRT service is the way vehicles are allocated to each service.

- Fixed vehicle allocation (V-SC1)

  The DRT service is defined with only one vehicle available. The characteristics of this vehicle determine to a large extent the type of DRT service.

- Extendable vehicle allocation (V-SC2)

  If the operator does not want to refuse passengers, the service can be defined starting from a given fixed number of homogeneous vehicles, but the use of extra vehicles can be considered within certain limits (for example, a co-operation with a taxi operator, to transport additional passengers that could not be picked up by the initial services).

- Dynamic allocation of vehicles (V-SC3)

  The operator of the DRT service will ideally have a pool of available vehicles to be used for the service operation. Different types of vehicles (capacity, accessibility, special features) will form part of such a pool. Eventually some of the vehicles can also be operated by other companies.

2.2.5 DRT SERVICE DEFINITION

Table 2 congregates the DRT system concepts definition by (Nelson 2004) and (López 2010), adopting the most appropriate aspects of each author's approach and augmenting with other aspects considered important.

Concept	**Code**	**Type**
Stops	(STP-1)	Fixed stops
	(STP-2)	Predefined stops with predefined passing time, only served on request
	(STP-3)	Predefined stops, only served on request
	(STP-4)	Non-predefined stop
Users	(USR-1)	Special groups
	(USR-2)	General public
Route and Time	(R-SC1)	Predefined route and timetable which is partly fixed
	(R-SC2)	Deviations on a scheduled service to predefined routes in a corridor
	(R-SC3)	Predefined stops in a corridor
	(R-SC4)	Predefined stops in an area
	(R-SC5)	Points in an area
Booking	(B-SC1)	Non pre-booked trips
	(B-SC2)	Direct booking
	(B-SC3)	Wide time window – trip notification
	(B-SC4)	Collecting requests – defining service
Booking Technology	(BT-1)	Operator
	(BT-2)	Terminal
	(BT-3)	Magnetic card
	(BT-4)	Interactive Voice Response
	(BT-5)	Internet
Network	(N-SC1)	Stand-alone service
	(N-SC2)	DRT feeder service
	(N-SC3)	DRT with multiple service role
Vehicle Allocation	(V-SC1)	Fixed vehicle allocation
	(V-SC2)	Extendable vehicle allocation
	(V-SC3)	Dynamic allocation of vehicles

Table 2 - DRT service aspects (adapted from (Nelson 2004; López 2010))

Table 2 can be used by service designers to define a given service concept by choosing the "ingredients" that make up that service. For instance, a service concept could be: a stand-alone service (N-SC1), with predefined stops with predefined passing time, only served on request (STPC-2), targeting general public (USR-2), with a predefined route and timetable which is partly fixed (R-SC1), requiring direct booking using the internet (BT-5) and operating with a fixed vehicle allocation (V-SC1).

2.3 DRT fare collection

The fare payment processing may be carried out interactively from on-board the vehicle, or as advanced payment (at the roadside, at operator's facilities or online, for instance). Integrated Payment Systems (IPS) system should be considered and, when successfully integrated, can provide benefits from the point of view of improved efficiency of the operator's fare collection operations (Nelson 2004). The ticket system should be equal with the existing Public Transport ticket system (FLIPPER 2008). These IPS may prove challenging if there are both bus and taxi operators involved.

On-board the vehicle, the use of automated fare collection devices allow automated management of payment operations and, additionally, provide more functions such as customer validation or passenger counting. With the recent developments in electronic cards, options of how passengers pay for public transport have increased. Smart-card technology represents one of the best Information and Communications Technology (ICT) alternatives for fare collection in DRT systems (Brake *et al.* 2006) .

Advanced payment can also be considered, via on-line web site, at the operators' facilities or ticket vending machines, with passes, multiple-trip tickets or just single tickets. Operators can encourage passengers to pay in advance by offering financial incentives, for instance.

2.4 DRT systems classification

Classification is essential in categorizing DRTs by characteristics that affect performance so that they are more appropriately compared. The classification offered by INTERMODE Consortium (Enoch *et al.* 2004) proposes four function-based types, each of which is described by the nature of the DRT service it represents and the market it serves: interchange DRT, network DRT, destination-specific DRT and substitution. (KFH Group 2008) established a simplified typology of DRT systems in order to classify and more easily compare them based on two criteria: market served and service area. In terms of service area therefore, (KFH Group 2008) divided DRT systems first into rural and urban systems (urban areas are then divided in small, large and largest areas). In terms of market served, three categories are identified: "ADA paratransit", "limited eligibility

DRT", and "general public DRT". (Potts *et al.* 2010) also follow a classification by service area: rural areas, small urban cities and urban and sub-urban areas. According to (Nelson 2004) the most important aspects to consider when classifying a DRT are the service concepts, the booking concepts, the network concepts and the vehicle allocation concepts.

2.5 DRT systems operation

The interaction diagram in Figure 3 briefly illustrates the operation of a DRT system. The black arrows represent the flow of the trip planning procedure and the gray arrows represent the user activities for making the trip.

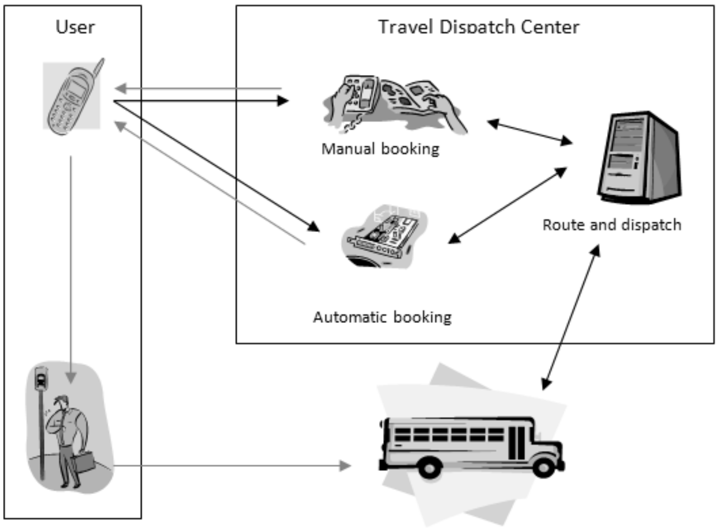


Figure 3 - DRT service operation

The user makes a transportation request to the Travel Dispatch Center (TDC) in any of a given number of ways (phone call, SMS, email, web page, dedicated device, PDA, Tablet, for instance). At the TDC, the operator, or an automatic booking system, introduces the user specified data, such as origin/destination and pickup/delivery times in the system. Depending on the DRT service type and the time the user contacts the operator, this data can be used, together with other user requests, to define routes and schedules for the vehicles before the service operating hours (static routing), or to change the on-going routes in real-time to accommodate the new request (dynamic routing). Then, the operator communicates the definitive schedule to the user (or rejects the request), who can cancel or accept the trip conditions. According to the user decision, the operator commits the necessary changes to the system. In static routing, before the service begins, the stored requests are used to define the routes and schedules for the operational horizon, whereas in dynamic routing the new routes and schedules are communicated to the affected vehicles in real-time. The vehicle makes the defined route, picking up and dropping off passengers at the agreed points and times and, in the meantime, in a dynamic service, the operator is free to receive new requests and change routes accordingly.

The importance of dynamic vehicle routing is increasing every due to, amongst other reasons, recent economic developments, where markets are ever more open and competitive. Logistic operators must comply with tighter and tighter deadlines not only to be competitive but even to survive. For that matter, real-time availability of information such as vehicle position or traffic conditions is critical. Dynamic DRT systems use a number of technologies in an integrated manner. These technologies include Automatic Vehicle Location (AVL) systems, automated routing and scheduling, geo-spatial technologies, wireless communications, vehicle navigation, and e-card technology, just to name the most relevant.

Figure 4, from (Larsen *et al.* 2008), shows a typical technological setup needed for a dynamic DRT service and the "information flows between the vehicle and the dispatching center".

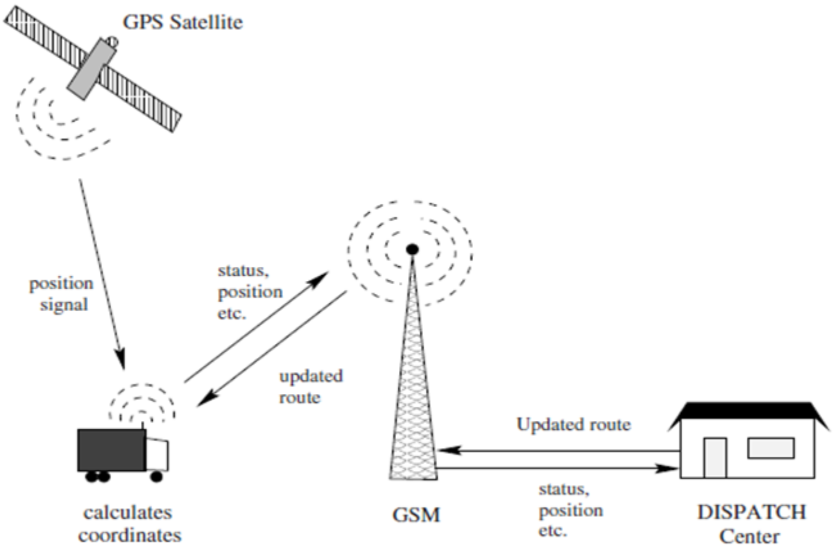


Figure 4 - Dynamic DRT systems technological setup (source: (Larsen *et al.* 2008))

2.6 Indicators for DRT systems performance

Standardized methods of measuring and assessing performance are needed in order to improve upon the performance and cost-effectiveness of DRT. It is still open to debate if traditional bus key performance indicators (KPI), such as, for instance, the *cost per passenger X kilometer* or the *cost per vehicle X kilometer*, apply equally to DRT systems. Nevertheless, concentrating on the most essential aspects of DRT system, (KFH Group 2008) suggests five key performance indicators (KPI) for assessing DRT systems as follows:

- Passenger Trips per Revenue Hour;
- Operating Cost per Revenue Hour;
- Operating Cost per Passenger Trip;
- Safety Incidents per 100,000 Vehicle kilometers;
- On-Time Performance.

A brief explanation on each of these KPIs follows.

Passenger Trips per Revenue Hour – It assesses the productivity of the DRT system and captures the ability of the DRT system to schedule and serve passenger trips with similar origins, destinations, and time parameters, using the least number of in-service vehicles and revenue hours (KFH Group 2008). This measure of productivity is calculated using the following expression:

$$\mathit{Passenger\ trips\ per\ revenue\ hour} = \mathit{Total\ passenger\ trips} \ / \ \mathit{total\ revenue\ hours}$$

Operating Cost per Revenue hour – it is a cost-efficiency measure that establishes the financial resources needed to produce an hour of revenue service (KFH Group 2008). This performance measure is calculated using the following expression:

$$\mathit{Operating\ cost\ per\ revenue\ hour} = \mathit{Total\ operating\ cost} \ / \ \mathit{total\ revenue\ hours}$$

Operating Cost per Passenger Trip – this is another cost-effectiveness measure combining the two previous indicators - the operating cost per revenue hour and the passenger trips per revenue hour - in order to relate productivity to the hourly operating cost (KFH Group 2008). The expression for this performance measure is as follows:

$$\mathit{Operating\ cost\ per\ passenger\ trip} = \mathit{Total\ operating\ cost} \ / \ \mathit{total\ passenger\ trips}$$

Safety Incidents per 100,000 vehicle Kilometers – this KPI incorporates an assessment of both service operations as well as passenger service quality and measures the safety of a DRT system. Since there are different ways to define and measure safety and accident rates, (KFH Group 2008) uses the American National Transit Database (NTD) definitions to define and measure safety and accident rates by using the classifications of NTD major incidents and NTD non-major incidents. The calculation for the safety performance measure uses the following expression:

$$Safety\ incidents\ per\ 100{,}000\ vehicle\ kilometers\ =$$

$$[(NTD\ major\ +\ non\_major\ safety\ incidents)\ /\ (total\ vehicle\ kilometers)]\ \times\ 100{,}000$$

On-Time Performance – although regarded as one of the, if not the, most important measure of service quality from a DRT passengers' perspective (KFH Group 2008), this KPI can be difficult to quantify accurately because of the varying definition of "on-time trips" among different operators, and the variations in the methods by which the data is collected. This performance measure is computed by the following expression:

$$On - time\ performance\ =$$

$$(total\ \mathrm{on\_time}\ trips + early\ trips)/(total\ completed\ trips + no\_shows\ +\ missed\_trips)$$

Additional performance measures also described by (KFH Group 2008) that assess more specific areas include the following:

- $no\_shows\ rate\ = total\ no\_shows\ /\ total\ number\ of\ scheduled\ trips$
- $cancellation\ rate\ = \text{total cancellations / total number of reserved trips}$
- $missed\ trip\ rate\ =\ total\ missed\ trips\ \ /\ total\ number\ of\ scheduled\ trips$
- $trip\ denial\ rate\ =\ total\ trip\ denials\ /\ total\ number\ of\ requested\ trips$
- $average\ passenger\ trip\ length = total\ passenger\ km\ /\ total\ nr.of\ passenger\ trips$
- $average\ travel\ time\ = total\ passenger\ travel\ time\ /\ total\ nr.of\ passenger\ trips$

2.7 Issues on DRT services

The advantages of a DRT service in terms of social cohesion, mobility, traffic, or environment, are fairly obvious. However, in terms of financial sustainability and quality of service, the design of this type of services may be rather difficult. Until now, there has not been a strong commercial case for DRT services, that typically have a relatively low productivity and corresponding high costs per trip when compared to fixed-route services

(KFH Group 2008). In (López 2010) the author observed that the main obstacles for the implementation DRT systems are from juridical, institutional and organizational nature. The technical difficulties are less complex to deal with than aforementioned obstacles, because these obstacles are more dependent on political agendas and stakeholders' attitudes, perceptions and (sometimes conflicting) objectives.

2.7.1 INSTITUTIONAL AND JURIDICAL OBSTACLES

For starters, the image of the services traditionally had a very institutional nature. The industry has been driven by the social inclusion agenda, and features schemes that are complex, expensive, custom-made and cost heavy (Enoch *et al.* 2004). Another key difficulty originates from the DRT own nature and strength, in that it is a hybrid system. As a relatively new form of public transport, the juridical status of DRT has been unclear, with applications being slowed down by issues of how to register services successfully (Brake *et al.* 2006). This means that DRTs do not relate well to the regulatory structure that has been designed with conventional buses and taxis in mind. Shifting DRT to a "legal" status would require the realignment of the overall public transport industry, its finances and regulation.

The development of DRT systems should be based in the European Union, national and local transportation policies. Sometimes it might be necessary to change the national transportation policies to accommodate the DRT systems (EC 1998). Nevertheless, the European experience shows that a DRT service is easier to implement in more regulated environments as there is less conflict with other public transport modes (Brake *et al.* 2004) and subsidies are most likely to be available in regulated environments - whereas in deregulated environments, subsidies are service specific (Mageean 2003).

2.7.2 ORGANIZATIONAL OBSTACLES

Moreover there are a variety of planning and implementation issues. What might be the appropriate mix of DRT with other forms of public transport? When (or where) should DRT replace buses? Or, in which circumstances might be better to have DRT as a service to support demand for conventional buses? What are the long-term costs of DRT and comparable conventional bus services – and what type of systems provide a better service to the user and is more effective for policy objectives?

In (Burri 2010), the author pointed the following problems in a DRT implementation:

- high total costs;
- high dispatching costs;
- low revenue-to-cost ratio: the viability of DRT services as a self-supporting system has not yet been demonstrated, and the issues of fares, and the cost of phone calls, subsidies, bus and control center operation are tricky (Brake et al. 2006);
- low occupancy rates;
- peak demands;
- general consumer acceptance.

(Burri 2010) and also (Brake *et al.* 2006) point to some actions to overcome these problems categorized by dimension. Table 3 presents these actions.

Dimension	**Actions**
Service planning	Organizational and operational actions for better demand aggregation (e.g. zones‘ subdivision, more time related restrictions for customer)
Vehicle fleet	More small vehicles, reduction of total number of vehicles
Operator model	Cooperation with private taxi firms;
Dispatching	Service characteristics need careful consideration;
Reservation	Strategic service changes may stimulate additional patronage;
Marketing	New organization based on existing technologies, acquisition of new applications, more automatization
Pricing	Pooling of the existent call centers, new reservation channels, internet-based reservation systems

Table 3 - Actions to overcome some DRT problems (adapted from (Brake *et al.* 2006; Burri 2010))

Service design is a critical stage in the development of DRT services, and so it will be the focus of a central chapter in this dissertation. Ideally service design should be completed in collaboration with key stakeholders who will normally include the commuters, bus (and other) operators, the local authority and the travel dispatch center (control center) manager, taking the following aspects into account:

- the objectives of the service must be clear and defined in the context of external constraints, such as political, legal, geographical and communication restrictions;
- given that a wide range of different service design concepts are available, they should reflect the outcome of a comprehensive user requirements process;
- only after the previous stages, the most efficient route design for the predicted demand levels should be considered;

- the costs of service design and implementation may be positively influenced by closer integration between multiple service providers.

Regarding the last point in this list, the trend in the recent evolution of flexible services has been the emergence of several types of partnership, in a movement towards multiple services. This is increasingly viewed as fundamental to the future development of DRTs (Nelson 2004). In the future many resources are likely to be integrated, including the pooling and optimization of investment capital, vehicles and human resources (Brake *et al.* 2007).

DRT services will be more efficient if there is a choice of operator and vehicle closer to the service time. This can best be achieved by the pooling of resources from all suppliers of public transport, enabling a more appropriate vehicle choice, providing better mobility and allowing better service integration (Brake *et al.* 2006). This will require breakthroughs in concepts, business models, organizational and operational models and in supporting technologies. Flexible Agency for Collective Mobility Services (FAMS) (EC 2002) was a EC-funded research project that has established an organizational structure and business model for DRTs, incorporating the required supporting technologies, to manage the entire service chain (Nelson 2004), from customer booking to service planning, monitoring and control, operating as a unique entity, through a dedicated Management Centre. The FAMS project identified five layers that reflect an increase in the level of complexity in the provision of DRT services (Nelson 2004):

- basic agency: one network with one service provider at one agency; booking and assignment is made manually at least one day prior to travel; no ITS support;

- standalone agency: with ITS support, enabling on-day, non-manual booking and assignment; ranges from one to many services through a single control center;

- expanded agency: more advanced structure, as it manages the routes operated by more than one service provider, i.e., it uses vehicles from several geographically overlapping networks, combining them into a more efficient aggregated network, to provide an integrated system from the user point of view;

- mature agency: stable integrated agency based on mature ITS platform; well understood processes by all stakeholders; easy to add a new supplier, a service or a customer interface;

- interacting agencies: optimization of modes and services between several agencies, carrying each other's customers, allowing access to an even greater range of vehicles and more opportunities for passengers to travel, in a larger geographical network.

The provision of such brokerage for all public transport services requires the development of computer systems that can intermediate rapidly between transport providers according to potentially complex criteria. The FAMS project developed a specific architecture based on a common service center (sharing a number of services for planning, managing and monitoring the different types of flexible services), e-business services between the different actors involved (including operators and users), and a communications network based on the GSM (Global System for Mobile Communications) and GPRS (General Packet Radio Service) technologies. Figure 5, from (Ambrosino *et al.* 2003), shows the structure of the FAMS business model for DRTs.

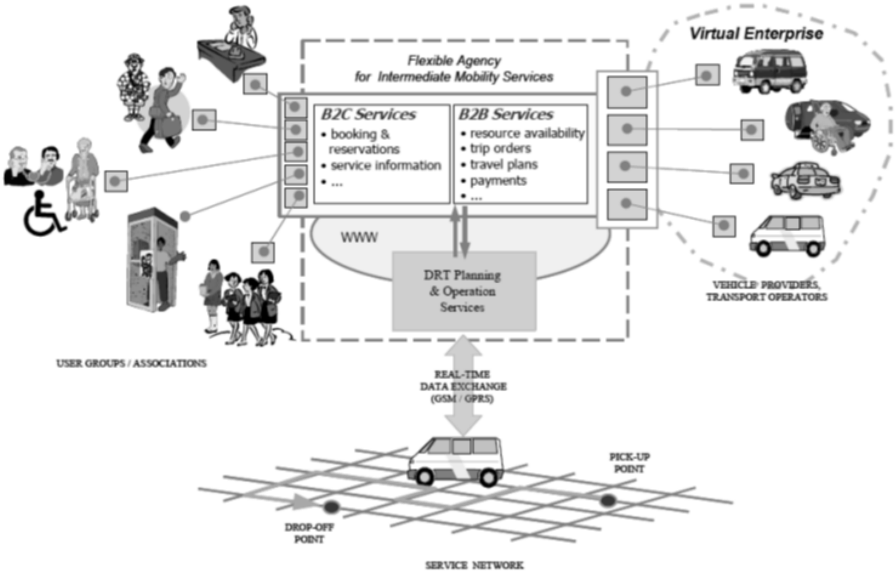


Figure 5 - Structure of the FAMS business model for DRTs (source: (Ambrosino *et al.* 2003))

FAMS tested the concept of a "Virtual Agency" to co-ordinate multi-modal DRT service delivery at sites in Scotland (Angus region) and in Italy (Florence).

Another relevant European project to overcome the problems faced by DRT services was FLIPPER - Flexible Transport Services and ICT platform for Eco-Mobility in urban and rural European areas (FLIPPER 2008). FLIPPER focused on capturing the best practices for a wide range of flexible transport options better tailored towards the needs of individual communities in cities, small towns and rural areas. The three year project (finished in August 2011) resulted in a greater understanding of the technological, organizational and operational requirements for the introduction of alternative flexible transport options at both regional and inter-national levels. This knowledge is made available on a virtual library. The FLIPPER Virtual Library is an on-line repository on Flexible Transport Systems. Originally developed in the CONNECT European project, FLIPPER has taken over management of the library and will be updating it in the future.

2.8 A framework for DRT systems operation analysis

Based on the concepts and information presented in the previous sections, namely DRT systems concepts section, we have developed a framework for the analysis of the operational aspects of DRT services. This framework was designed to support the study of a given DRT service, focusing on the aspects that define its operation characteristics. Table 4 illustrates the developed framework for the analysis of DRT services operation.

Service Name:	the commercial name of the service
City:	the location where the service operates
Description/Route scenario	brief service description, with the operational scenario and/or role, types of stops and routes
Role	role in the global public transport offer
Service hours:	the service operating period (day, night or 24 hours)
Passengers:	types of users entitled to use the service
Operation:	
Vehicles:	types of vehicles operating the service
Service points:	types of stops
Time window:	information on the possibility to defined pickup and/or delivery time windows
Service frequency:	information on service operation frequency
Service request:	
Booking	type of booking scenario
Technology:	technology means the commuters can use to place trip requests
Request time:	time interval where reservations must the placed by the users and information if real-time requests are allowed or not
Information provided:	information commuter provides to make a reservation
Price:	service fare price

Table 4 - Framework for DRT service operation analysis

Using this framework, a survey was made addressing 25 existing DRT services from different European countries, with a special focus on the technical and operational aspects, based on the concepts presented in DRT systems concepts section. Table 5 presents the number of DRT services analyzed by country.

Country	Number of DRT services
Austria	1
Belgium	2
England	5
France	4
Germany	1
Italy	4
Ireland	1
Netherlands	1
Portugal	1
Scotland	1
Spain	1
Sweden	2
Switzerland	1

Table 5 - Number of DRT services analyzed by country

The proposed framework structure makes it very easy to add new services. Annex A presents the raw data of the survey.

The survey points to a strong relationship between the function of a DRT service and both the route flexibility and the market it serves (correlation factor 0,64): stand alone or substitution services mostly serve special user groups, whereas interchange DRTs serve a more general market; and DRTs that serve a more general public or both general and special groups tend to be more flexible than those DRTs that serve only special groups.

Another strong relationship was also found between the area served and the type of users (correlation factor 0,69) - the survey indicates that in large urban areas, DRTs are mostly used to serve special user groups whereas in rural/small urban areas DRTs tend to serve both special groups and the general public.

Next, we analyze some findings of the survey, following the framework components presented in Table 4.

2.8.1 ROUTE SCENARIO

Eight (32%) of the studied services operate using a door-to-door scenario (R-SC5), five (20%) use predefined stops in an area (R-SC4) and another five (20%) use predefined stops in a corridor (R-SC3). Four (16%) DRT services combine predefined stops without predefined passing times in an area with either door-to-door service (12%), or with predefined stops without predefined passing time in a corridor (R-SC3). Three services (8%) operate using deviations on a scheduled service to predefined routes in a corridor (R-SC2). The pie chart in Figure 6 illustrates the findings in terms of route scenarios for the surveyed DRT services.

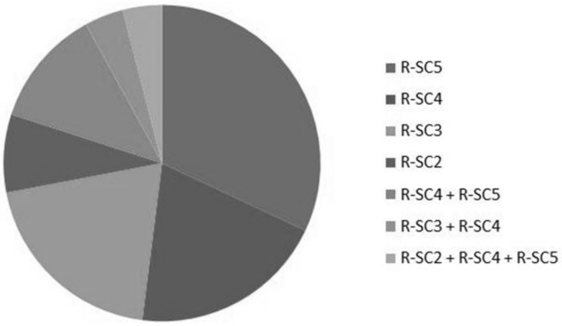


Figure 6 - DRT services route scenarios analysis

2.8.2 SERVICE ROLE

Looking at the service role, 72% are stand-alone DRT services (N-SC1), while the other 28% are equally distributed between feeder-systems (N-SC2) and combined systems (N-SC3). In a per country analysis, it is interesting to notice that:

- in Belgium, all analyzed services are offered to the general public, at regular stops, but with a flexible route;
- in England all services surveyed are quite flexible, operating in a door-to-door scenario (R-SC5) or using predefined stops in an area (R-SC4) while servicing mostly special groups;
- almost all surveyed DRT services in France (3 out of 4) operate as feeder systems (N-SC2); almost all feeder systems in France (2 out of 3) operate using predefined stops in an area (R-SC4) with a predefined passing time served on request (STP-2) - these conclusions corroborate the findings in (López 2010): in France, most systems use predefined stops, are open to the general public and, usually, operate as feeder systems for the public transportation services;
- in Italy, the systems are more flexible than in France: although they use predefined stops (R-SC4), the passing time is demand driven (STP-3) – this is also in line with (López 2010); most services are offered to the general public, but, alongside, there are special services for special groups;
- in Sweden, door-to-door services for special groups also have a big share.

Figure 7 shows the most relevant route scenarios in countries with more DRT services surveyed (England, France and Italy).

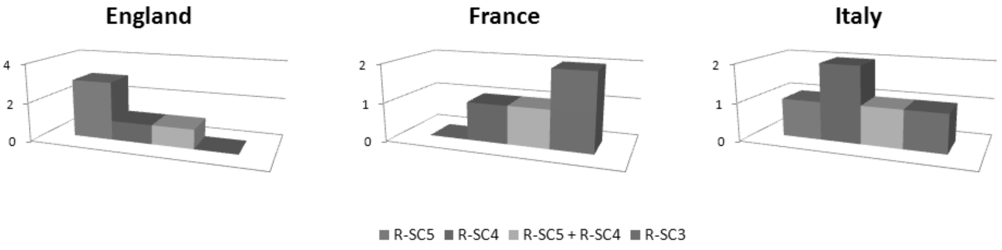


Figure 7 - Route scenarios for countries with more surveyed DRTs

In rural areas, around 50% of the DRT services operate using predefined stops in an area or door-to door scenarios, 38% operate using deviations on a scheduled service to predefined routes in a corridor (R-SC2) - alone or in combination with a more flexible route scenario (R-SC4) -, and the remaining services operate using predefined stops in a corridor (R-SC3).

In small urban areas, 20% of the services operate using predefined stops in a corridor (R-SC3) and 40% use predefined stops in an area/door-to-door (R-SC4 or R-SC5). Finally, for medium and large urban areas, around 67% of the services used predefined stops in area scenarios or door-to-door (R-SC4 or R-SC5). Figure 8 illustrates these findings.

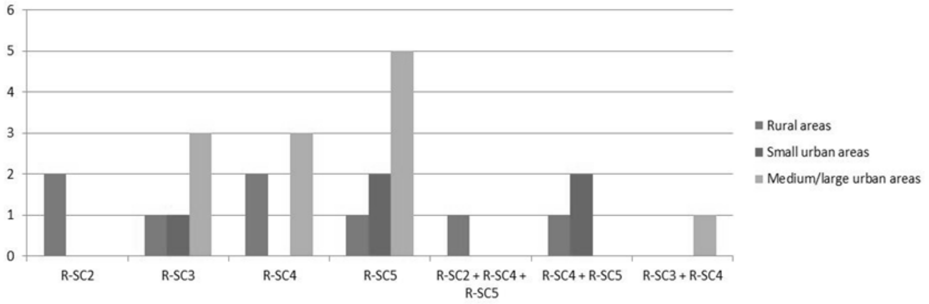


Figure 8 - Route scenarios according to service area

2.8.3 SERVICE HOURS

In terms of operating period, most services (around 63%) operate during the day (D) while 21% of the services operate day and night (D and N) using different scenarios in each of these periods. A non-neglecting percentage of services operate 24 hours (around 13%). Only 4% operated exclusively during night time periods. Services that operate during the night period or 24 hours use predefined stops in an area (R-SC3) or door-to-door (R-SC4). The use of more flexible route scenarios for night time services is probably explained by security reasons. Figure 9 shows the number of DRT services operating in each period of the day.

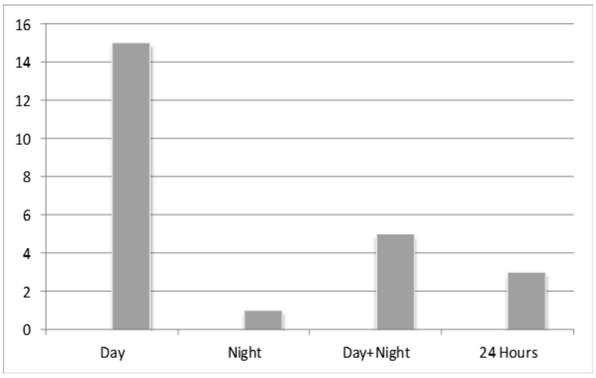


Figure 9 - Operating period for the surveyed DRTs

It is interesting to compare these findings with the North-American reality, as surveyed in (Potts *et al.* 2010): around 85% of the operators indicated that the DRT service was operated at all times of the day, only 4 % indicated that the service was only operated at night, and 7% indicated the service was only operated on weekends. The percentage of night-only services is the same in both sides of the Atlantic, but while in Europe most services are day-time only, in North-America the large majority of the services operate at all times of the day.

2.8.4 TYPE OF USERS

Most surveyed DRT services (40%) are offered to the general public (USR-2), 28% are offered to both special groups and general population (USR-1 and USR-2) and 32% are offered only to special populations groups (USR-1). So, in fact, general population can use 68% of the surveyed services. This is also in line with the findings in (López 2010): although DRT services were initially aimed at special population groups, they are offered to the general public in most cases (around 70%). Figure 10 illustrates the user group targeted by the surveyed DRTs.

Figure 10 - Type of users targeted by the surveyed DRTs

2.8.5 SERVICE POINTS

Most services (32%) used door-to-door service (STP-4) or predefined stops without timetable only served on request (STP-3), 28% (in (López 2010) 40% of the services operated door-to-door). 12% of the services used a combination of both stop types (STP-3 and STP-4). So, 72% of the surveyed DRT services are door-to-door or use a set of predefined stops without timetable. 12% of the surveyed services use predefined stops with timetable only served on request (STP-2). There are few situations of combination of type of stops, and those cases, typically, combine a less flexible service during the day time with a more flexible service during night time. (López 2010) also noted that there are few hybrid situations. Only one surveyed service allowed for a sort of hail-and-ride: the passenger can get on board if there are still seats not assigned and he agrees to share the route already planned. Figure 11 illustrates the type of stops in the DRT services surveyed.

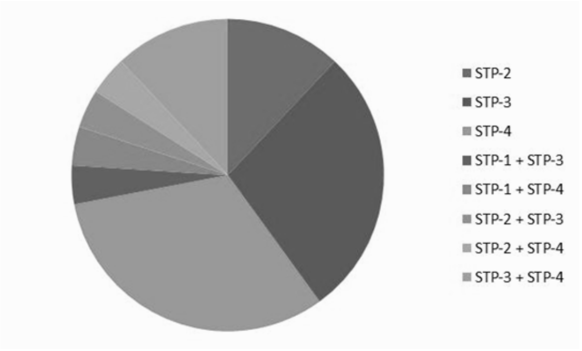


Figure 11 - Type of stops used by the surveyed DRTs

2.8.6 SERVICE REQUEST

Regarding the booking scenario, 64% of the services operate in a direct booking scenario (B-SC2) where the customer issues a request to the operator, receives one or more detailed service proposals, decides and, finally, confirms the booking. One of these services operating in direct booking also allowed for non-pre-booked trips (the service that allowed for hail-and-ride already mentioned). Only one service operated with solely non-pre-booked trips (B-SC1). The remaining of the surveyed services (28%) operates in a "collecting requests to define service scenario" (B-SC4). In this scenario the operator will first collect all requests of the customers and then calculate the most optimal route taking into account defined optimization criteria. It is interesting to notice that all services that collect requests to define the service (B-SC4) operate using a door-to-door route scenario (R-SC5) and/or predefined stops in an area (R-SC4) route scenario. Figure 12 shows the booking scenario distribution of the surveyed DRT services.

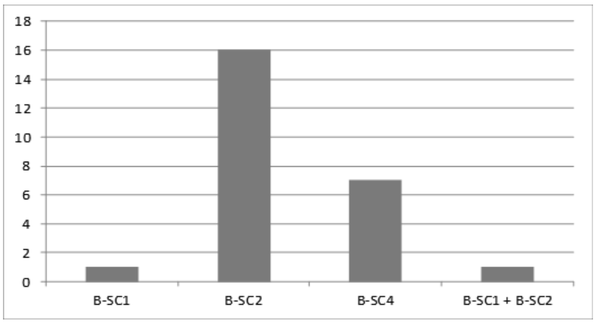


Figure 12 - DRT services booking scenarios analysis

Only one service allowed to make a reservation by other means than the telephone call (namely by Internet and SMS). All the other services only offered telephone call booking. This could be explained by the fact that surveys shown that these users are not prepared for new information technologies, such as Internet and SMS, and, consequently, the service booking must be as simple as possible (Vasconcelos *et al.* 2006).

Figure 13 illustrates the time limit for the user to book the service.

Figure 13 - Time limits for booking in the surveyed DRTs

It is clear that the closer to the time of travel that the route is determined, the more responsive it is (Brake *et al.* 2004). 40% of the surveyed services required the booking to be made in the previous day, 10% required the booking to be made 2 hours before the trip, 25% required the booking to be made 1 hour before the trip, and another 25% allowed the user to book the trip less than 1 hour before the required pickup time – the shortest time limit allowed found was 15 minutes. One service did not required booking. One surveyed service required all bookings to be made at least 30 minutes before the service beginning. From the services that required longer overhead booking times, 70% were aimed to special groups of users, i.e., typically services aimed at special groups needed more time for booking.

Six services had time windows around the pickup time and their size ranged from 10 minutes to as much as 30 minutes - in (Nuworsoo 2011), surveyed operators in USA assigned time windows of 15 to 30 minutes for pick-up and delivery of passengers. Once again, it is interesting to compare these findings with the North-American reality booking procedures as surveyed by (Potts *et al.* 2010): half of the operators said that passengers using DRT could be picked up without prior reservation (B-SC1) at any established stop along a route. Nearly 40 % said that the passenger must make prior booking (B-SC2). For flexible pickup locations, 55% of the operators require an advance booking in the previous day (B-SC4), while a total of 37 percent of respondents allow passengers to call within 2 hours or less to request a flexible pick-up. For the large majority of services, 68% passengers must call the Travel Dispatch Center, while a limited number of services, 14%, allow passengers to call the driver directly and around 9% allow booking via a website.

Regarding the information required for booking, except for one service that only required the delivery location, all other services required the specification of pickup location, pickup time and delivery location. Only 16% required also the specification of the delivery time. 25% of the services required the specification of the number of passengers.

2.8.7 TYPE OF VEHICLES

Around 20% of the surveyed DRT services had a heterogeneous fleet. The most commonly used vehicles are adapted mini buses (50% of the services use them). Regular mini buses are used by 39% of the services, taxis (eventually shared) are used by 26% of the services and adapted vans by 10%. North-American reality as surveyed per (Potts *et al.* 2010) shows that nearly half of the operators (46%) used small buses, while 28 percent used vans to operate the service. Figure 14 shows the type of vehicles used by the surveyed DRT services.

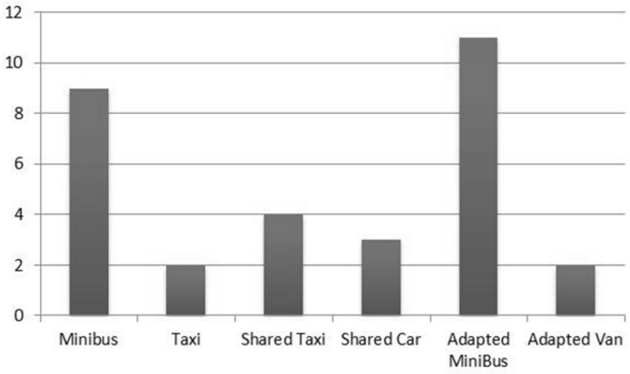


Figure 14 - Vehicles used in the surveyed DRTs

2.8.8 SERVICE FARE

Finally, in terms of fare rates, 45% of the services have a fare equal to the regular public transportation service, 40% have higher fares than the regular public transportation service, and 15% are free. Only one requires the user to buy a monthly pass. The service fares that are more expensive than the regular public transportation service go from 1 to 6 euro (one of them charges twice the equivalent of a taxi ride service). Some services have different prices according to the role (flexibility of the service) in different periods of the day. (Potts *et al.* 2010) show that in North-America 70% of the operators charge the same fare for the DRT service as the fare charged for fixed-route service. From the operators that charge a different fare for DRT, more than a half, around 60%, charge a higher fare for the DRT service than for the normal fixed service.

2.9 Chapter summary

Several factors, such as the migration of industries and people to more peripheral areas with lower population densities, new mobility patterns induced by flexibility of working hours and increasing leisure-oriented trips, the over-use of private vehicles, among other factors, affect the provision of quality public transportation, which is based on significant numbers of passengers travelling together. If the requests are not aggregated in time or the origins/destinations are spread across the service area, high capacity vehicles are not efficient because their occupancy rate is low and have a high cost per seat.

To mitigate these problems, transportation systems that adapt to the observed demand were envisaged, using smaller vehicles, like mini buses or taxis, to be able to increase the frequency while assuring a high occupancy rate. These new transportation systems are usually called Demand Responsive Transportation (DRT) systems. Demand Responsive Transportation is an emerging term that covers services that are flexible in terms of route, vehicle allocation, vehicle operator, type of payment and passenger category. According to (Nelson 2004) the most important aspects for the definition of a DRT are the following:

- the service concepts – essentially route and time concepts;
- the booking concepts;
- the network concepts;
- the vehicle allocation concepts.

There are some classifications possible for categorizing DRTs. The classification offered by the INTERMODE Consortium (Enoch *et al.* 2004) proposes four function-based types, each of which is described by the nature of the DRT service it represents and the market it serves. (KFH Group 2008) established a simplified typology of DRT based on two criteria: the market served and the service area. (Potts *et al.* 2010) also follow a classification by service area: rural areas, small urban cities and urban and sub-urban areas. Besides categorization, in order to compare and improve upon the performance and cost-effectiveness of DRTs, standardized methods of measuring and assessing performance are needed.

In terms of financial sustainability and quality of service, the design of DRT services may be rather difficult. Until now, there has not been a strong commercial case for DRT services, that typically have a relatively low productivity and corresponding high per trip costs when compared to fixed-route services (KFH Group 2008). In (López 2010) the author observed that the main obstacles for the implementation DRT systems are from juridical, institutional and organizational nature. The technical difficulties are less complex to deal with than aforementioned obstacles, because these obstacles are more dependent on political agendas and stakeholders' attitudes, perceptions and (sometimes conflicting) objectives.

In this chapter, we have developed a framework to support the study of a given DRT service, focusing on the aspects that define its operation characteristics.

2.10 Chapter highlights

Demand Responsive Transportation (DRT) contextualization.

Presentation of main DRT systems concepts.

DRT systems classification and performance assessment.

Proposal of a framework for DRT systems operation analysis.

Survey of 25 European DRT services.

Chapter 3

SERVICE DESIGN

3.1 Introduction

In terms of implementation, a lot of questions remain as to how DRT services can be effectively developed and marketed and, until now, there has not been a strong commercial case for DRT. Service design is critical in the development of DRT services. The main objectives of this chapter are to propose a new approach to DRT service design based on a framework for a DRT service development process, to conceive a simulation model for DRT services and to identify DRT service design patterns.

It is important to match the service architecture and the number of vehicles, for instance, to the estimated demand structure, but, even with careful design, usually the planning of routes for DRTs vehicles cannot take into account all of the real-life aspects, such as travel time variability and user delays at stop, for example. It is important to have tools to empower service planners to test a proposed service design in estimated operational conditions. Such effects are often studied by simulation and will be detailed in section Simulation. A design pattern conveys the idea that the essence of what works well in one DRT service can be analyzed to provide general guidelines to be applied else-where. Design patterns promote high levels of re-utilizations, shortening learning and implementation times. Design patterns can be seen as re-usable micro-architectures.

3.2 DRT services development

Prior to undertaking the implementation of new DRT services, we need to analyze existing conditions, elicit comprehensive user requirements, determine a financial framework, plan and schedule services, select vehicles and technology and, finally, market and promote the new service (Brake *et al.* 2007).

3.2.1 ANALYZE EXISTING CONDITION

(Koffman *et al.* 2007) describes demand estimation strategies for DRTs targeting special groups. (Potts *et al.* 2010) describe strategies for DRT service design that are appropriate for rural areas, small cities, and specific applications in urban and sub-urban areas. Before implementing a new DRT service in any of these areas it is important to analyze the existing conditions.

Rural Areas

Definitions of "rural areas" vary significantly throughout Europe, and the criteria used for definition ranges from population to geographical position, from land-use to income (EC 1999). Nevertheless, "rurality" means a relatively low density of population and geographical isolation.

According to (Potts *et al.* 2010), for rural areas, operators should review and understand the following data when considering DRT services definition:

- population density;
- senior citizen density;
- youth density;
- low-income housing;
- senior citizen housing;
- trip destination locations;
- trip purpose.

Public transportation in rural areas usually serves the most "captive" populations - users that have restricted transport choices. Population densities are an important indicator to predict trip origins. If the operator is already providing public transportation in the area, then trip patterns should be analyzed to identify common destinations. The thresholds for the values of the different indicators should be analyzed in a per case basis. The next step would be to determine whether the origin is suitable to group trips in a scheduled DRT service zone route. Careful analysis of trip purposes is needed: if the trips are time sensitive, such as work or school commutes, DRT services may result in a loss of ridership (Potts *et al.* 2010).

Small Urban Areas

Small urban areas are probably the best candidates for the route deviation or point deviation DRT services (Potts *et al.* 2010) – see DRT systems concepts section in Chapter 2. In small urban areas, the following data should be reviewed and understood when considering DRT services implementation:

- existing routes productivities;

- population density;
- senior citizen density;
- youth density;
- income levels;
- trip purpose.

As an example, (Potts *et al.* 2010) suggests, based on the small urban areas analyzed, that if a fixed-route service operating in those areas has less than 16 passengers per hour, the substitution for a DRT service should be considered. A second factor to consider is the trip purpose of the current users: if passenger trips are mostly work or school commutes, there is less potential for a successful DRT service because work and school commuters typically want to minimize their travel time. In these cases, the operator could consider operating flexible services during off-peak periods. Population densities are also an important consideration because concentrations of captive users may impact the number of deviations and the scheduled trips time (Potts *et al.* 2010). Again, the thresholds for the values of the different indicators should be analyzed in a per case basis.

Medium and large urban areas

Due to the higher number of users and the high use of public transportation for work and school commutes in these areas (when compared to rural and small urban areas), a wide adoptation of DRT services is usually not advisable (Potts *et al.* 2010). According to these authors the most frequently reported applications for DRT services in urban areas are the following:

- suburban residential and mixed use, as feeder to other transit connections;
- replacement of an unsuccessful bus route;
- urban night service - as, for instance, the *Gato* night service in Porto (STCP-GATO 2011);
- residential communities constrained by geographic barriers - such as lakes or others;
- new suburban residential areas;
- areas never served by public transport.

Key data to examine when considering DRT services in urban areas are the following (Potts *et al.* 2010):

- population density;
- size of potential service area;
- travel time to connector;
- employment density;
- household density and auto ownership;
- senior citizen density;
- youth density;
- median income;
- productivity of existing routes.

The thresholds for the values of the different indicators should be analyzed in a per case basis.

As in small urban areas, if a fixed-route outside the core area has less than 16 passengers per hour, the substitution for a DRT service can be considered (Potts *et al.* 2010). Good candidates for DRT introduction are also areas with origins and destinations near a public transportation connection and that are not yet served by public transportation, as well as periods of the day when demand is low but public transportation is needed.

3.2.2 STAKEHOLDERS' REQUIREMENTS

Service design should be undertaken in collaboration with the main stakeholders, such as users, transport system operators, local authorities and dispatch center managers. Here the key issues include the need to elicit comprehensive user requirements and the identification of constraints involved in service planning.

The requirements of the DRT service to be developed must be clearly elicited, understood, analyzed and documented in a practical and systematic process where trade-offs have to be made to find the best solution, using a requirements engineering approach (Kotonya *et al.* 1998). Figure 15 shows the inputs and outputs of the requirements engineering process for DRT services.

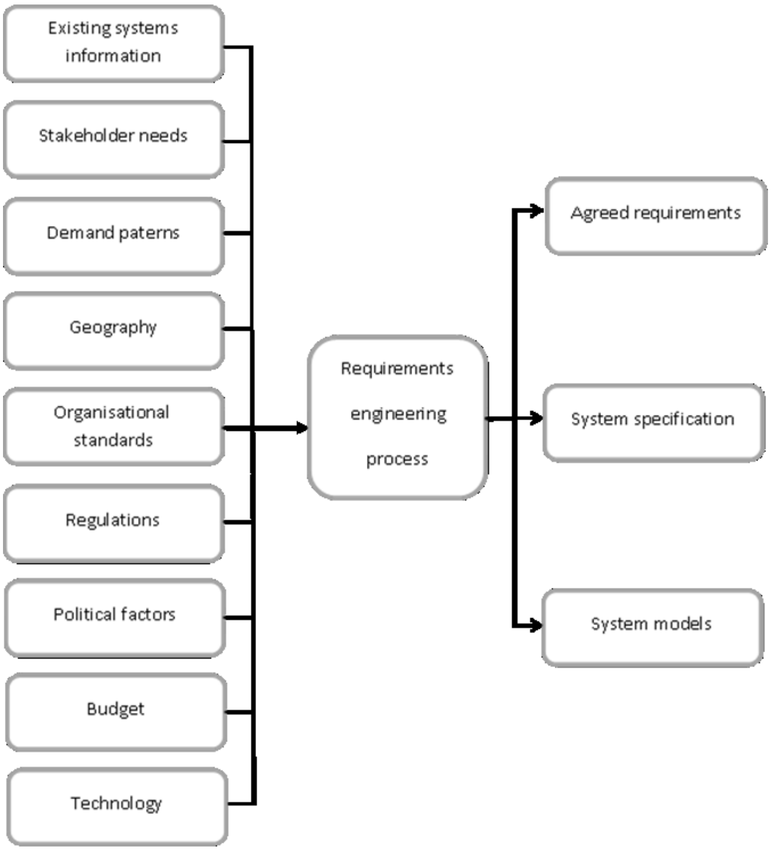


Figure 15 - Inputs and outputs of the requirements engineering process for DRT services (adapted from (Kotonya *et al.* 1998))

Typical activities in requirements engineering process include (Sommerville 1995):

- *requirements discovery*: interacting with stakeholders to discover their requirements; domain requirements are also discovered at this stage;
- *requirements classification and organization*: groups related requirements and organizes them into coherent clusters;
- *prioritization and negotiation*: prioritizing requirements and resolving requirements conflicts;
- *requirements documentation*: requirements are documented and input into the next round of the spiral process.

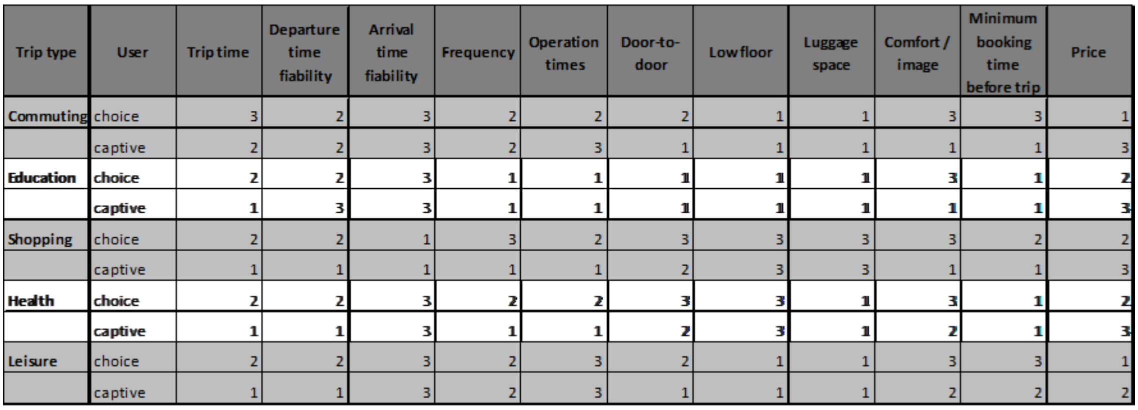
Requirements discovery

User requirements may be elicited by making site visits, one-to-one interviews, public meetings, website forums or by holding focus groups (Brake *et al.* 2007). The CIVITAS ELAN project "Mobilizing citizens for vital cities", funded by the European Commission within the CIVITAS Initiative from 2008-2012 (EuropeanUnion), took an approach where “Putting the citizen first” was at the core of the work. For the definition of a DRT service – *Gato* - in Porto, different techniques were used for requirements elicitation, such as online questionnaires, face-to-face surveys and user interviews (Marega *et al.* 2012).

Establishing the stakeholders’ requirements is one of the most important phases in DRT services development (Brake *et al.* 2007). Since a wide spectrum of different service designs are possible, they should reflect the outcome of a comprehensive requirements elicitation exercise. However, it is extremely difficult to conduct such process due to both the novelty of the concept and the nature of public transport itself. Nevertheless, obtaining potential users input on decisions such as the definition of appropriate routes, service levels, booking characteristics and the area to be served is of vital importance to service planners and local authorities. The community should be engaged early on in the planning process and stay engaged through implementation and operations.

Requirements classification and organization

In terms of user requirements, (Enoch *et al.* 2004) found that that there are key differences in the user requirements of the “choice” and “captive” markets and we need to have these differences in mind when designing a DRT service. Traditionally, DRT services have been driven by social inclusion objectives and the market has been the “captive” users. The following table adapted from (Enoch *et al.* 2004) shows important differences between the choice and captive markets, and also how these vary with trip type. In the table, “1” means “not important”, “2” means “quite important” and “3” “very important”.



Trip type	User	Trip time	Departure time fiability	Arrival time fiability	Frequency	Operation times	Door-to-door	Low floor	Luggage space	Comfort / image	Minimum booking time before trip	Price
Commuting	choice	3	2	3	2	2	2	1	1	3	3	1
	captive	2	2	3	2	3	1	1	1	1	1	3
Education	**choice**	**2**	**2**	**3**	**1**	**1**	**1**	**1**	**1**	**3**	**1**	**2**
	captive	**1**	**3**	**3**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**3**
Shopping	choice	2	2	1	3	2	3	3	3	3	2	2
	captive	1	1	1	1	1	2	3	3	1	1	3
Health	**choice**	**2**	**2**	**3**	**2**	**2**	**3**	**3**	**1**	**3**	**1**	**2**
	captive	**1**	**1**	**3**	**1**	**1**	**2**	**3**	**1**	**2**	**1**	**3**
Leisure	choice	2	2	3	2	3	2	1	1	3	3	1
	captive	1	1	3	2	3	1	1	1	2	2	2

Table 6 - Differences between choice and captive markets by trip type (adapted from ((Enoch *et al.* 2004))

Regarding this data:

- one factor that is rated highly across all trip types for both captive and choice users is certainty of arrival time (with the exception of shopping trip type) (Brake *et al.* 2007);

- trip time is a factor highly rated by choice users, especially for commuting;

- low floor, easy access buses is a very important factor for shopping and health trips, but not important for others (Brake *et al.* 2007);

- times of operation appear to be of importance for commuter and leisure trips, with choice commuters scoring higher (Brake *et al.* 2007);

- door-to-door service is valued mainly for shopping and health; women also value more door-to-door service than men because of the perception of security (Brake *et al.* 2007);

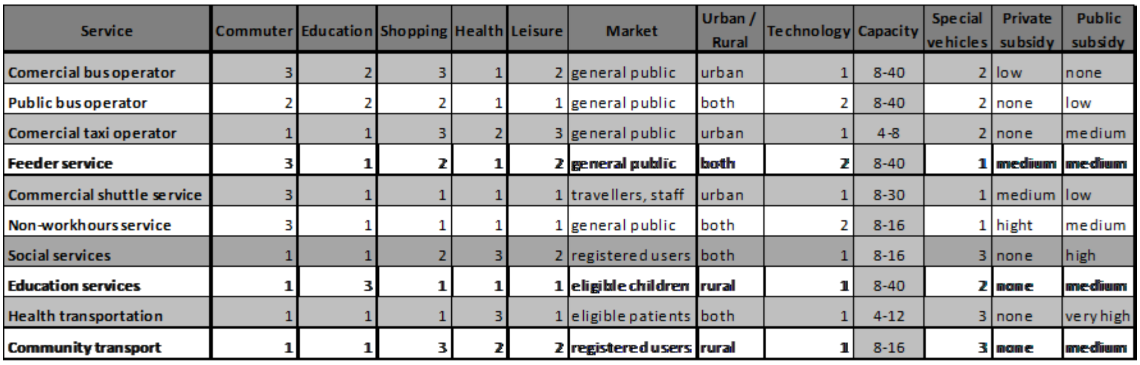
- regarding the price, there is a major contrast between choice and captive users; price is a very important issue for captive users, but less so for choice users;

- comfort and image is far more important for choice users than for captive users (although comfort scores higher for health trips and leisure trips for the latter) (Brake *et al.* 2007);

- it is also possible to observe that minimum booking time before trip scores higher for choice users for commuting and leisure, mainly, and also for shopping.

A DRT service designed mainly for shopping, health and leisure trips by captive users should combine a different set of attributes than one aimed at car commuters: "Captive users value bus-like attributes. Choice users value taxi type attributes" (Brake *et al.* 2007).

Having looked at user requirements, (Enoch *et al.* 2004) also compared them to the needs and preferences of around 40 operators. Table 7 categorizes key operational aspects by the type of DRT operator/DRT service.



Service	Commuter	Education	Shopping	Health	Leisure	Market	Urban / Rural	Technology	Capacity	Special vehicles	Private subsidy	Public subsidy
Comercial bus operator	3	2	3	1	2	general public	urban	1	8-40	2	low	none
Public bus operator	2	2	2	1	1	general public	both	2	8-40	2	none	low
Comercial taxi operator	1	1	3	2	3	general public	urban	1	4-8	2	none	medium
Feeder service	**3**	**1**	**2**	**1**	**2**	**general public**	**both**	**2**	8-40	**1**	**medium**	**medium**
Commercial shuttle service	3	1	1	1	1	travellers, staff	urban	1	8-30	1	medium	low
Non-workhours service	3	1	1	1	1	general public	both	2	8-16	1	hight	medium
Social services	1	1	2	3	2	registered users	both	1	8-16	3	none	high
Education services	**1**	**3**	**1**	**1**	**1**	**eligible children**	**rural**	**1**	8-40	**2**	**none**	**medium**
Health transportation	1	1	1	3	1	eligible patients	both	1	4-12	3	none	very high
Community transport	**1**	**1**	**3**	**2**	**2**	**registered users**	**rural**	**1**	8-16	**3**	**none**	**medium**

Table 7 - Key operational aspects by type of DRT operator/DRT service (adapted from (Enoch *et al.* 2004))

As before, “1” means “not important”, “2” means “quite important” and “3” “very important”. The first five columns are the markets served. One thing that becomes clear from the analysis is that the sectors in which DRTs have focused are different from sectors conventional bus services have focused. In fact, more recent DRTs are seeking to be general public transport, whereas the established DRT operations, at the bottom of the table, serve a restricted market.

3.2.3 FINANCIAL CONSIDERATIONS

(Brake *et al.* 2007) identify three general market niches where DRT could be efficient:

- low-tech, low-quality, small-scale simple DRT services can be implement in areas where captive users are satisfied by any form of public transport but are only able to pay low fares;
- there are niches where DRT operators can target choice users who appreciate luxury and are prepared to pay a premium for a service that is far away from a bus, with small-scale, simple to operate systems (e.g., employer shuttles, airport shuttles);
- large-scale, complex network DRT systems require high-tech equipment if they are to operate efficiently; as a result they will be relatively expensive to operate; however, providing that savings can be made (usually by substituting them for even more expensive specialist transport trips), these services may be cost effective.

Table 8, with information adapted from (Enoch *et al.* 2004), shows the three market niches identified by (Brake *et al.* 2007) where DRT could be efficient.

Market	**Operation**	**Users**	**Public policy drivers**	**Comercial drivers**	**Finance**
low-tech,low-quality,small-scale	simple route structure; simple to understand; low cost	captive users	social inclusion; low cost provision	niche services	low cost; low fares
luxury niches	simple route structure; simple to understand; low cost	choice users		niche services (e.g.: airport and employer shuttles)	low cost; premium fares
large-scale, complex network	large scale; complex networks; high cost	choice user; captive users	substitute specialized transpots		hight cost; medium fares

Table 8 - Three market niches where DRT could be efficient (adapted from (Enoch *et al.* 2004))

It seems clear that the combination of low quality of service and high technology use in DRTs should be avoided. High use of technology has cost implications (Khan 2009) that cannot be covered by a low quality service that will be used only by captive users (i.e., choice users typically want higher quality services) that are unable to pay the higher fares needed to cover service costs.

Budget constraints must obviously be taken into account when designing the service. For many DRT schemes, the continuous need for subsidy relies upon the idea that, on a per trip basis, DRT is still often cheaper for public authorities than running a set of parallel services for health, education, or social service transport. Practical aspects of service design include using vehicles with education/social services during one part of the day and general public during another. This multi-tasking vehicle, although strategically advisable in terms of better use of vehicles, it is not necessarily the best solution for the general public (Brake *et al.* 2007).

When introducing a DRT service, it is important to be able to anticipate its expected financial performance. (Enoch *et al.* 2004) classifies the DRTs financial performance according to four groups:

- commercially viable DRT: services that are either profitable, or operate within a commercial balance;
- acceptable subsidy DRT: services that require only the same (or less) subsidy than other comparable services;
- justifiable higher subsidy DRT: services for which a subsidy above that provided to tendered services can be justified; this may be due to the operational area (e.g. deep rural areas) or other factors;
- financially unsustainable DRT.

During its lifetime, a DRT service can move from one group to another – ideally upwards. An economically viable service is often regarded as one where costs and revenues are at least even. Unless this is the case, a service will require subsidy. Experience with DRTs suggests that services are not sustainable without direct subsidy. (Palmer *et al.* 2004) found that the use of financial incentives could have a detrimental impact on operating cost: many operators use of financial incentives was linked only to "on–time pickup" performance - contractors can dispatch vehicles in a relatively unproductive way in order to satisfy the "on–time" performance criteria established in their contracts. When a negative gap between revenues and costs persists during the lifetime of the service, there should be an analysis whether costs can be reduced or revenues can be increased (Brake *et al.* 2007).

Costs

Cost analyses for conventional buses are usually described by average operational cost. (Button 1992) defined an operational cost model described by vehicle-kilometers, vehicle hours and peak vehicle needs. DRT services, however, require additional communications and scheduling technology that may exceed the technology needs of fixed-route public transportation. Due to its flexibility, as the final route is selected much closer to the time of travel than with fixed routes, the implementation of a DRT service requires a route scheduling and dispatching system and staff at a Travel Dispatch Centre (TDC) for order management, route planning, vehicle assignment, trip time estimate, scheduling and service planning and service monitoring, and these costs must be accounted for when designing the service. The selected level of technology must be appropriate to the objectives and long-term strategy for the DRT services and it will constrain the parameters of operation, with strong cost implications.

The development of real-time booking, scheduling and dispatching technologies made it possible to design DRT services that can handle large numbers of users and vehicles and handle same-day requests for travel (Nelson *et al.* 2010). Manual dispatching is not appropriate in a large numbers of trips scenario. For instance, (Takeuchi 2010) found that computer automated dispatching is more cost effective than manual dispatching if the number of users is over 150 per day. The customer devices available to support interactive automated trip booking and service information are telephone, automated voice responding devices (Interactive Voice Response Systems), web-based services and smartphone applications. The decision can also be separated into whether the dispatching service should be in-house or sub-contracted and similarly with the vehicles operations.

We might finally say that all costs incurred through the addition of the DRT service to the public transport offer, and also those that will not be incurred if the service is not run (known as avoidable costs), are relevant to the decision-making process. These include (Brake *et al.* 2007): administrative costs, capital costs (office equipment, computers, software) and operating costs.

Revenue

Costs are one important economic factor to understand if a given DRT has the potential to be commercially viable or to operate with an acceptable subsidy level. The other key factor is, of course, revenue. This relates to the market position of DRT services. (Enoch *et al.* 2004) note that many of the commercially viable or low-subsidy DRT are premium products. They seek to deliver a near-taxi level of service for fares that are closer to taxi fares than to bus fares – such as up market niches as air travelers, even using regular sized buses. These are not the markets that public policy DRT schemes have so far sought to address. Instead, as already noted, they have aimed at a totally different market position that reflects a social inclusion agenda. But, because these users are also the most price sensitive, there is little potential of such services achieving an acceptable level of subsidy (i.e., comparable to the bus). And even worse, the type of DRT being used is often the most complex and high-tech (and with very high costs), with new buses, call center and route planning software. In order to become commercially viable, or, at least, be able to provide services at an acceptable level of subsidy, serving appropriate markets combined with proper fare pricing is essential.

Fare setting is often constrained by the need to make a certain level of revenue (Brake *et al.* 2007). DRT fares are usually set in a distance-based way, either as a fixed kilometer rate or, more usually, as a zonal system (Brake *et al.* 2006). However, some current DRT services use a flat fare and this is likely to work well when the service area is relatively small. But DRT services where users are offered a door-to-door service should pay a higher fare. Where implemented, a premium charge needs careful explanation to the users as they perceive DRT services as public transport where "normal" fares should prevail. At the planning stage, a useful rule of thumb for identifying whether fares are too high or too low is to look at avoidable costs divided by the average fare (Brake *et al.* 2006). This roughly estimates the target number of passengers that will be required to cover avoidable costs and this can be compared with the predicted patronage for the service. In North America, according to (Potts *et al.* 2010), 70% of the operators charge the same fare for the DRT service as for the fixed-route service. Around 60% of the operators that charge a different fare for DRT charge a higher fare for DRT service than normal fixed service. In Europe, the survey from Chapter 2 showed that 45% of the services have a fare equal to the regular public transportation service, 40% have higher fares than the regular public transportation service, and 15% are free.

Fare collection devices allow the automated management of payment operations and additional functions such as customer validation or passenger counting. With the recent developments in electronic cards, options of how passengers pay for public transport have increased, and this may have a significant on DRT operations and efficiency. It would also be interesting to encourage passengers to book ahead by offering financial incentives – a method used very successfully by the low cost airlines.

3.2.4 OPERATIONAL CHARACTERISTICS

The DRT-specific operational characteristics include: type and size of DRT vehicle; route flexibility; timetable flexibility; level of technology; mode of booking; and call center technology (Enoch *et al.* 2004). Theoretically, it should be possible to design a DRT service from any combination of the mentioned operational characteristics, however, there are a number of regulatory and financial issues, as well as target user requirements that constrain the spectrum of possible designs. For instance, if the vehicles are to be used for users with mobility impairments, they need to comply with certain requirements such as space for wheelchairs or low floor access.

Choice of vehicles

A number of considerations affect the choice of vehicles, including the following:

- demand level;
- users characteristics;
- width of road lanes;
- route or zone distances;
- costs;
- government regulations.

Vehicle size should theoretically be based on the predicted level of demand. In (Häll 2011), simulation tests showed that vehicles with a capacity of 7 seats were enough, but also showed that when the acceptable journey time was increased, there were positive effects using vehicles with a capacity of 14 seats, allowing for the combination of more requests, although most of the time these vehicles had low occupation rates (see section 3.3). But there is also a number of other factors involved. First, there are regulations to take into account at the licensing process concerning the operators, vehicles, drivers and routes. Second, there are mandatory requirements if the vehicles are to be used for users with mobility impairments, such as space for wheelchairs or low floor access. Third, particularly for general public DRT services, image and comfort are crucial.

In (Potts *et al.* 2010) nearly half of the North American operators (46%) use small buses, while 28% use vans to operate the service. Our survey (see Chapter 2) shows that in Europe around 20% of the surveyed DRT services had a heterogeneous fleet (the services with homogeneous fleet use mini buses). The most commonly used vehicles are adapted mini buses (50% of the services). Regular mini buses are used by 39% of the services, taxis (eventually shared) are used by 26% of the services, and adapted vans by 10%.

Route flexibility

The degree of route flexibility is affected by the demand and by its distribution. Fully flexible routes can be inefficient because of the 'first-come first-served' nature and service designs where a zone system can be introduced with deviations can be more efficient (Enoch *et al.* 2004). Reducing the flexibility also has the effect of making it easier for passengers to understand the operation of the service.

According to our DRT survey (Chapter 2), most studied services operate using a door-to-door scenario, followed by predefined stops in an area or corridor. In North America, according to (Potts *et al.* 2010), route deviation is by far the most common form of demand responsive transportation service, followed by request stops (vehicles operating in conventional fixed-route, fixed-schedule mode and also serving a limited number of undefined stops along the route in response to passenger requests).

Timetable flexibility

Another design characteristic that can be used to achieve flexibility is the service scheduling. Services that only run on demand range from extremely high frequency operations to very low demand scenarios.

(Potts *et al.* 2010) point out that:

- from the operators who do route deviation, 44% schedule routes with a limited number of short deviations to known locations, and 45% schedule routes with additional time for deviations throughout the route for unspecified locations;
- operators who use more flexible services, such as point deviation or zone routes, said the service was scheduled with few time points, with most time available for deviations (64%,) or with time for deviations to unspecified locations but only within some portions of the route (28%).

Access to infrastructure

Since a wide spectrum of different service designs are possible, different DRT schemes have different infrastructure requirements, but most need a terminus area at the beginning and for the end of the routes, and a Travel Dispatch Center (TDC). There may also be a need for other fixed stopping points along routes (regular bus stops or meeting points).

Level of technology

The first DRT experiments in Europe date back to the 1980's decade, with elderly and disabled groups of users in northern Europe countries. But the experience showed that services were not cost effective given the technologies available. Recent years, however, provided the necessary frog leap in the technology (and reduction in its costs) necessary for DRT services recapture academic as well as industry focus, thus returning to their "smart" nature.

Operators of traditional systems typically employ technology to achieve a higher level of passenger service, reduce service operating costs, manage fleets, and improve service reliability. In the case of DRT services, the same holds true, but they use technology predominantly for communications and scheduling. However, technologies are still relatively expensive to introduce, and there are still occasional problems installing and using the equipment. (Potts *et al.* 2010) refer to voice radio as the most frequently used technology for DRT services in North America. In the same study, voice radio was followed by cell phones and computerized scheduling systems. Only 18 percent used automated vehicle locators (AVL) or global positioning systems (GPS), and even less (8%) indicated that they used the Internet for DRT services.

There is no doubt that the use of technology can greatly affect the reliability and quality of DRT services, and with a well-coordinated reservation/scheduling/dispatch process and a good communications system, operators can better control the increasing costs of providing DRT services (Goodwill *et al.* 2008). However costs, staffing, as with the training of drivers and the dispatch center staff, are issues that must be considered.

A key decision for DRT operators is to make the right choice between levels of technology that are available and appropriate for the scale and complexity of the service. An efficiency evaluation methodology for the technology related investments, focusing on public transportation systems, has been proposed in (Khan 2009). For instance, for a many-to-one operation (many possible origins but a single destination, such as an health care center) with few vehicles, a complex routing software is probably not required (Enoch *et al.* 2004), but this will not be the case for many-to-many services (many possible origins and many possible destinations) involving different types of users, it may be required. On the other hand, we should have in mind that manually assigning vehicles to even a simple network is a job requiring specialized staff with scheduling knowledge.

The FAMS 5 layer model (EC 2002) (see Chapter 2 for more details) shows how DRT services can be provided and how they could be designed, taking into account the level of technology supplied, starting with the basic layer having a single TDC scheduling and dispatching service for one operator. Technology also allows operators to monitor and analyze service patterns, potentially allowing the system to evolve more effectively.

Mode of booking

As already mentioned in Chapter 2, there are several modes of DRT booking, including boarding at the terminus, “hail-and-ride” along the route (by hand or sometimes by pressing a button at a stop), via the Internet, by telephone, automated Interactive Voice Response Systems (IVR) and magnetic cards.

The booking system needs to be as intuitive as possible. The key variables in choosing the mode of booking are the set-up cost, the running cost, flexibility, notice of the proposed trip, and the user's preference for minimal booking overhead time. Until recently, technological limitations meant that in most cases trips would have to be booked at least a day in advance. Booking modes where call center staff answer telephones and manually assign the customer to a vehicle are cheap to set up but expensive to run and not very flexible (Enoch *et al.* 2004). On the other hand, fully automated systems are expensive to set up, but less costly to operate, and may be justified for larger/more complex DRT services. One may, for instance, adopt a scalable approach: start with a simple, low-tech booking mode and then automate as demand for the DRT service increases. The main tension here is between the operator's ideal to have notice of the proposed trip request much in advance, and the user's convenience in having a minimal booking overhead time. According to the DRT survey presented in Chapter 2, 40% of the analyzed services required the booking to be made in the previous day, 10% required the booking to be made 2 hours before the trip, 25% required the booking to be made 1 hour before the trip, and, finally, 25% allowed the user to book the trip less than 1 hour before the required pickup time – the shortest time limit allowed found was 15 minutes.

The telephone is still the most common approach, but there is the cost of the call involved. In the future, Internet technology seems promising: it has the advantage of possibly offering automated (cheaper) booking, and is already widely encouraged by low cost airlines so the user's mental model is already in place. Smartphones add the possibility of graphical feedback and more features such as map and route visualization and also seems a promising technology, given the recent proliferation.

Promotion and image

Public transport services must be promoted by the most appropriate means. Effective marketing is about giving comfort and dissipating the doubts and fears that a new customer may have (Brake *et al.* 2007). Promotion is a continuous activity – from the beginning of the development to the post-service installation.

The success of a new transportation initiative clearly requires potential users to be aware of it. In the case of DRT services, this awareness is even more critical, as they require an understanding of how their operational principles differ from conventional bus services, with many schemes requiring pre-booking and/or having flexible route and/or flexible timetables. Furthermore, where services perform a range of different functions (serving rail stations or school, shoppers and social transportation for example), perhaps in different areas on different days or at different times of the day, then it is understandable that potential users may be confused. Simplifying the service, for example, makes it easier to understand, and passenger information becomes less complicated. Good information cannot, of course, compensate for bad network design. Networks need to be understandable, with simple routes, simple timetables, and simple fares. They should also be consistent.

(Brake *et al.* 2007) identified a number of critical marketing factors such as the visibility of the DRT services themselves and the promotion options available to service operators and to users. Paradoxally, the more flexible the service becomes, the less visible it is to the end user. For example, a sign placed on a bus stop where a DRT service does not necessarily stop, can give regular public transport users wrong assumptions about the service. The more clearly branded the vehicle is, the more quickly it becomes recognized by the general public. Finally, the importance of word-of-mouth from satisfied users should not be underestimated. Figure 16, from FLIPPER project (FLIPPER 2008), shows a branded vehicle from the *Flexibus* service (Almada, Portugal). FLIPPER (Flexible

Transport Services and ICT platform for Eco-Mobility in urban and rural European areas) was an initiative funded via the EU INTERREG IVC program, focusing on capturing best practices for a wide range of flexible transport options that are better tailored towards the needs of individual communities in cities, small towns and rural areas.

Figure 16 - Branded vehicle from the *Flexibus* service (source: (FLIPPER 2008))

A DRT service needs to get away from having a bus type image. The interior design of vehicles should be spacious, comfortable, clean, well heated and ventilated and easily accessible. But off-vehicle comfort is also an issue, although it could be argued that waiting at home is far more pleasant for the user than waiting at a bus stop. However, this may be the case for door-to-door services, but not all DRT schemes offer such service. Some have local "pickup" or "meeting points". Therefore waiting places should offer a shelter, a seat, or at least the reassurance of a clearly marked pole sign to provide a feeling of some certainty that the bus is supposed to arrive.

(Potts *et al.* 2010) present a list of the most common methods for promoting DRT services among 195 North-American operators. Each operator used several methods, but the most common were community presentations and operator website promotion, followed by system maps and brochures and, to a less extent, paid ads, bus ads and mailings.

Figure 17 shows a brochure used in the *Gato* night time service provided by STCP operator in the city of Porto, Portugal ("Gato" means "cat" in Portuguese).

STCP

Gato QUERO FESTAS

ÀS QUINTAS, SEXTAS E SÁBADOS!

RESERVA A TUA VIAGEM

PARTIDAS DE HORA A HORA
ENTRE AS 0H30 E AS 5H00

ENTRE O PÓLO UNIVERSITÁRIO
DA ASPRELA E O CARMO

ATÉ DIA 8 DE JANEIRO DE 2012, A SUPER BOCK
OFERECE-TE AS VIAGENS.

AGORA PODES IR CURTIR A NOITE
COM OS AMIGOS SEM PREOCUPAÇÕES

SABE TUDO E RESERVA A TUA VIAGEM EM GATO.STCP.PT

PATROCINADOR OFICIAL

Com apoio da União Europeia

Parceiros

Gato.
A noite é tua.

Figure 17 - Brochure from *Gato* service (source: (STCP-GATO 2011))

STCP presented *Gato* as an urban night flexible service (STCP-GATO 2011). The service was operated in experimental regime in the framework of the CIVITAS-ELAN project (EuropeanUnion).

The *Gato* brochure clearly states the type of users the service wants to capture ("festas" in Portuguese means both "party" and "caress"), the operating period of the service, the service area, the frequency, the booking method and the web URL for more information. The "cat" picture also suggests the user that this is a night service with a "mysterious" (no completely defined) path.

3.2.5 DRT DEVELOPMENT PROCESS FRAMEWORK

A systems development process framework provides a sequence of activities for system designers to follow, such as planning, analysis, design, and implementation.

A systems development process tries to attain four objectives, according to (Booch 1994):

- provide orientation about the sequence of realization of the activities involved;
- specify the descriptive models of the system to be developed;
- manage intervenients' tasks as a whole;
- provide monitorization and evaluation criteria for the models and activities of the project.

The activities that form the engineering process can vary depending on the organization and the type of system being developed, but typically include:

- *Initiation*: identification of opportunity and concept proposal;

- *Planning*: define project management plan, analysis of resources needed;
- *Specification*: stakeholder needs elicitation and analysis, non-functional requirements analysis, constraints on the system;
- *Design*: how to deliver required functionality, produce a model of the system;
- *Implementation*: convert the design concepts into products, creating system operation environment, testing, refining, operation and testing documentation;
- *Test and Validation*: check if the system meets the required specifications, resolution of problems;
- *Installation*: introduce the system in its operational environment;
- *Maintenance and Evolution*: training and support, post-installation and in-production reviews and evaluation, description of operation and maintenance tasks.

Not every project will require these phases to be executed sequentially. However, the phases are usually interdependent.

The process should have a number of characteristics such as:

- *Understandability*: is the process clear?
- *Acceptability*: is the process accepted by all stakeholders?
- *Robustness*: is the process robust?
- *Maintainability*: can the process evolve to meet changing needs?
- *Rapidity*: how fast can a system be produced?

As already mentioned, for the implementation of new DRT services it is necessary to analyze existing conditions, elicit comprehensive user requirements, determine a financial framework, plan and schedule services, select vehicles and technology and, finally, market and promote the new service (Brake *et al.* 2007). These activities should be framed in a systems development process framework. As establishing the stakeholders' requirements is one of the most important phases in DRT services development (Brake *et al.* 2007), a DRT systems development framework must have the stakeholder needs and risk management concerns at its core, in a simulation driven approach - because it is not only important to be able to solve the underlying model in an efficient way, but also understand how different ways of operating the service affect customers and operators. Developing DRT services is a user centered activity, much like developing a complex software system: this means a shift from perceiving users as a "problem", towards their inclusion as the most important and constructive part of the solution.

One appropriate DRT systems development framework is the WinWin Spiral Model (Boehm *et al.* 1994). A DRT system, due to its user-centric nature, can be seen as a Product-Service System (PSS). The concept of PSS is a systemic approach for enabling a transition from selling physical goods to providing product–service solutions that fulfill customer-specific and changeable needs. Car-sharing, for instance, is a typical use-oriented PSS (Yang *et al.* 2009). (Pezzotta *et al.* 2012) tries to understand the main characteristics, the structure and the sequence of phases characterizing a PSS engineering process model. From the analysis of several case studies and their comparison with engineering reference process models available in literature, (Pezzotta *et al.* 2012) also points that the most appropriate approach seems to be the Spiral Model: it gives relevance elements which result fundamental in a PSS context, such as the Customer Communication and Evaluation and the structure of the engineering and iteration processes. (Pezzotta *et al.* 2012) presents a possible PSS engineering Spiral Model adapted by the WinWin Spiral Model that takes into account the relevance of the iteration process and of the customer involvement with a comprehensive lifecycle perspective. To the best of our knowledge, the Spiral Model, and particularly, the WinWin Spiral Model, was never used, not even proposed, for DRT services development.

WinWin Spiral Model for DRT services

The Spiral Model (Boehm 1986) was originally conceived as a software development process combining elements of both design and prototyping in which, as the name suggests, the activities can be organized like a spiral. The iterations along the spiral can be seen as evolutionary levels that develop increasingly detailed elaboration's of a system's definition, culminating in incremental releases of the system's operational capability, using prototyping and/or simulation as a risk reduction mechanism – the spiral model introduces risk management at regular stages in the development cycle. This risk driven nature of the Spiral Model allows it to accommodate any mixture of specification-oriented, prototype-oriented, simulation-oriented or some other approach. An important feature of the model is that each cycle of the spiral is completed by a review, which covers all the products developed during that cycle, including plans for the next cycle. There are no fixed phases such as specification or design - loops in the spiral are chosen depending on what is required (Boehm 1988).

The structure of the Spiral Model is shown in the Figure 18, from (Boehm 1986).

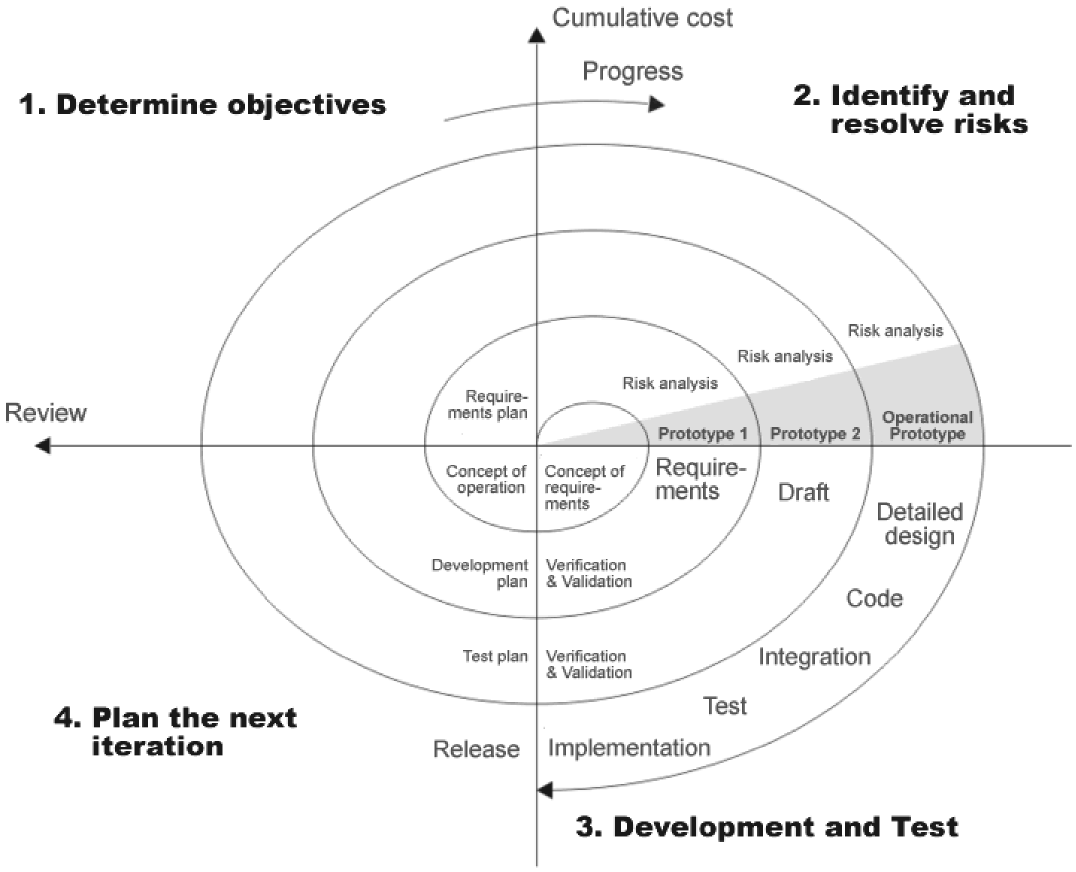


Figure 18 - Structure of the Spiral Model (source: (Boehm 1986))

In the spiral model, the radial dimension represents the cumulative cost in accomplishing the steps done so far and the angular dimension represents the progress made in completing each cycle of the spiral. Each cycle involves four main activities (Sommerville 1995):

- *Objective setting*: elaborate the system or subsystem's product objectives, constraints, and alternatives;
- *Risk assessment and reduction*: evaluate the alternatives with respect to the objectives and constraints; identify and resolve major sources of product and process risk;
- *Development and validation*: an appropriate model is chosen for the next phase of development; develop and verify next-level product and process;
- *Planning*: the project is reviewed; plan the next cycle, and update the life-cycle plan, including partition of the system into subsystems to be addressed in parallel cycles; this may include a plan to terminate the project if it is too risky or infeasible.

Each cycle in the spiral begins with the identification of objectives for that cycle and the different alternatives for achieving the objectives complying with the constraints. The next step in the spiral life cycle model is to evaluate these different alternatives identifying uncertainties and risks involved. Then, strategies are developed to resolve the uncertainties and risks. This step may involve activities such as benchmarking, simulation and prototyping. Next, the product is developed by keeping in mind the risks. Finally the next cycle is planned. It may be an evolutionary approach that involves developing a more detailed prototype for resolving the risks. Or, if the product development risks dominate and previous prototypes have resolved all the user-interface and performance risks, the next step can follow a basic waterfall approach (Jalote 2005), for instance. In fact, the spiral model can be considered as a meta-model because it can be composed of several other models.

However, the spiral model does have its disadvantages too. To follow the spiral model, highly skilled people in the area of planning, risk analysis and mitigation and development are needed. And, as the process needs to be iterated more than once, it requires more time and may involve high costs. But one of the major difficulties in using the spiral model is to determine where the objectives, constraints, and alternatives come from, i.e., it is much more "risk driven" than actually "user driven". The WinWin Spiral Model (Boehm *et al.* 1994) tries to solve this issue. The WinWin Spiral Model uses Theory W to develop system requirements and architectural solutions as win conditions negotiated among the several project's stakeholders (Boehm *et al.* 1998) making it quite suitable to develop DRT services.

The *Theory W* is a management theory and approach which states that making winners of the system's key stakeholders is a necessary and sufficient condition for project success. The WinWin Spiral Model extends the Spiral Model by adding three Theory W activities to the front of each cycle (Boehm *et al.* 1994):

- identify the system or subsystem's key stakeholders;
- identify the stakeholders' win conditions for the system or subsystem;
- negotiate win-win reconciliations of the stakeholders' win conditions.

Figure 19, from (Boehm *et al.* 1998), shows the WinWin Spiral Model.

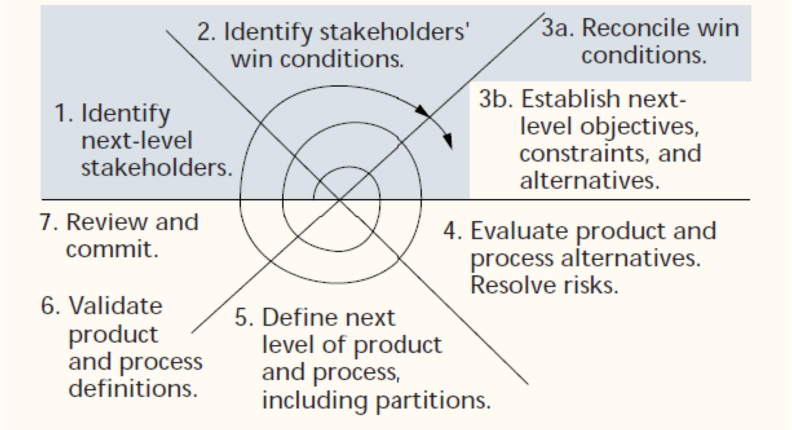


Figure 19 - WinWin Spiral Model (source: (Boehm *et al.* 1998))

Another weakness of the Spiral Model addressed by the WinWin Spiral Model is the lack of milestones. The WinWin Spiral Model has a set of three process milestones, or ”anchor points”, that help establish the completion of one cycle around the spiral and provide decision milestones before the project proceeds:

- *Life Cycle Objective* (LCO) - what should the system accomplish;
- *Life Cycle Architecture* (LCA) - what is the structure of the system;
- *Initial Operational Capability* (IOC) - the first product version.

In essence, this decision milestones represent three different views of progress as the project traverses the spiral (Boehm *et al.* 1998). The LCO focuses on establishing a business case for the system. The LCA commits to a single choice of architecture and elaborates it to the point of covering all major sources of risk in the system's life cycle. The LCA is the most critical milestone in the system's life cycle (Boehm *et al.* 1998). Finally, the IOC anchor point has three key elements:

- system preparation, including both operational and support systems (software and others) with appropriate documentation, the necessary licenses and rights for operation and appropriate operational readiness testing;
- site preparation, including facilities, equipment, supplies, and commercial arrangements;
- user, operator, and maintainer preparation, including selection, team building, and training for familiarization use, operations, or maintenance.

The WinWin Spiral Model has been used with success in several areas, including not only complex software systems development (Boehm *et al.* 1998) but even in Software

Engineering education curricula definition (Boehm *et al.* 1999) and, more recently, Product-Service Systems (PSS) (Pezzotta *et al.* 2012).

One possible way of using the WinWin Spiral Model to develop DRT services involves 4 cycles through the spiral, as in (Boehm *et al.* 1998):

- *Cycle 0*: the objective of this initial cycle is to determine the feasibility of a DRT service;
- *Cycle 1*: develop life-cycle objectives (LCO milestone), prototypes, plans, and specifications for the DRT service and verify the existence of at least one feasible architecture for it;
- *Cycle 2*: establish a specific, detailed architecture (LCA milestone), verify its feasibility and determine that there are no major risks in satisfying the plans and specifications;
- *Cycle 3*: the objective here is to achieve a workable initial operational capability (IOC milestone) for the DRT service.

Cycle 0

After the identification of an opportunity, cycle 0 starts by analyzing the existing conditions and making a comprehensive user requirements elicitation to clearly identify the different stakeholders win conditions for this cycle. An example of win conditions for the potential travelers could be to have some sort of transportation, low fares and short walking distance to meeting points/stops. For the operators, win conditions could be, for example, to use few vehicles, have short travel distances and increase levels of ridership. For the travel dispatch center manager, a win condition could be to have a new and efficient routing software and/or not to have to hire new staff. For the tendering authorities, a win condition could be to increase social inclusion levels. After identifying the win conditions, follows the negotiation of win-win reconciliations of the stakeholders' win conditions and constraints to the service. Then a financial framework should be identified, along with the main sources of risk and corresponding reduction strategies. A concept of the envisaged service should be put forward.

Cycle 1

Having gone through cycle 0, the main objective of cycle 1 is the LCO milestone – what should the DRT service accomplish. The cycle starts with a new round of requirements elicitation and win conditions establishment with the same stakeholders (to cope with the service alternatives identified in the previous cycle and/or new stakeholders for this cycle). The contents of this milestone are the following:

- definition of operational concept: top-level system objectives and scope; operations and maintenance scenarios; organizational life-cycle responsibilities (stakeholders);
- definition of system requirements;
- definition of system and architecture: top-level definition of at least one feasible architecture;
- system prototype(s) - exercise key usage scenarios; resolve critical risks.

The feasible service alternatives for next level cycle and risk reduction strategies should be tested using simulation.

Cycle 2

In Cycle 2, a specific architecture is chosen and the content of LCO artifacts is elaborated to the level of detail required for the LCA milestone:

- elaboration of system objectives and scope by increment;
- choice of final architecture and its elaboration by increment;
- elaboration of operational concept:
- choice of vehicles;
- route flexibility;
- timetable flexibility;
- access to infrastructure;
- level of technology;
- mode of booking;
- financial framework definition;
- plan and schedule service.

The chosen service architecture comprised by the above mentioned elements, the identified risk and their reduction strategies should be thoughtfully tested using simulation and open issues should be solved before moving to the next cycle.

Cycle 3

Cycle 3 represents the first production-ready version of the DRT service. If necessary, this cycle can begin with the identification of the stakeholder win conditions in terms of production-ready version of the service and its operational environment. The key elements of this cycle are:

- system preparation, including both operational and support systems (software and others); the necessary licenses and rights for operation and appropriate operational readiness testing;
- site preparation, including facilities, route stops, equipment, vehicles and commercial arrangements;
- user, operator, and maintainer preparation, including selection, team building and training for familiarization use, operations or maintenance;
- marketing and promotion of the new service.

Figure 20 sums up the described WinWin Spiral Model to develop DRT services.

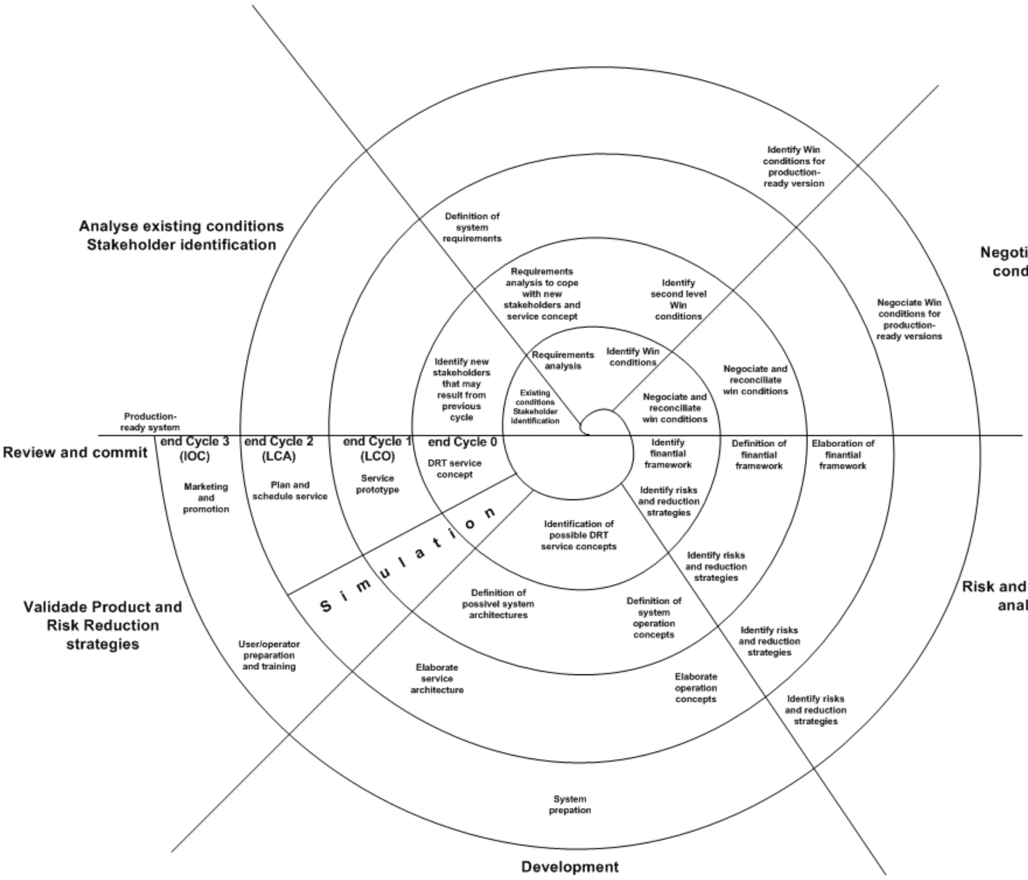


Figure 20 - WinWin Spiral Model to develop DRT services

3.3 Simulation

The flexibility of DRT systems can cause a set of organizational challenges:

- the number and type of users' requests can require an exceedingly high number of vehicles;
- very sparse requests can be hard to combine efficiently, forcing vehicles to complete extremely long trips or to carry only a few passengers, affecting the service cost-efficiency;
- the quality of the service in terms of delivery/pickup time and travel duration might not be guaranteed with the available resources or because random unpredictable events occur.

When designing a DRT service, it is not only important to be able to solve the underlying model in an efficient way, but also to understand how different ways of operating the service affect customers and operators. Usually, the planning of journeys for DRT vehicles cannot take into account all real-life aspects, such as travel time variability and user delays at stop, for example. Such effects are often studied by simulation. The purpose of simulation is to obtain a better understanding of the behavior of a system under a given set of conditions, even with uncertain events. Performance of the system can be determined by observing what happens on the network, during simulation, with different conditions.

(Altiok *et al.* 2007) considers modeling in general, and simulation modeling in particular, a complex activity that combines art and science. (Chung 2003) defines simulation modeling as “the process of creating and experimenting with a computerized mathematical model of a physical system”.

Models can be physical (simplified or scaled physical object), mathematical/analytical (a set of equations or relations among mathematical variables) or digital/computerized (a program description of the system). Figure 21, from (Law 2006), shows the different possibilities to study a given system.

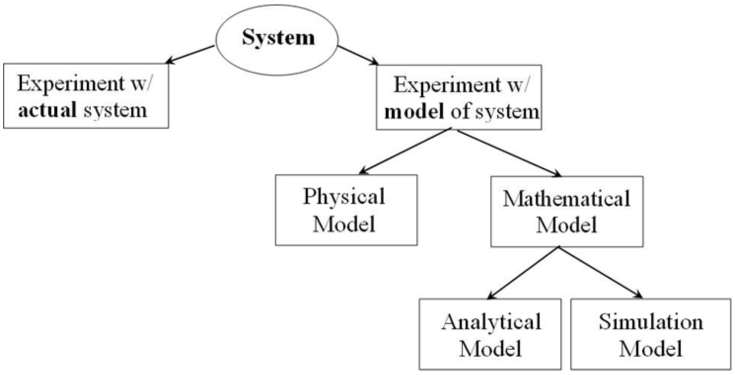


Figure 21 - Different possibilities to study a system (source: (Law 2006))

But real world complex systems seldom can be modeled via sufficiently detailed analytical models (Law 2006). A simulation model is implemented in a computer program and it is generally used as an alternative to analytical modeling. The analytical model is used to find the solution of a mathematical problem while the simulation model is used to execute a simulation program to generate sample system histories (scenarios) and observing system behavior over time. The model describes the system structure, while the histories generated describe the system behavior (Altiok *et al.* 2007).

Some advantages of simulation:

- the process of building the simulation model can help understanding the real system (and sometimes this is even more useful than "running" the final simulations);
- sometimes it is the only type of model possible for complex systems;
- allows for sensitivity analysis and optimization without the need to operate or interfere with the real system (Pegden *et al.* 1995);
- allows better control over experimental conditions than real system;
- allows the evaluation of the system on a slower or on a faster time scale than the real system (time analysis).

Some disadvantages of simulation (Law 2006):

- models of large systems are usually very complex;
- it may be very costly and time consuming to build the simulation;
- can consume a lot of computer time;

- a polished user interface and good output graphics may lead the user to "believe" in an incorrect output;
- the idea that simulation is "just programming" (thus suggesting that modeling is not and important activity).

Simulation models can be classified according to the nature of the system that they try to represent.

A continuous simulation model is one where the state of the system changes continuously over time. A discrete system is one in which the state of the system changes at discrete points in time – the events. Between two consecutive events the state of the system remains unchanged. An event is defined as an instantaneous occurrence that may change the state of the system. When the number of these events is finite, the simulation is known as discrete event simulation.

Most operational models are dynamic, stochastic and discrete - the so called discrete-event simulation models. Discrete-event simulation models a system evolving over time where the state variables change at distinct points in time when events occur. Each event is labeled with its simulation time of occurrence (its timestamp). Simulation events are kept in a data structure called Future Event List (FEL) that supports the following operations:

- insert a new event at time t;
- remove an arbitrary event;
- extract the event with smaller timestamp.

Executing the model is done by executing all the events in the FEL in non-decreasing timestamp order. Discrete-event simulation is appropriate for dynamic environments and allows different combinations of decision strategies to be evaluated.

Simulation, however, can only evaluate a given design and does not really support optimization. Therefore, the integration of simulation and optimization is needed. Recent years have witnessed the integration of optimization techniques into simulation and this integration has become common practice (Michael 2002). How the optimization and simulation phases relate to each other can be seen from two perspectives. The first, is to find an optimal solution to a specific case and, then, simulate which effects this solution have on the system performance, customer behavior and other key performance indicators – simulation for optimization. The second perspective, is to find a good overall design by the use of simulation, and then use optimization to find the best solution to a specific instance of the given design - optimization for simulation. Our approach aimed at finding a good overall design by the use of simulation and then to use a Decision Support System (DSS) to deal with the combinatorial nature of the problem and with the multiple perspectives of the different stakeholders. The next section briefly reviews some previous works on simulation for DRTs.

3.3.1 DRT SIMULATION STUDIES

As can be seen in the WinWin Spiral Model for DRT services, Figure 20, simulation has a very important role in the design process of DRT services to identify uncertainties, resolve risks and evaluate different service architecture alternatives and verify the feasibility of a DRT service through every cycle in the Model.

There were not many applications in the area of DRTs until the last decade (Fu 2002). Simulation studies of dial-a-ride systems were pioneered by (Wilson *et al.* 1969). In this work, the authors presented a comprehensive simulation model to test and compare a variety of routing algorithms. While many aspects of their simulation system are still valid for evaluating DRTs designed and/or operated today, it is limited in terms of the representation of road networks, technology options and characteristics (Fu 2002).

(Bailey *et al.* 1987) developed a model to investigate changes of performance when the dial-a-ride system is run with a different number of vehicles. A series of experiments with the model indicate that customer waiting time is relatively insensitive to changes in demand but highly sensitive to changes in fleet size.

In (Deflorio *et al.* 2002) simulation was used to evaluate the impacts of recent developments in Intelligent Transport Systems (ITS) in the efficiency and reliability of DRTs in a realistic situation, based on data from existing demand in a given territory. The network chosen for the simulation study represented an area in the north of Italy, close to Turin. Four aspects of service operations were investigated in order to determine their relevance and assess both the level of service supplied to users and the efficiency of the system:

- punctuality of departure time of vehicles from the depot;
- waiting time of drivers picking up late users at stops;
- punctuality of users at stops;

- time spent by users while waiting for late vehicles.

An interesting simulation software is LITRES-2 (Horn 2002), developed by the Australia's National Science Agency, Commonwealth Scientific and Industrial Research Organization (CSRIO), Mathematics, Informatics and Statistics division. The LITRES-2 system was designed to model the operation and performance of urban public transport systems, from conventional timetabled services to various kinds of demand-responsive services, and associated traveler information technologies, in order to investigate their performance. This system simulates the route choices and use of the transportation service based on generalized costs: monetary costs and travel times.

The main objective of LITRES-2 is to simulate commuter's behavior as realistically as possible. From aggregated demand, the system generates time-ordered travel requests. These requests are the inputs to a real-time passenger information and booking service (the request-broker and journey-planner modules) that tries to satisfy each request by reference to pre-defined service timetables and also to a fleet of vehicles. The fleet is managed by a dynamic routing/scheduling module. Travel planning on demand-responsive modes is realistic in terms of workloads, road network conditions, and events that can be modeled. LITRES-2 has a micro-simulation approach to passenger travel planning, while requiring pre-specifications of aggregated passenger demand and of parameters for estimating costs (Horn 2002). The request-broker and fleet-manager are the “control modules” and can be replaced by “user-made” modules.

Figure 22, from (Horn 2002), shows the LITRES-2 system architecture.

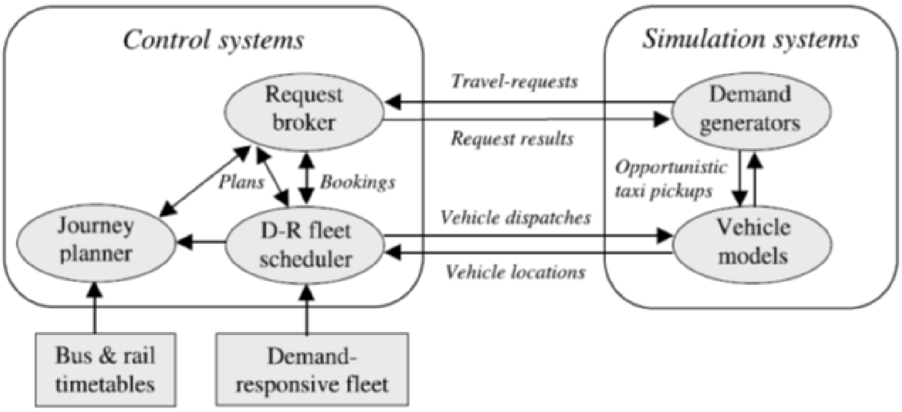


Figure 22 - LITRES-2 architecture (source: (Horn 2002))

Different forms of public transportation can be simulated with LITRES-2: “fixed”/traditional public transport (bus, train, metro), demand responsive services and hybrid services, as well as journeys built up by combinations of these modes. LITRES-2 was used in a high number of transport studies in the region of southern Queensland, with various combinations of timetabled and demand-responsive modes, with extensive sensitivity testing. So, LITRES-2 seems to be a useful simulation modeling tool to design and assess the performance of:

- new types of transport services;
- changes to existing services (public transportation network, timetables);
- inter-modal coordination;
- changes to fare structures;
- changes in transport demand patterns.

Another important simulation system in the literature is SimParatransit (Fu 2002). The aim of this system was to evaluate the potential operational advantage that new technologies, such as Automatic Vehicle Location (AVL) systems, can have on a dial-a-ride service. The work discusses the general concepts, models and computational techniques applied in the simulation system, focusing on how various components are modeled and how they interact with each other in the overall simulation framework. The simulation results have shown that the AVL benefits due to increased flexibility in dynamic scheduling was highly case-dependent.

The work of (Jayakrishnan *et al.* 2002) provides a more general discussion about the need of a simulation system intended to simulate different commercial fleets and different types of vehicles and services, such as dial-a-ride. The main objectives of the work are to understand the needs of broad multiple-class simulations, to provide insights into attempting such modeling and to suggest possible schemes for simulation. The modeling scheme suggested is suitable for simulating any kind of flexible real-time routed service modeled under real time traffic conditions – i.e., the study of dispatching rules based on the real-time stochastic modeling of the network congestion dynamics. The basic simulation system is composed by three fundamental data structures: the *Network*, the *Customer* and the *Fleet*. The *Network* data structure keeps the information contained in the network, reading information from a “network conditions update” routine, and fed directly from the detailed microscopic network conditions. The *Customer* data structure keeps all the information obtained from a demand table, which can be either known in advance or generated during the simulation. Finally, the *Fleet* data structure keeps the details and behavior of all vehicles in aggregated level. The simulation system allows two discrete events: "Service request" and "Transit vehicle reaches a stop".

(Noda *et al.* 2003) used simulation to understand if dial-a-ride services are a reasonable option in large scale towns. Real-time dial-a-ride systems and fixed route systems are compared through simulation to understand under what conditions a dial-a-ride service can be a better alternative, for the operator, than a fixed route service. The authors conducted simulations of dial-a-ride and fixed-route systems in order to compare the usability and profitability of both systems. Usability is defined as the average time between the time that a request occurs until it is satisfied, and profitability is defined as the number of requests occurring in a time period per bus. To conduct the simulation, the authors designed a virtual town with a square shape and streets arranged in a grid pattern where all the stops are at the crossings. Requests occur at constant frequency with departure and destination points decided randomly. The simulation results indicated that:

- the usability of the dial-a-ride system with a fixed number of buses drops very quickly when the number of requests (demands) increases;
- when we increase the number of buses proportionally to the demand, the usability of the dial-a-ride system is improved more significantly than that of the fixed-route system;
- when frequency of demands is sufficiently large, the dial-a-ride system is a reasonable solution from both the usability and the profitability perspectives.

(Palmer *et al.* 2004) used simulation to study the impacts of management practices and advanced technologies on DRT systems. At the time, the authors felt that many advanced technologies and management practices had been proposed and implemented with the objective of improving the efficiency of service, but, evidence for the effectiveness of these actions had yet to be found. The idea was to evaluate the impact of several advanced technologies and management practices upon the productivity and operating costs of DRT systems. They presented the results of a study involving 62 public transportation operators in the United States of America (USA). The analysis indicated that the use of a Computer Aided Dispatching (CAD) system provided productivity benefits while the use of financial incentives had a detrimental impact on productivity. The use of advanced communication technology had a beneficial impact on the operating costs while the use of financial incentives had a detrimental impact.

(Diana *et al.* 2007) used simulation to compare the emissions of DRT services to those of conventional public transportation systems. The authors apply an emission model to find the least polluting public transportation system under a broad range of scenarios with different road networks, service quality levels and demand patterns. On the other hand, the distances traveled for the DRT fleet are dependent on the particular demand patterns and scheduling processes, and have been computed on the basis of the simulation. Results indicated that DRT services minimize emissions for high quality service level and low demand density scenarios. Furthermore, the possibility of employing smaller vehicles with lower emission factors guarantees additional substantial benefits in terms of atmospheric pollution.

(Barceló *et al.* 2007) propose the integration of vehicle routing and dynamic traffic simulation models that emulate the actual traffic conditions to determine the optimal dynamic routing and scheduling of the vehicle. This methodology has been developed in the projects SADERYL-I and II, sponsored by the Spanish "Dirección General de Ciencia y Tecnología" (DGCYT). Fleet operators should be able to respond to changes in demand, to driver and vehicle availability and should also take into account the changes in traffic network conditions. The dynamic traffic simulation models emulate the traffic conditions providing, at each time interval, information that is used by the fleet management system to determine the optimal vehicle routing and scheduling. The modeling framework presented in (Barceló *et al.* 2007) consists of a Decision Support System (DSS) in combination with a simulation system. The DSS includes a Database Management System, a Model Base, a Model Base Management System and a GIS based Graphic User Interface. As for the simulation system, a dynamic traffic simulation model - AIMSUN, Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks, (Casas *et al.* 2010) - was used to account for the dynamics of urban traffic flows. This information is then used by a "Dynamic Router and Scheduler" - the default vehicle routing and scheduling algorithms can be replaced by user defined algorithms. The proposed methodology was tested in the European Project MEROPE (Frosini *et al.* 2004) of the INTERREG IIIB Program, in two test sites in Italy (Lucca and Piacenza).

(Quadrifoglio *et al.* 2008) employed simulation to study how time window settings and "zoning versus no-zoning" strategies affect the total trip time, deadhead distances and fleet size for a dial-a-ride service. Naturally, customers prefer small time-windows. However, to maintain small time-windows, operators may have to decrease the ridesharing and increase their fleet size, thus increasing costs and lowering productivity. The setting of the time-window size needs to balance customer service with the impact on productivity and cost. Also, it is not uncommon for operators to divide their service area into regions, contracting the service in each of these regions to a different provider, as a way to simplify the service management. This practice, known as zoning, is also motivated by the drivers' preference to be assigned to a smaller region instead of the whole service area. The simulation model presented by the authors was based on demand data provided by Access Services Incorporated (ASI) for Los Angeles County and the results of the simulation model pertain to the Los Angeles County network. However, the methodology is easily adaptable and applicable to other service areas for any DRT service with basic data (vehicle fleet, service parameters and description of demand). The study results suggest the existence of linear relationships between operating practices and performance measures: for each minute increase in time-window size, the service saves approximately 2 vehicles and 260 miles driven. Also, a no-zoning strategy was able to satisfy the same demand by employing 60 less vehicles and driving 10,000 total miles less with respect to the current zoning strategy.

(Häll 2011) presents a modeling system for simulation of dial-a-ride services, used as a tool to study how different ways of designing and setting the service and cost parameters affect the total cost for the operator, the performance and the efficiency of the service. The simulation system offers the possibility to simulate the operation of dynamic dial-a-ride services with multiple and heterogeneous vehicle fleets and possibly different schedules and depots. The system was also used to examine the effects of using zone-based distance estimates instead of true, address-based, distances when computing the schedules. The results show only small differences.

In (Häll *et al.* 2011), the authors describe the different modules in a modeling system for simulation of dial-a-ride services and its possible uses. In (Häll *et al.* 2008), the authors use the already mentioned LITRES-2 (Horn 2002) public transport modeling system to try to demonstrate that simulation can be used to analyze and evaluate how the attractiveness and operating costs of a service depend on the type of demand responsive service used, the design parameters and the fleet of vehicles. In addition, two fundamental changes of the service were also tested: a) door-to-door service vs. meeting points and b) the use of DRT-type vehicles without any fixed route service during time periods with low demand. The results of the simulation runs also give guidelines to help operators of public transport to design the service. These results were evaluated according to a given number of criteria (such as number of requests accepted, monetary costs and average journey time, just to name a few). The number of DRT-type vehicles available seemed to have a linear effect on the number of requests that could be accepted. Naturally, when the DRT service picks up and delivers users at the exact location of their origins and destinations, instead of at meeting points close to these locations, this gives a better quality of service for the customers. Simulation results indicated that, whether the DRT services used meeting points or provided door-to-door service, did not seem to result in any major differences - the higher quality of service provided by the door-to-door service could be offered without any noticeable loss in efficiency. The results of the simulation also acknowledged the difficulties of operating a DRT service without integration with a traditional fixed route service. Scenarios of low and sparse demand made the coordination of the journeys in a way acceptable for the customers a hard task.

3.3.2 DRT SIMULATION MODEL

The simulation model developed in this doctoral project can be used as a tool to understand and study how different service designs and different ways to operate a DRT service affect its performance and efficiency, so the main contribution is the easiness of how planners can accurately model the demand structure, in terms of spatial and temporal distributions, and physical network of the scenario at hand. To the author's knowledge, the trip requests generation problem for analyzing the DRT performance in a realistic environment has not been addressed to a great extent and therefore little literature exists on the subject, with (Deflorio 2011) being one of the most recent and prominent examples. Another purpose of the model is to study the effects on the solution (service) produced by different heuristics and algorithms for computing routing plans.

Regarding the stochastic dimension of the envisaged DRT services, there are three major aspects of analysis:

- space: the spatial distribution of the transportation requests, i.e., we want to know the probability distribution of the requests according to the geographical locations of origins and destinations;
- time: birth time of the transportation requests, i.e., we want to know the arrival rate/process of requests to the system;
- travel: expected travel time between two points in the network.

In the simulation model proposed in this work, transportation requests are either known beforehand and/or assumed to arrive in a random way (following a Poisson distribution, as in other transportation related works (Larson *et al.* 1981)) in real time. For transportation requests known *a priori*, i.e., static routing, the (probabilistic) spatial distribution of transportation requests and the arrival rate of requests to the system do not influence our routing algorithm, but the expected travel time does play an important role: there is, very often, considerable uncertainty about how long it will take to travel between any two points in a city due to traffic fluctuations (especially true under peak traffic conditions), accidents, changes in weather conditions, road works, breakdowns and other unpredictable events. So, if one accounts for the expected travel time instead of a deterministic travel time, the planned routes can be quite different. As in our approach to dynamic route planning the algorithm is re-run each time a new request arrives, the aforementioned rationale applies: only the expected travel time seems to have an impact in our algorithm. If, for instance, a pre-calculated scenarios approach had been followed, not only the expected travel time should have been accounted for, but also the spatial distribution of the transportation requests and their arrival rate to (pre) build "realistic" scenarios.

The simulation model proposed in this work entails 4 components:

- service area model;
- trip request model;
- vehicle model;
- real-time events model.

Figure 23 show the simulation components and their inter-relationships. The integration of the simulation system in the Decision Support System (DSS) will be presented in Chapter 5.

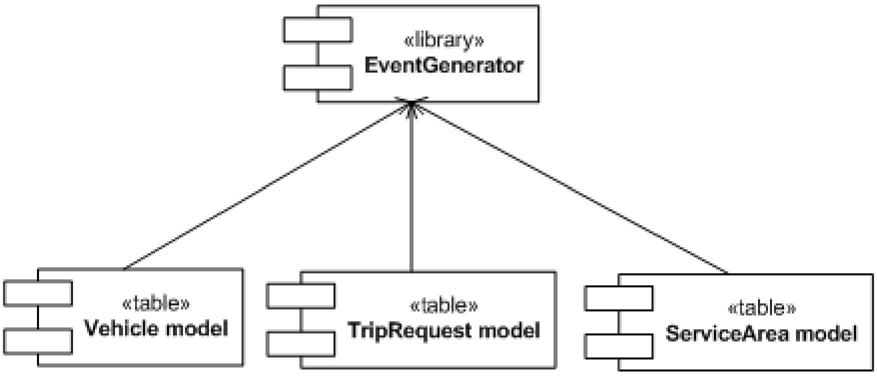


Figure 23 - Simulation components

The simulator generates time-ordered travel requests based on the Trip Request model. These requests are the inputs to a routing and scheduling algorithm that tries to satisfy each request taking into account: a) the multiple perspectives of the different stakeholders; b) a fleet of vehicles with their corresponding locations and other attributes (Vehicle model); and c) the expected trip times (ServiceArea model).

The next subsections describe each of the four simulation model components in detail.

Service area model

To realistically trace vehicle movements, the simulation has to model the physical road network and the stochastic variation of travel time on the links in the network. The simulated road network is a graph defined by a set of nodes, representing the available stops and links, representing the roads connecting the stops. Intersections and one-way streets are not represented. Each link is associated with the mean and standard deviation travel times as function of the period of the day, based on historical data. This allows a simple modeling of temporal and spatial (as values are link-specific) traffic conditions when no real-time data is available. The simulation model proposed does not use micro-simulation, although such systems can be easily connected and used as data feeders. Figure 24 shows a graph of a hypothetical road network with a set of eleven nodes representing the available stops, links representing the roads directly connecting the stops and the service depot represented by a square.

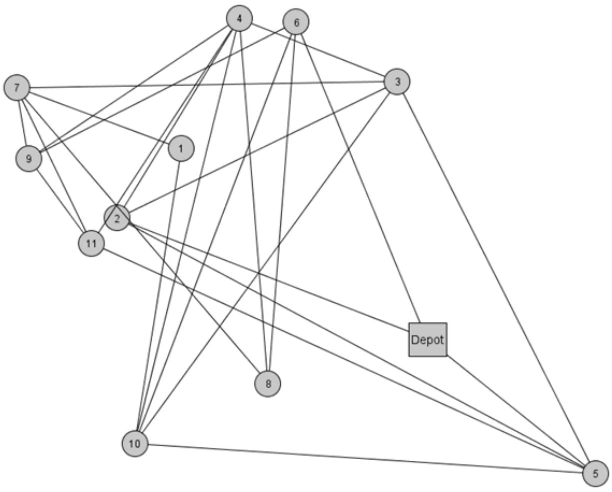


Figure 24 - Graph representation of a hypothetical road network

This model does not consider traffic flows in detail nor delays at intersections or traffic lights, but we assume that such delays are included in the link travel times. For simulation purposes, when a vehicle enters a given link, the travel time is randomly selected from a lognormal distribution with mean and standard deviation as functions of the time when the vehicle entered the link. The vehicle speed is then calculated from the link length and is assumed that the vehicle travels at this speed for the entire link. The choice of a lognormal distribution for travel times distribution follows the proposal by (Taniguchi 2001). In future developments, the "network" model could read information fed directly from detailed microscopic network conditions.

Trip request model

The performance of DRTs seems highly related to the structure of the demand and its variability. A trip is a transportation service from a pick-up point to a delivery point in the service area using a single transportation mode. The objective of the trip request model is to generate trip requests with a structure consistent with the studied area and the road network within which the service operates. (Deflorio 2011) points several difficulties for this task:

- the number of requests is difficult to identify - it varies in time and is influenced by several factors, such as the quality of the service, fare structure or marketing policies, just to name a few;
- the novelty of the DRT concept itself can lead to lack of data;
- an appropriate analysis of the study area is required;

- using a zoning scheme that has been defined for other modes might lead to errors;
- the estimation of origin–destination (OD) matrices estimation is very difficult, and might be irrelevant because values tend to be very small.

The simulation system proposed here generates two types of transportation requests: advanced transportation requests and real-time transportation requests. Advanced requests are made before the service start time. Real-time transportation requests are made during the operation period of the service. The common attributes of transportation requests are: number of seats, desired pick-up time, pick-up location, desired delivery time and delivery location. Real-time requests are similar to advanced requests but have an additional attribute: request time (time when the user books the service). Each trip has a status attribute that can take one of the following the values: waiting service, onboard, delivered, no-show or canceled.

Trip requests arrival rate - TRAR

The total number of requests generated by the simulation n is, thus, the sum of both advanced and real time requests. One can define a degree of dynamism (DOD) as the ratio between the number of real-time requests over the total number of requests. Different instances can be generated with different DODs, e.g.: 0%, 10%, 20%,…, 100%. For a DOD, x, there are $n(1-x)$ advanced requests. Real-time transportation requests arrivals are modeled as a Poisson process (Larson *et al.* 1981) with parameter $\lambda = nx/h$, being h the service horizon (operation period). The time between each pair of consecutive real-time Requests Arrival Time (RAT) to system has a negative exponential distribution.

Request time limit - RTL

The DRT survey presented in Chapter 2 found that 25% of the studied services require the booking to be made 1 hour before the trip, 25% allowed the user to book the trip less than 1 hour before the required pickup time and the shortest time limit found was 15 minutes. So we also adopted 15 minutes as the shortest time limit and randomly select request times with uniform probability between 15 to 60 minutes. We do not consider dwell (or service) time at each stop, as this is, in general, negligible. The time window size can be adjusted, to study, for instance, the effects of different time windows on the service quality. The default time window is 10 minutes, for this is the smallest value found in the European DRT survey study, while in the USA, operators considered time windows of 15 to 30 minutes (Nuworsoo 2011).

Pickup and delivery times

Adding the Request Time Limit to the Request Arrival Time to the system (given by the trip request arrival rate), we have the user desired pickup time, i.e., pickup time=RTL+RAT. As the simulation system has to generate both the desired pickup time and the desired delivery time, a procedure for defining the desired delivery time is needed. For each transportation request, one could look for the travel time as defined in the service area model or look into mobility studies for the service area understudy to find mean trip times. We adopted the later strategy, because the former a) would assume that the commuters knew the travel times between origin and destination of their transportation requests, and b) would not allow for very flexible routes (i.e., if users specify delivery times equal to the time needed to go from the origin to the destination, detours between those points to serve other requests would, necessarily, be delays). For instance, according to Instituto Nacional de Estatística (INE) in 2001, the mean trip time for a commuter using a public bus transportation system in Porto is 35 minutes, or 53 minutes if one considers all Porto's metropolitan area (AMP 2008). So, for the users' "expected" travel time (i.e., to simulate the desired delivery time) we use a normal distribution, with mean 35 minutes and standard deviation of 17 minutes (Melo 2002). Outliers are not expected.

Spatial distribution of transportation requests

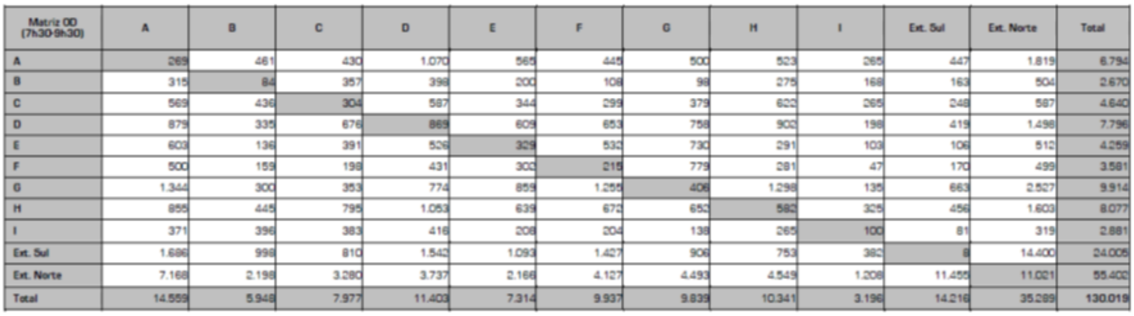
In terms of spatial distribution of the transportation requests, one could simply assume that all nodes in the network have the same probability of being departure or destination points, i.e., assume that demands occur uniformly in any place of the city. In fact, this was our first approach. However, although the assumption of a uniform demand over the complete area is an acceptable first approximation to many existing transport patterns (Lowson 2004), this is not realistic because pick-up and delivery location distributions are not statistically independent, as (Quadrifoglio *et al.* 2008) points out:

- customers typically do not require transportation service when the delivery point is very close to the pick-up point;
- when customers request a delivery (pick-up) at high demand locations (such as hospitals, shopping malls or schools), they would most likely choose the ones closest to their pick-up (delivery) location (home, work, for instance);
- recurrent customers or "standard" routes induce strong links between some particular pick-up/delivery location pairs.

So, ideally, it would be necessary to generate a different delivery (or pick-up) location distribution for each pick-up (or delivery) point in order to simulate their actual dependency and replicate the actual demand in the simulation model. But, naturally, this would be very complex to implement.

We adopted a compromise approach between a) demands occurring uniformly in any place of the service area; and b) different drop-off (or pick-up) location distribution for each pick-up (or drop-off) point. In the past, smaller single center cities had mobility patterns which were dominated by the demand for transportation trips to and from the center. (Noda *et al.* 2003) assume that there is a center of convergence of demands in the middle of the town and, when a demand is generated, one departure point or destination is the center in a certain ratio, called convergence ratio. But, cities have, in general, multiple centers, with disperse demand patterns, with demands converging to these centers (Lowson 2004). Therefore, we generate origin and destination locations of the requests following the spatial distribution found in the OD matrices of the service area found by the available mobility studies for the different operation periods.

Next, we present an application of this procedure for the city of Porto. Figure 25, from (Oliveira *et al.* 2007), shows an OD matrix for individual transportation in the morning rush hours (07:30am to 09:30am) in 9 areas of Porto.



Matriz OD (7h30-9h30)	A	B	C	D	E	F	G	H	I	Ext. Sul	Ext. Norte	Total
A	269	461	430	1.070	565	445	500	523	265	447	1.819	6.794
B	315	84	357	398	200	108	98	275	168	163	504	2.670
C	569	436	304	587	344	299	379	622	265	248	587	4.640
D	879	335	676	869	609	653	758	902	198	419	1.498	7.796
E	603	136	391	526	329	532	730	291	103	106	512	4.259
F	500	159	198	431	300	215	779	281	47	170	499	3.581
G	1.344	300	353	774	859	1.255	406	1.298	135	663	2.527	9.914
H	855	445	795	1.053	639	672	653	582	325	456	1.603	8.077
I	371	396	383	416	208	204	138	265	100	81	319	2.881
Ext. Sul	1.686	998	810	1.542	1.093	1.427	906	753	382	8	14.400	24.005
Ext. Norte	7.168	2.198	3.280	3.737	2.166	4.127	4.493	4.549	1.208	11.455	11.021	55.402
Total	14.559	5.948	7.977	11.403	7.314	9.937	9.839	10.341	3.196	14.216	35.289	130.019

Figure 25 - OD matrix for the morning peak hour in Porto (source: (Oliveira *et al.* 2007))

From this OD matrix data, we can identify the areas that generate more trips and the ones that capture more trips and one can use this spatial distribution to generate the origins and destinations of the requests taking the demand into account. Figure 26, from (Oliveira *et al.* 2007), shows the number of trips with origin in a given Porto city area from 7:30am to 9:30am and Figure 27, also from (Oliveira *et al.* 2007), shows the number of trips with destination in a given Porto city area for the same time period. Although, the zoning system in both Figure 26 and Figure 27 is somewhat oversized for the high definition zoning necessary for demand modeling for DRT systems, it, nevertheless, can provide useful insights.

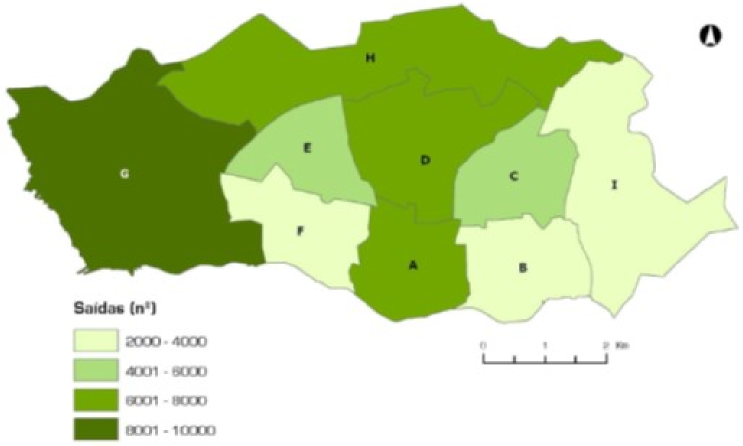


Figure 26 - Number of trips with origin in a given Porto city area, from 7:30am to 9:30am (source: (Oliveira *et al.* 2007))

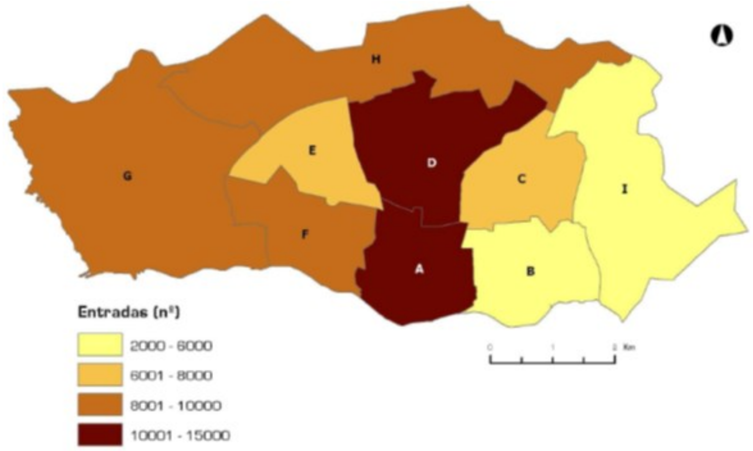


Figure 27 - Number of trips with destination in a given Porto city area, from 7:30am to 9:30am (source: (Oliveira *et al.* 2007))

However, to go one step further in terms of realism, one must recognize that the data refers to the morning rush hour, a period in which there is a high proportion of house/work trips and that is not a suitable scenario for the application of DRT services. Nonetheless, the OD matrix data offers useful insights regarding mobility flows. Figure 28, from (Oliveira *et al.* 2007), shows that the ratio between the number of trips originating in a given zone and the respective resident population is relatively high for some non-residential areas (C, E, F and A), so, there are not so many house/work trips in these areas. This ratio is lower for areas D, G, I and B. (Oliveira *et al.* 2007) points that this can be explained by the fact that areas I and B correspond to more captive resident population (elderly and low income).

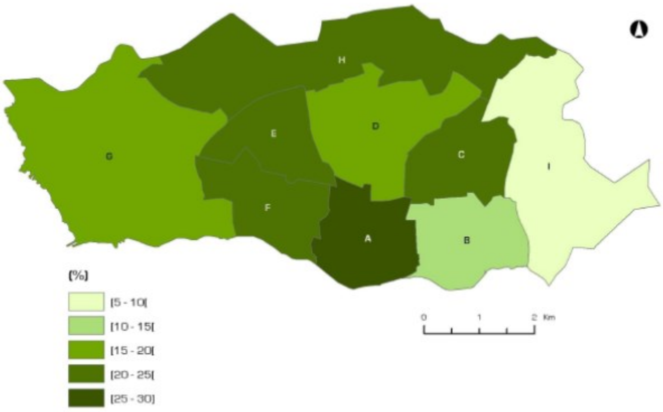


Figure 28 - Ratio between the number of trips originating in a given zone and the respective resident population (source: (Oliveira *et al.* 2007))

The authors also found that Boavista roundabout, Boavista avenue and surroundings, show high atractivity. On the other hand, commercial areas and areas related with universities and hospitals (such as area H) have more trips beginning there than ending there. The opposite is true for residential areas.

As DRT services try also to deal with low, unpredictable demand during night time in the city environment, and given that this particular OD matrix corresponds to the morning rush hours (07:30am to 09:30am), one can also try to "adjust" the flows analyzing the ratio between day time and night time population densities of the different zones, for some insights. Analyzing the data from Instituto Nacional de Estatística (INE) in 2001, (Melo 2002) points out that Santo Ildefonso, Victória, São Nicolau, Sé, Miragaia are the Porto city areas with more population density during the day time, followed by Cedofeita, Bonfim, Massarelos, Paranhos, Ramalde and Aldorar. Figure 29, adapted from (Melo 2002), shows the population density (inhabitants per square kilometer) for Porto city areas during the day time.

Figure 29 - Day time population density for Porto city areas (adapted from (Melo 2002))

The biggest population density drops during the night time occur in Santo Ildefonso, Vitória, Miragaia, Massarelos, Sé, São Nicolau and Cedofeita areas. Figure 30, adapted from (Melo 2002), shows the population density (inhabitants per square kilometer) for Porto city areas during the night times.

Figure 30 - Night time population density for Porto city areas (adapted from (Melo 2002))

Vehicle model

Vehicles can, essentially, be distinguished by their capacity, operating costs, the availability period and their depot location. The simulation system deals with two types of vehicles: own fleet vehicles and subcontracted vehicles. Fleet vehicles are homogeneous, all have the same capacity, operating costs and depot location (but it is easy to relax this restriction to simulate also heterogeneous fleet services). It is possible to define the fleet size or let the system calculate the optimal size. As for the subcontracted vehicles, they possibly represent taxis that the operator can contract in case it runs out on vehicles in the fleet to satisfy extra transportation requests. These subcontracted vehicles have different (usually higher) costs, different capacities and different depots than the fleet vehicles. During the simulation, the system keeps track of and updates the status of the vehicles. The vehicles can be in any of the following states: at the depot, at a stop picking-up and/or delivering passengers and on the road. Vehicle idling at a stop is not allowed. For each vehicle, the system keeps a set of data at all times, such as its assigned route and schedule (list of stops and visiting times), visited stops, current network link being travelled, current speed, current position and possible delays. For each vehicle, assigned demands are stored in a queue. In this queue every assigned demand is divided two way-points: the departure point and destination point, which are inserted at appropriate positions. The vehicle always runs towards a point at the top of the queue, and removes it from the queue upon arrival.

Real-time events

The real time events in the system can be broadly categorized in customer-related events and vehicle related events.

Customer-related events include new real-time requests, cancelations and no-shows. Every time a customer asks for service, the central dispatcher (aided by a computer algorithm in our case) has to take a decision on routing and scheduling, changing the conditions of the system. The system decides which vehicle has to serve the new customer, and in which position of the specific current vehicle' route. Once this decision is made, the vehicle path is modified in order to insert the new request into the original vehicle route, changing the predefined vehicle path. As noted by (Nuworsoo 2011), the most common causes for disruption of service schedules are late trip cancellations or no-shows. High rates of these occurrences result in large decreases in efficiency and productivity. In (Fu 2002) the cancelation requests are assumed to be Poisson distributed and we assume the same both for cancelations and no-shows.

Vehicle related events are, basically, reaching a stop, breakdowns during service and delays. Every time a vehicle reaches a stop, a transfer (pickup and/or delivery) operation happens. Breakdowns are also assumed to follow a Poisson distribution. The delay event can occur when a vehicle does not comply with the specified pick-up or delivery time window, due, for instance, to a larger travel time in some link, or to a breakdown.

3.4 DRT design patterns

> *"There is one timeless way of building. It is thousands of years old, and is the same today as it has always been. The great traditional buildings of the past, the villages and tents and temples in which man feels at home, have always been made by people who were very close to the center of this way. It is not possible to make great buildings, or great towns, beautiful places, places where you feel yourself, places where you feel alive, except by following this way."*

(Alexander 1979)

(Gamma *et al.* 1993) define a *design pattern* as the essence of a proved good solution for a recurrent problem in a given context. By capturing the essence of a solution, a design pattern assures its re-utilization as long as the implementer is capable of adapting it to the specific problem at hand.

Consider the following example of a design pattern from (Alexander 1979):

Design pattern: Ring Road

Problem: "It is not possible to avoid the need for high speed roads in modern society; but it is essential to place them and build them in such a way that they do not destroy communities or countryside."

Solution: Place high speed roads so that:

- at least one high speed road lies tangent to each local transport area;
- each local transport has at least one side not bounded by a high speed road but directly open to the countryside;
- the road is always sunken or shielded along its length by berms, or earth or industrial buildings, to protect the nearby neighborhoods from noise.

Design patterns allow the documentation of the best practices and solutions, effectively transmitting that knowledge. Thus, they promote high levels of re-utilizations, shortening learning and implementation times. Design patterns can be seen as re-usable micro-architectures.

Despite the complexity of defining the right design-pattern for a given situation, given the large spectrum of DRT services architectures and multitude of real-life scenarios in terms of land-use, demand levels and their dispersion, it is clear that the degree of flexibility of each service can be identified as a key characteristic (Brake *et al.* 2007). DRT services are flexible in several operational dimensions such as: route, timetable, vehicle allocation, vehicle operator, type of payment and passenger category. The level of technology used must also be appropriate to the objectives of the DRT service and will constrain the parameters of operation. For example, a computer-based service offers a faster calculation of routes, according to the typology defined for each service.

Figure 31 shows different 3-dimensional zones of financial-technical viability of DRT services. The eight zones represented are associated to different values of financial-technical viability characterized in shades of gray – white represents the least viable and dark gray the most viable. The 3 axis are associated to the levels of flexibility, technology use and service quality.

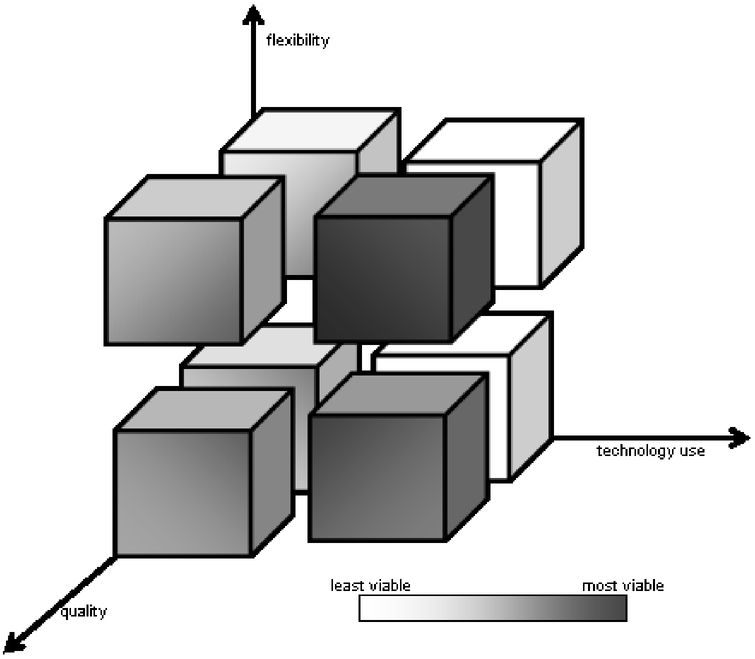


Figure 31 - Financial-technical viability of DRT services

High use of technology in DRTs has cost implications that cannot be covered by low quality services that will be used only by captive users that are unable to pay the higher fares needed to cover service costs. Figure 31 tries point this issue: white cubes for technology intensive, low quality services, regardless of the envisaged flexibility. For low quality services with low level of technology, it is more difficult to have higher flexibilities in terms of route, timetable, vehicle allocation, vehicle operator, type of payment and passenger category. Figure 31 also tries to point that higher quality DRT services and more flexible services benefit with higher levels of technology. As already mentioned in Chapter 2, the trend in recent evolution of flexible services has been the emergence of several types of partnership in a movement towards multiple services and this is increasingly seen as fundamental to the future development of DRTs (Nelson 2004). In the future, many resources are likely to be integrated, including the pooling and optimization of investment capital, vehicles and human resources (Brake *et al.* 2007). Multiple service provision is crucially dependent on the employment of appropriate technology level since this enables the required level of management information with the possibility of a real-time dimension (EC 2002). Nevertheless, if only a low level of technology is available and the operator wants to offer a high quality service, the provided service should be less flexible. What Figure 31 does not show is that the majority of low tech DRT schemes tend to be classified as commercially viable or acceptable subsidy dependent, with premium fares meeting the extra cost involved in providing the higher quality services. High tech schemes tend to be either justifiable higher subsidy dependent DRT services (thanks to efficiencies gained from substituting expensive to provide specialist transport services), or financially unsustainable DRT services.

When studying proved good DRT solutions for a recurrent problem in a given context, i.e., DRT design patterns, DRT services can be classified according to service type and according to service area. We have made a survey on European DRT services (see Chapter 2) that shows a strong relationship between the function of a DRT service and both the route flexibility and the market it serves (correlation factor of 0,64): stand alone or substitution services mostly serve special user groups, whereas interchange DRTs serve a more general market; and DRTs that serve a more general public or both general and special groups tend to be more flexible than those that do not.

Another strong relationship was also found between the area served and the type of users (correlation factor of 0,69) - the survey indicates that in large urban areas DRTs are mostly used to serve special user groups, whereas in rural/small urban areas DRTs tend to serve both special groups and the general public.

3.4.1 DRT SERVICE TYPES

(Brake *et al.* 2007) conclude that there is a strong link between the flexibility of a particular service and the function of the service provided. In this context, the classification offered by the INTERMODE Consortium (Enoch *et al.* 2004) proposes four function-based types, each of which is described by the nature of the DRT service it represents and the market it serves: interchange DRT, network DRT, destination-specific DRT and substitution service DRT. All four types can be low tech, but this is especially true for interchange and destination-specific DRTs. For network and substitution DRTs, the scale and complexity of schemes tend to increase the usefulness of higher-tech options.

Interchange DRT

The "Interchange DRT" is characterized as providing feeder links to conventional public transport (N-SC2 scenario presented in the Chapter 2). Typically this would be a service where the passengers use the DRT as a means to reach another transportation service. Integrated fares and tickets for interconnecting services might be more attractive to users. Interchange DRT systems can be a cost-effective way of increasing the availability of the public transport system as a whole, and are particularly useful to complement a direct service between two important centers in order to avoid deviations in that direct service.

(Enoch *et al.* 2004) state three conditions for such feeders to be effective:

- interchange is usually only worthwhile for longer trips or where the mode being changed to has a significant speed advantage;
- for places where demand is low and/or dispersed, a fixed-route feeder is not viable;
- reliability of connections is important, although less so where the DRT is feeding into a high frequency operation.

Typical policy objectives of an interchange DRT service include social inclusion and increase patronage of main service being fed into. The core trip purposes found in (Enoch *et al.* 2004) for an interchange DRT service type were shopping, leisure and health trips and commuting. The core users for this service are persons without private car, commuters going to big city centers and senior citizens. Route scenarios for this type of service are influenced by the land use patterns. Timetable flexibility is the crucial issue when it comes to designing interchange DRT services. The feeder must deliver its passengers to the long distance mode in time for the transfer to be made. For less transport intensive areas, i.e., where the main service being fed does not have a high frequency, a dedicated service with a specially arranged timetable integrated with the service being fed should be provided. The fare structure is also important when feeders are a major function of a DRT service. Integrated fares might be more attractive to users and discounts for certain user groups or pre-booked trips should be considered.

A minibus is appropriate for this type of DRT service, with a fixed vehicle allocation (V-SC1). Carrying a large number of passengers on an interchange service can lead to long trip times and unreliability of connections. The vehicle interior comfort should be high and as close to a taxi environment as possible. This is particularly important for "choice" users such as commuters. In addition, there needs to be a special concern with mobility impairment users.

Network DRT

The "Network DRT" enhances public transport either by providing additional services, or by replacing inefficient services in a particular place or at certain times of the day or days of the week, when demand for conventional public transport is low or dispersed.

Especially in rural environments, the DRT service can be operated without any time or spatial relation with other services. The opening hours and location of the community or health services can be the main elements for the definition of the service. Behind this network role is the recognition that different forms of public transport have different strengths and weaknesses and will thus be better suited to serve different market segments.

Typical policy objectives of a network DRT service include social inclusion, commuter satisfaction and a decrease in costs of local transport. The core trip purposes for a network DRT service type were shopping, school and health trips and commuting. The core users for this service are registered disabled and senior citizens, commuters going to big city centers and school children. The degree of route flexibility ranged from fully flexible systems (R-SC5) to systems that deviate from the core route (R-SC2). The timetable of the services was typically fully demand responsive, according to the needs of the market. Most services required booking by telephone, with few accepting hail-and-ride stops. Also, most services had a high frequency or run as an hourly service. In terms of fares, it is usual to charge a supplement for door-to-door pickups or deliveries.

The type of vehicles used to provide network DRT type of service includes heterogeneous fleets with taxis and minibuses (dynamic allocation of vehicles, V-SC3) and homogeneous fleets of small buses (fixed vehicle allocation, V-SC1) .

This type of DRT requires a more complex and complete level of technology when compared with the previous interchange DRT type of service.

Destination-specific DRT

The "Destination-specific DRT" is a particular case of the above described network DRT service type that serves specific destinations, such as employment locations, shopping malls or airports. A particular feature of many of these DRT services is the existence of a partnership between the transport operator or local authority and the "destination" (e.g., a company, an airport, shopping mall). This kind of services tends to be targeted at particular markets. Therefore, either the "destination" subsidizes the commuter trips (for instance, sometimes companies subsidize the trips of their employees), or else the users see the trips as a one-off and understand that they have to pay a premium (e.g., airport shuttle passengers). Timetables can be defined specifically to meet the particular needs of the site(s) served.

Typical policy objectives of destination-specific DRT services include social inclusion, reduce car use and provide fixed transportation service for commuters. The core trip purposes for this DRT service type were commuting, shopping and air travel. The core users for this service are commuters, shoppers and air travelers.

In terms of design, destination-specific DRT services seam easier than other DRT service types: they, typically, involve a many-to-one operation, which is by definition simpler than a many-to-many operation; there is a regular demand base, and optimum routes and schedules can be planned in advance. Being easier to design and operate also means that using complex/expensive technology is probably redundant in many cases. The typical degree of route flexibility ranged from fixed routes to fully flexible. Timetables can be designed specifically to meet the particular needs of the destinations served. Depending on the destination, minibuses or full size buses are used for this type of services. In terms of booking, these services usually adopt a registered user's only scheme, pre-booking or hail-and-ride.

Substitution DRT

A "Substitution DRT" is a DRT system that totally (or substantially) replaces conventional bus services. A general DRT can be cheaper for public authorities to provide than running a set of parallel services for health, education or social service transport. Social inclusion concerns have played a major part in many substitution DRT schemes. So, the key issue behind a substitution DRT is resource efficiency. As already mentioned, (López 2010) observed that the main obstacles for the implementation of DRT systems are of a juridical, institutional and organizational nature. In setting a substitution DRT, these obstacles are particularly acute (Enoch *et al.* 2004).

Typical policy objectives of destination-specific DRT services are social inclusion and costs reduction. The core trip purposes found in (Enoch *et al.* 2004) for this DRT service type were social and healthcare. The core users for this service are senior citizens and lower income users. The typical degree of route flexibility are either fixed routes (R-SC1) or fully flexible (R-SC5). Timetables are either semi or fully demand responsive. In terms of booking, some schemes require pre-booking by telephone and others operate on hail-and-ride. Also, some services operated in an on-demand frequency, while others just operate some trips per day. In terms of vehicles, shared taxis and vans provide the services.

3.4.2 DRT SERVICE AREA

(Potts *et al.* 2010) describe strategies for the design of DRT service that are appropriate for rural areas, small cities, and selected applications in urban and sub-urban areas: the authors conducted a comprehensive review of around 195 DRTs operated in the United States and Canada over 10 years. In this review, key information was collected on the characteristics of the DRT operators, the way that services were implemented and operated. Finally, the document identifies some of the best practices for implementing DRT services, including helpful "decision guides". Figure 32 synthesizes these guidelines.

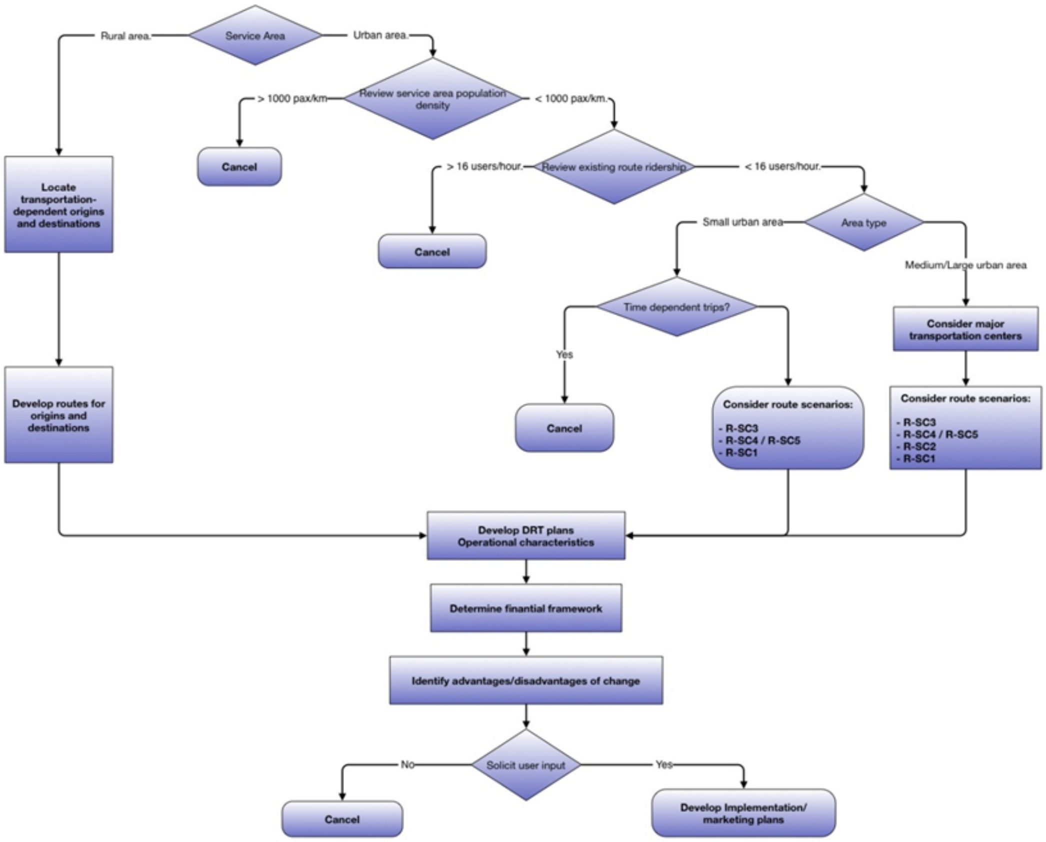


Figure 32 - DRT services guidelines

(Potts *et al.* 2010) found that DRTs were structured differently and served very different needs depending on the area served. The areas served were classified in: rural areas (under 50.000 persons), small urban areas (50.000 to 200.000 persons) and large urban areas (more than 200.000 persons). The smallest operator served a rural area of 2.000 persons, while the largest operator served a population of over two million people. Most operators indicated that DRT services were provided in rural areas (36 percent) and small towns (20 percent). However, over 40 percent of the operators stated that the services were operated in urban and suburban areas also. Most operators implemented DRT services in response to community needs, either senior centers or health centers. In many locations, operators indicated that their DRT services acted as a feeder service to other transport modes (interchange DRT). A large majority of operators indicated that senior citizens (29%) and persons with disabilities (27%) were the main users of DRT services. Around 85% of the operators indicated that the DRT service was operated at all times of the day, only 4 percent indicated that the service was only operated at night and 7% indicated the service was only operated on weekends. It is interesting to compare these results with the European DRT survey presented in Chapter 2: in that survey most services operate during the day (D) - 58%, but there were also 21% of services operated day and night (D and N) in different scenarios in each of these periods. There was also a non neglectable percentage of services operating 24 hours (13%). Only 4% were operated only during night time periods. There is the same percentage of nigh-only services in both sides of the Atlantic, but while in Europe most services are day-time only in North-America the large majority of the services operate at all times of the day.

DRTs for rural areas

Non time-sensitive trip purposes (social, shopping and non-emergency medical), for the "captive" users market, represent the most viable DRT services for rural areas, although there are youth activities, such as social or shopping, that could also be considered viable (Potts *et al.* 2010). The demand for a DRT service is higher where rural population densities approach the high end of low-density (150 persons per square kilometer) and where the demographics of "captive" users is higher than average.

Point deviation services may be preferable to route deviation services in rural areas because they allow more routing options and requests for service to be negotiated or deferred in order to maintain the schedule. In extremely low density areas, services may not operate a full day or every day. A less flexible service, such as route deviation, would be preferred where passengers would be waiting along the route to be picked up without advance booking, and a more flexible service, such as point deviation, would be preferred when a service needs to be more responsive to changing or variable demand.

According to (Potts *et al.* 2010), for rural areas route deviation services work well where:

- the deviations are a relatively small part of the overall demand and the overall running time of the route;

- the majority of the users are not highly time-sensitive;

- door-to-door service is important to some but not all passengers.

- Route deviation services do not typically work well where:

- most trips are time sensitive;

- for some reason, a basic route structure is not desirable for this community.

We also need to analyze trip origin and destination options by trip purpose to design a DRT service. The rationale is to focus in the "captive" users using origins, routes, and destinations that have trip purposes that are not time sensitive:

- in terms of origins, (Potts et al. 2010) point out that a trip origin is viable for DRT service when it is close to captive users areas (such as activity centers, elderly housing or subsidized housing) or is a convenient public gathering;

- regarding trip destination options, a location is viable as destination for DRT services if it provides the trip purpose that captive users need (non-emergency medical services, for instance) (Potts et al. 2010); destinations such as hospitals or clinics, for non-emergency medical trip purposes, have a high potential for DRT services.

Experience seems to point out that the types of DRT services best suited for very rural areas are the following:

- demand-responsive feeder services: work better when there are no viable trip origins but there are public transportation connections to viable trip destinations within a defined area;

- predefined route and timetable which is partially fixed (R-SC1): works better when passengers are given the opportunity to use the fixed-route system (even a deviated fixed route) along the corridor;

- deviations on a scheduled service to predefined routes in a corridor (R-SC2): works better when there is an area where no viable trip origins exist, but a public transportation trip demand is prevalent;

- predefined stops in a corridor (R-SC3): works better when no demand corridor exists, but viable trip origins and/or trip destinations exist within a defined zone.

Operators that serve smaller rural areas can also operate the other types of route scenarios:

- more flexible deviations on a scheduled service to predefined routes in a corridor service (R-SC2): works better where there are defined origins and destinations along a corridor that have high viability for flexible public transportation services; given the low-density nature of the area, service can deviate off the route as needed;
- predefined stops in an area (R-SC4): works best when there are no viable trip origins, but there are viable trip destinations within a defined service area or when there are no viable trip destinations, but there are viable trip origins.

After developing a route that has stop points at all major origins and destinations according to the purpose of the trips and after calculating the running time, 20 to 25 percent additional time should be added for expected daily deviations (Potts *et al.* 2010).

DRT for small urban areas

For small urban areas, we need to understand the main features of the zones to be served, the street system, and the locations for service to "meet".

The literature suggests that small urban fixed-route public transportation systems that have 5 to 16 passengers per hour are strong candidates for a DRT service and that the type of DRT route scenario that is implemented most frequently in these areas is the one with predefined stops in a corridor (R-SC3), but also that with predefined stops in an area/door-to-door (R-SC4 or R-SC5) or predefined route and timetable which is partly fixed (R-SC1) are also possible scenarios (Potts *et al.* 2010). The survey presented in Chapter 2 shows that 20% of the services in small urban areas operated using predefined stops in a corridor (R-SC3) and 40% predefined stops in an area/door-to-door (R-SC4 or R-SC5).

There are two mistakes small urban public transportation systems should avoid (Potts *et al.* 2010): a) the DRT service should not be marketed as only for persons with disabilities; and b) the service should be designed from scratch in a demand-responsive service perspective instead of a fixed-route service perspective (it should be designed from the start with deviations and not added as an afterthought). Smaller vehicles are usually used in providing DRT services in small urban areas and fares are often low. When planning and scheduling a DRT service for small urban areas, the unscheduled time should be approximately 50 percent of the actual time (Potts *et al.* 2010).

DRTs for medium and large urban areas

The DRT concept is specially well suited in situations where operators, while having to reduce their costs, also need to provide transportation services in low demand scenarios, such as some periods of the day (e.g., the night-time or weekends) or specific zones in urban areas. (Potts *et al.* 2010) point out that large urban fixed-route public transportation systems that have routes or areas that approach 5 to 16 passengers per hour are good candidates for DRT services. (Noda *et al.* 2003) also showed through simulation that in these areas the usability (the average time between the time that a request occurs until it is satisfied) of a DRT system with a fixed number of buses drops very quickly when the number of requests (demand) increases (see section 3.3 of the present chapter).

In planning and scheduling DRT services in large urban areas, we need to understand the main features of the service area, the street system, the natural and man-made barriers, and the locations for the service to target. The DRT service area must be defined to facilitate optimal service operations but, it should be small enough to allow buses to penetrate and return in useful times. If service area becomes too wide, the vehicle operation time and the on-board ride time for each user becomes too long and, consequently, the quality of service decreases. Both (Takeuchi 2010) and (Potts *et al.* 2010) point out that, if the distances in the service area are longer than 15km, the DRT services are not appropriate.

Low-density urban areas, in which major transportation centers (such as rail stations, multimodal transportation hubs, shopping centers, medical centers, employment parks, and schools) are located, have high potential for DRT services. Literature suggests that services offering predefined stops and/or points in an area service (R-SC4 or R-SC5) and scheduled checkpoints perform significantly better than those that do not (Potts, Marshall et al. 2010). Our survey presented in Chapter 2 also show this tendency: around 67% of the services operating in medium/large urban environments offered predefined stops in area scenarios or door-to-door (R-SC4 or R-SC5). The important time points are provided at the major transportation activity centers such as rail stations, shopping centers, and transit centers. The unscheduled time should be approximately 50 percent of the actual time to allow for flexibility and recovery (Potts *et al.* 2010).

3.5 Chapter summary

Theoretically, it should be possible to design a DRT service from any combination of the DRT-specific operational characteristics, however, there is a number of regulatory and financial issues, as well as target user requirements, that constrain the spectrum of possible designs. Prior to undertaking the implementation of new DRT services, it is necessary to analyze existing conditions, elicit comprehensive user requirements, determine a financial framework, plan and schedule services, select vehicles and technology and, finally, market and promote the new service. These activities should be framed in a systems development process framework. As establishing the stakeholders' requirements is one of the most important phases in DRT services development, a DRT systems development framework must have the stakeholder needs and risk management at its core, in a simulation driven approach. The WinWin Spiral Model uses Theory W to develop system requirements and architectural solutions as win conditions negotiated among the several project's stakeholders, making it quite suitable to develop DRT services.

The purpose of simulation is to obtain a better understanding of the behavior of a system in a given set of conditions, even with uncertain events. Usually the planning of journeys for DRTs vehicles cannot take into account all of the real-life aspects, such as travel time variability and user delays at stop, for example. The simulation model developed in this work can be used as a tool to understand and study how different service designs and different ways to operate a DRT service affect its performance and efficiency.

3.6 Chapter highlights

Presentation of the main DRT service development concepts.

Proposal of a DRT development process framework.

Literature review on DRT simulation works.

Proposal of a DRT simulation model.

Definition and discussion of DRT design patterns, grouped by service types and service area.

Chapter 4

SERVICE OPERATION

4.1 Introduction

The operation of DRT services corresponds, basically, to the vehicle assignment to transportation requests and the corresponding vehicle routing. The operation objectives and constraints are deeply dependent on the service design and are closely related to the Vehicle Routing Problem (VRP) (Dantzig *et al.* 1959), and, in particular, the Dial-A-Ride (DARP) (Cordeau *et al.* 2003a) models. These are highly complex problems (Lenstra *et al.* 1981). In fact, the Dynamic Vehicle Routing for Demand Responsive Transportation is a NP-Complete problem. The VRP originates from the well-known NP-Hard Travelling Salesman Problem (TSP), so it is also NP-Hard. The VRP with Time-Windows (VRP-TW) is also NP-Hard for it extends the classic VRP. The VRP with Time-Windows and a limited number of vehicles is NP-Complete because if one finds a solution without enumerating all possibilities for this problem, that algorithm would also solve the VRP-TW. The VRP with Variable Travel Times is also NP-Complete by the same rationale. The Dynamic Vehicle Routing for Demand Responsive Transportation is NP-Complete, for it is in fact a VRP with time-windows, a limited number of vehicles and variable travel times.

4.1.1 THE VEHICLE ROUTING PROBLEM

The Vehicle Routing Problem it is a NP-Hard combinatorial optimization problem, dating back to the 50's (Dantzig *et al.* 1959), that lies at the intersection of two well-known and studied problems (Machado *et al.* 2002): the Travelling Salesman Problem (TSP) and the Bin Packing Problem (BPP). In the TSP, one is interested in finding a minimum Hamiltonian circuit. In the BPP, the problem is to pack a set of items of different size and/or weight in a container not exceeding its maximum capacity. In VRPs, given a limited fleet of vehicles, a depot as start and end point and given the demands of known geographically separated clients, the objective is to find the set of routes, that with the minimum, cost serves all demands (Fisher *et al.* 1995).

The Dynamic Vehicle Routing for Demand Responsive Transportation (DVRDRT) extends the "classical" VRP in a number of ways, being, at least, as complex as the later

(Cordeau *et al.* 2007c). It is clear that, in DRT context, vehicles have a limited capacity (known as Capacitated VRP), demands should be served in a certain time window (VRP with Time Windows), and each stop along the route can be both a pickup and a delivery point (Pickup-and-Delivery VRP). There is still the uncertainty and variability associated with the number of stops along the route because of the possibility of having real-time user requests – thus making the problem dynamic. But DRTs drift away from "classical" VRP in the sense that, instead of the vehicles leaving the depot loaded to serve the demand along the route, in DRTs they have leave the depot empty and have several points of pickup and delivery – possibly simultaneously - along the route, before returning empty to the depot.

4.1.2 THE DIAL-A-RIDE PROBLEM

There is a more suitable class of problems for DRTs, known as Dial-A-Ride Problem (DARP) (Cordeau *et al.* 2007a). In the DARP, one tries to plan the set of vehicle routes and schedules for a set of transportation requests between origins and destinations specified by the users. These transportation requests are performed by an homogeneous fleet of vehicles starting from a depot, providing a shared service in the sense that several users may be in a vehicle at the same time (Cordeau 2006). The biggest difference between the DARP and the VRP (and the Pickup-and-Delivery VRP variant) is what we could call the human dimension of the problem. In DARP, one is interested not only in minimizing the operating costs or the distance travelled by the vehicles, but also (and sometimes more significantly) in maximizing the quality of the service, expressed by indicators such as the average passenger waiting time or the on-board passenger time (Paquette *et al.* 2010).

In DARP, there are usually outbound and inbound trips (Cordeau *et al.* 2007b), in what we could call pendular movements, but in the present DRT problem there are just outbound trips – i.e. users specify pickup and delivery locations, but no return trip. Also, in most existing DARP literature instances the pickup points set is disjoint from the delivery points set (in some cases there is only one delivery point) which, clearly, should not be the case in a flexible DRT system. In a flexible DRT system, users could specify any origin or destination point according to their transportation needs.

Static-DARP

Dial-a-Ride services can operate in a static or dynamic mode. In static mode, all requests are known before the route planning phase takes place (advanced requests), whereas in the dynamic mode transportation request are gradually revealed during the planning horizon, along the service operating time and routes have to be adjusted to meet the demand (Psaraftis 1995). In practice, however, "pure" dynamic services are not common since some requests are usually known beforehand.

Dynamic-DARP

In practice, during service operation, several dynamic events may occur, like new requests, vehicle breakdowns, road work, delays, traffic congestion, request cancelling, new requests, just to name a few.

In a dynamic environment, when a new request arrives at a given time instant, the route planning system must deal with it and, eventually, calculate new routes. Route sections already traversed until the arrival of the new request are, obviously, unchangeable. Thus, the problem is to re-optimize the remaining part of the initial solution after the insertion of the new request(s), taking in account that all the previous feasible requests are already in the on-going routes and can be in one of three states: i) "not yet picked up", ii) "picked up but not delivered" or iii) "picked up and delivered". In problems with time windows constraints, the insertion of new request in real-time is more complex: sometimes this new request has to be refused because it is not possible neither to include it in any routes nor to have another vehicle to start a new route.

In many dynamic vehicle routing problems there is some sort of information related to future requests (travel times, requests location or number of passengers), usually in the form of a probability distribution. Problems for which there is, or can be obtained from historical data, such information are known as stochastic vehicle routing problems (Gendreau *et al.* 1996). Regarding the stochastic dimension, Dynamic Vehicle Routing for DRT services there are three major aspects of analysis:

- space: the spatial distribution of the transportation requests, i.e., we want to know the probabilities of the geographical locations of origins and destinations;
- time: the arrival rate/process of requests to the system, i.e., we want to know when requests are made by the passengers;
- travel: expected travel time between two points in the network.

The number of studies on dynamic vehicle routing increased in the last few years, namely the ones focusing on strategies and performance evaluation. The importance of dynamic vehicle routing is increasing every day because logistic distribution scenarios where the information is revealed during the operations are more and more common and, thanks to advances in computer power, real-time data processing is easier and less costly. This growing interest in dynamic routing models also comes from economic developments, where markets are ever more open and competitive. Logistic operators must comply with tighter deadlines, not only to be competitive but even to survive. Flexible and efficient logistic solutions require new approaches for solving the Vehicle Routing Problem. For that matter, real-time availability of information such as vehicle positions or traffic conditions is critical. Several examples of these problems can be found in practice: mail services, emergency services, pickup and delivery of parcels or Demand Responsive Transportation services, just to name a few. (Flatberg *et al.* 2007), for instance, presents two examples of application of dynamic vehicle routing: one for a freight distribution system and another one for a passenger transportation system. The example presented for passenger transportation is a Dial-A-Ride service, for reduced mobility and elderly users. In order to achieve an efficient utilization of the vehicles, it was important to plan routes that combine several requests, reducing the number of vehicles needed and reducing the total distance. For each request, passengers must specify the pick-up location, the desired puck-up time and the desired delivery location. Some users are regular users, whereas others place transportation requests during the operation time of the service.

4.2 Dynamic Vehicle Routing for Demand Responsive Transportation

The vision for the Dynamic Vehicle Routing for Demand Responsive Transportation is a ubiquitous shared-vehicle system with real-time scheduling and routing. The system would operate as an automated system and human interaction would be minimally required, although the option for human interaction would be available during all operation phases. The system should automatically be able to identify origins and destinations of all passengers onboard or requesting the service, to identify vehicle locations, to accept input on route conditions, additional transportation requests and other real-time events and to re-route the vehicles accordingly. After an analysis of the existing models and services, this model vision seemed more generic and more flexible, being able to accommodate several service design architecture and to incorporate the stakeholders' multiple objectives.

The Dynamic Vehicle Routing for DRT is similar to the DARP presented in (Madsen *et al.* 1995). In the Dynamic Vehicle Routing model for DRT, we assume that passengers specify origins and destinations from a set of pre-defined possible route points, a pickup time and a desired arrival time for their transportation needs. They are to be served by a fleet of vehicles of equal capacity (number of seats) – in (Madsen *et al.* 1995) passengers only specify one of the possible time, either pickup or delivery but not both. Each possible route point, with the exception of the depot, can be a pickup-only point, a delivery-only point, or both. At a given route pickup location, different passengers entering the vehicle can have different destinations and different time windows. Several users can be simultaneously transported in one vehicle, like a mini-bus. The vehicles start and end their trips at a single depot and transportation requests can be received at any time, from any origin. Since different users may have different transportation needs, each point (stop) along the route can have multiple (possibly disjoint) time-windows (both pickup and delivery), which, in association with the real-time arrival of new requests, may require several visits to a given stop at different periods. This is a major difference from all known variants of the VRP and DARP problems – and quite a fundamental one, thus requiring innovative approaches. Finally, we have the variable travel time between two points in the network.

Summing up, the main DVRDRT characteristics are:

- multiple vehicles with equal capacity;
- single depot where vehicle routes start and finish;
- simultaneous pickup and delivery;
- users specify transportation requests from anywhere to anywhere (many-to-many), at any moment (dynamic);
- users specify pickup and delivery time-windows;
- multiple (possibly overlapping) time-windows at each stop;
- time-dependent travel time between two points in the network.

Figure 33 tries to capture the relationship between the VRP (namely, the Pickup-and-Delivery VRP), the DARP and the DVDRT, highlighting only the main differentiating characteristics.

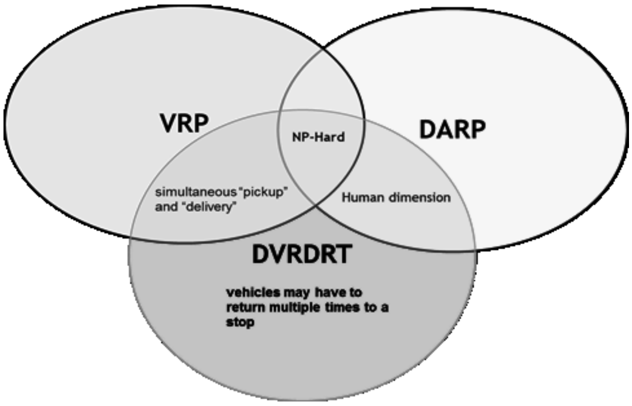


Figure 33 - Relationship between the VRP, the DARP and the DVDRT

For combinatorial optimization problems such as the presented, one is often "just" interested in feasible solutions that can be obtained in useful time. Given the complexity of the problem, optimal solutions can take an enormous amount of time to be found, ruling out their usefulness in the context at hand. Besides, in a multiple criteria decision analysis, the concept of an "optimal" solution is, in general, complex to define because it is impossible to satisfy all (usually contradictory) objectives at the same time (Branke *et al.* 2008). So we are interested in finding a set of efficient solutions, hopefully close to the Pareto front (set of solutions that are Pareto efficient, i.e., solutions for which no objective function can be made better off without making at least other objective value worse off). The goal is not only to minimize the operating costs incurred to satisfy the maximum possible number of requests but also to maximize the quality of the service, expressed by the average passenger waiting time and the on-board (ride) time.

To illustrate the initial state for a static DVRDRT problem, we devised a hypothetical scenario depicted in Figure 34. In a dynamic environment, during the time period in which vehicles perform the calculated routes, new transportation requests would stochastically arrive in real time from any point. Figure 34 represents a very limited sub-set of stops that belong to a hypothetical network where the service operates.

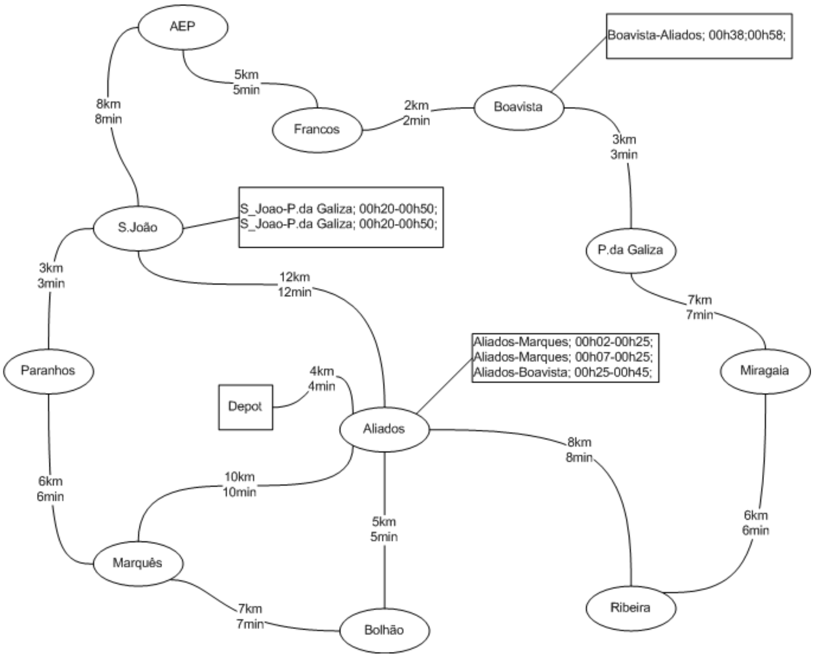


Figure 34 - Hypothetical initial state for a static DVRDRT problem

Figure 34 shows a set of bus stops represented as ellipses, the road network represented as arcs with distance and travel time connecting the stops, one depot represented by a square and the transportation requests represented as tags at their origins. Suppose that the service operator set the DVRDRT service to start at midnight (00h) and time windows have a size of three minutes. Each transportation request is formed by origin, destination, pickup time and delivery time. Around each value of pickup and delivery time is built a (customizable) time window. In the above example, there are, for instance, two transportations requests with origin in "S.João" and destination in "P. da Galiza", with the same pickup and delivery time: 00h20m and 00h50m, accordingly. Being 3 minutes the time windows dimension, the pickup time is, more precisely, between 00h20m and 00h23m, and the delivery time is between 00h50m and 00h53m. At "Aliados", for instance, there are three transportations request, two of them with the same destination and similar pickup times and one with a completely different destination and pickup time (i.e., multiple destinations and multiple time windows). Notice also that "Boavista", in the example depicted by the Figure 34, is simultaneously a pickup and delivery stop for different transportation requests also with different time windows.

4.3 DRT modeling

For the dynamic routing, we followed a rolling horizon approach, which is, having an initial route, to solve static scenarios (Psaraftis 1995) when a new request arrives and/or travel times change – real time optimization. There is an initial route schedule that incorporates all data currently known and this route schedule is adjusted only when required using the most recent data. Each submodel represents a Vehicle Routing for DRT Problem at a particular point in time. Each of these Vehicle Routing for DRT Problems involves vehicles that may depart from current nodes or from the depot, visit unserviced nodes and return to the depot. Thus, the problem is re-optimize the remaining part of the initial solution after the insertion of the new request(s), taking in account that all the previous feasible request are already in the on-going routes and can be in one of the three states presented before: "not yet picked up", "picked up but not delivered", "picked up and delivered". Once a passenger has been served, i.e. picked up and delivered, that passenger will be removed from the planned route thereafter. Passengers not yet picked up can be served by any vehicle but passengers already picked up must be delivered, naturally, by the same vehicle. So, the set of passengers already picked up but not delivered has a big importance in each time instant. On problems with time windows constraints, the insertion of new request in real-time is more complex: sometimes this new request have to be refused because it is not possible to neither include them in any routes, nor have another vehicle to start a new route.

We also consider travel time dependency, which accounts for variations in travel speed due to traffic congestion. For instance, if travel times have changed due to unexpected incidents, in order to fulfill time windows constraints and obtain a lower travel cost, scheduled requests may have to be re-scheduled based on position and load factor of route vehicles. The dispatching center needs to quickly respond to both new real-time requests and time-dependent travel times. As in (Malandraki *et al.* 1992), we assume that time-dependent travel times differ according to the time of day. Time-dependent travel times are characterized by a step-wise function, which represents predictive travel times at different time intervals. Once an unexpected incident happens, the predictive travel times need to be updated in real time. As a result, the vehicle routes need to be updated, too.

For the DVRDRT problem, we present a formulation based both in the static DARP 3-index formulation in (Cordeau 2006) and in the Vehicle Routing Problem formulation in

(Chang *et al.* 2003). The presented formulation is intended to be flexible, easily allowing new constraints and variants of the problem, like a generic framework, allowing for the design of different multi-objective customizable algorithmic approaches for different kinds of DRT systems.

4.3.1 PARAMETERS AND INDICES

Let w denote the number of transportation requests (i.e., pickup or delivery requests). Each request has a time window defined between an earliest service time e_w and a latest service time l_w. The dynamic vehicle routing problem for DRT can be defined on a loop less asymmetric multi-graph $G = (W, A)$, with node set $W = \{0, \dots, 2w + 1\}$ and arc set A, $A = \{(i, j): i, j \in W, i \neq j, i \neq 2w + 1, j \neq 0\}$. As in (Malandraki *et al.* 1992), to each of these arcs is associated a proportional traversal time (cost) $c_{ij}(\tau_i)$, which is a known step function of the time of the day τ at the origin node i. Once the time interval during which the vehicle starts traversing arc (i, j) is known, the travel time between nodes i and j is a known constant. Each arc (i, j) can, thus, be replaced by M_{ij} links from i to j, where M_{ij} is the number of distinct time intervals considered in the step function $c_{ij}(t_i)$ (Malandraki *et al.* 1992). For simplicity, we also consider that the number of time intervals is the same for all arcs and use M instead of M_{ij}. So, $c_{ij}^{m}$is the travel time (cost) from no i to j if starting at i during interval m. Let T_{ij}^{m} be the upper bound for time interval m for arc (i, j).

Nodes 0 and $2w + 1$ represent the depot at different time instants (the route start and the route end). Each passenger (transportation request) i is associated with a pickup node w and a delivery node $w + i$, so subset $W^+ = \{1, \dots, w\}$ is the subset of W composed by all pickup nodes and, analogously, $W^- = \{w + 1, \dots, 2w\}$ is the set of all delivery nodes. To each pickup node there is a monetary return $r_w : w \in W^+)$ associated. At any time τ, $W_{as}^+ (\tau)$ is the set of assigned and already served pickup requests (i.e., on route, but not delivered, otherwise it wouldn´t even need to be considered), $W_{an}^+(\tau)$ is the set of assigned but not yet served pickup requests and $W_u^+(\tau)$ is the set of unassigned pickup requests. So $W^+(\tau) = W_{as}^+ (\tau) \cup W_{an}^+(\tau) \cup W_u^+(\tau)$ and, particularly, at the beginning of the service, $W^+(0) = W_u^+(0)$. In an analogous way, at time $\tau, W_a^- (\tau)$ is the set of assigned delivery requests and $W_u^-(\tau)$ is the set of unassigned delivery requests. To each node $\mathrm{w} \in \mathrm{W}$ is associated a load $\mathrm{q_w}$ satisfying $\mathrm{q_0} = \mathrm{q_{2w+1}} = 0 \wedge \mathrm{q_w} = -\mathrm{q_{w+i}} (\mathrm{i} = 1, .., \mathrm{w})$.

Let $\mathrm{K} = \{1,2, \dots, \mathrm{k}\}$ be the set of vehicles, all with the same capacity (number of seats) Q, that we launch from the depot (we assume the same speed for every vehicle k). $\mathrm{Q_w^k}$ is the load of the vehicle k after leaving node w. At any time τ, $\mathrm{K_0}(\tau)$ is the set of vehicles at the depot, while $\overline{\mathrm{K_0}}(\tau)$ is the set of vehicles en route, $\mathrm{K}(\tau) = \mathrm{K_0}(\tau) \cup \overline{\mathrm{K_0}}(\tau)$. $\mathrm{k_w} \in \overline{\mathrm{K_0}}(\tau)$ is the vehicle on route that served (pickup) request $\mathrm{w} \in \mathrm{W_{as}^+}$. Note that at any time τ, $\mathrm{k_w}$ is known.

4.3.2 DECISION VARIABLES

$\mathrm{x_{ij}^{km}} \in \{0,1\}$ is 1 if the vehicle $\mathrm{k} \in \mathrm{K}$ travels directly from node i to node j during the period of the day m, and is 0 otherwise.

4.3.3 AUXILIARY VARIABLES

We define an auxiliary variable τ that is the time when events (such as transportation requests) occur. τ_w^k represents the time when the vehicle k serves request w (i.e., reaches that node). We consider service time to be zero, so τ_w^k also represents the time vehicle k leaves node w for travel time between nodes calculations.

4.3.4 OBJECTIVE FUNCTIONS

The goal of the Dynamic Vehicle Routing for DRTs at any point in time is to find a set of efficient solutions, minimizing the operating cost, the waiting time and the on-board passenger ride time and maximizing the number of service requests served.

Minimize cost

$$\min \sum_{m \in M} \sum_{k \in K} \sum_{i \in W(\tau) \setminus \{2w+1\}} \sum_{j \in W(\tau) \setminus [\{0\} \cup W_{as}^+(\tau)]} c_{ij}^m x_{ij}^{km} - \sum_{m \in M} \sum_{k \in K} \sum_{j \in W(\tau) \setminus \{2w+1\}} \sum_{i \in W^+(\tau) \setminus W_{as}^+(\tau)} (2x_{ji}^{km} - 1) r_i \tag{1}$$

Minimize waiting time

$$\min \sum_{m \in M} \sum_{k \in K} \sum_{j \in W(\tau) \setminus \{2w+1\}} \sum_{i \in W^+(\tau) \setminus W_{as}^+(\tau)} (\tau_i^k - e_i)\, x_{ji}^{km} \tag{2}$$

Minimize on-board ride time

$$\min \sum_{m \in M} \sum_{k \in K} \sum_{i \in W(\tau) \setminus \{0,2w+1\}} \sum_{j \in W^-(\tau)} (\tau_j^k - \tau_{(j-w)}^k) x_{ij}^{km} \tag{3}$$

Maximize number of serviced requests

$$\max \sum_{m\in M} \sum_{k\in K} \sum_{j\in W(\tau)\setminus\{2w+1\}} \sum_{i\in W^{+}(\tau)\setminus W_{as}^{+}(\tau)} x_{ji}^{km} \tag{4}$$

4.3.5 CONSTRAINTS

Several constraints have to be considered.

$$\sum_{m\in M} \sum_{k\in K} \sum_{i\in W(\tau)} x_{ij}^{km} \le 1 \qquad \forall j \in W^{+}(\tau) \tag{5}$$

$$\sum_{m\in M} \sum_{j\in W^{+}\setminus W_{as}^{+}(\tau)} x_{0j}^{km} \le 1 \qquad \forall k \in K_0(\tau) \tag{6}$$

$$\sum_{m\in M} \sum_{j\in W^{-}(\tau)} x_{0j}^{km} = 0 \qquad \forall k \in K_0(\tau) \tag{7}$$

$$\sum_{m\in M} \sum_{i\in W^{-}(\tau)} x_{i,2w+1}^{km} = 1 \qquad \forall k \in \overline{K_0}(\tau) \tag{8}$$

$$\sum_{m\in M} \sum_{k\in K} \sum_{i\in W^{-}(\tau)} x_{i,2w+1}^{km} = \left|\overline{K_0}(\tau)\right| \tag{9}$$

$$\sum_{m\in M} \sum_{j\in W^{+}(\tau)\setminus W_{as}^{+}(\tau)} x_{0j}^{km} - \sum_{m\in M} \sum_{j\in W^{-}(\tau)} x_{j,2w+1}^{km} = 0 \qquad \forall k \in K_0(\tau) \tag{10}$$

$$\sum_{m\in M} \sum_{i\in W(\tau)} x_{i0}^{km} = 0 \qquad \forall k \in K(\tau) \tag{11}$$

$$\sum_{m\in M} \sum_{j\in W(\tau)} x_{2w+1,j}^{km} = 0 \qquad \forall k \in K(\tau) \tag{12}$$

$$\sum_{k\in K} \sum_{j\in W(\tau)\setminus\{0,2w+1\}} x_{0j}^{k} < |K_0(\tau)| \tag{13}$$

$$\sum_{m\in M} \sum_{j\in W\setminus\{2w+1\}} x_{ji}^{km} - \sum_{m\in M} \sum_{j\in W\setminus\{0\}} x_{ij}^{km} = 0 \qquad \forall i \in W^{+}(\tau) \cup W^{-}(\tau), \forall k \in K \tag{14}$$

$$\sum_{m\in M} \sum_{j\in W(\tau)\setminus\{2w+1\}} x_{ji}^{km} - \sum_{m\in M} \sum_{j\in W(\tau)\setminus\{0\}} x_{i+w,j}^{km} = 0 \qquad \forall i \in W^{+}, \forall k \in K \tag{15}$$

$$\sum_{m\in M} \sum_{j\in W(\tau)\setminus\left(\{2w+1\}\cup W_{as}^{+}\right)} x_{ji}^{km} = 1 \qquad \forall k \in K(\tau), \forall i \in W_{an}^{+} \tag{16}$$

$$\sum_{m\in M} \sum_{j\in W(\tau)\setminus\{0,2w+1\}} x_{j,i+w}^{k_w m} = 1 \qquad \forall k_w \in \overline{K_0}(\tau), \forall i \in W_{as}^{+} \tag{17}$$

$$e_i < l_i \qquad \forall i \in W \tag{18}$$

$$l_i < e_{i+w} \qquad \forall i \in W^{+} \tag{19}$$

$$e_i \le \tau_i^k \le l_i \qquad \forall i \in W^{+} \cup W^{-}, \forall k \in K \tag{20}$$

$$\tau_i^k < \tau_{i+w}^k \qquad \forall i \in W^{+}, \forall k \in K \tag{21}$$

$$\tau_i^k - \tau \geq 0 \qquad \forall i \in W^+ \cup W^-, \forall k \in K \tag{22}$$

$$\tau_j^k \geq \left(\tau_i^k + c_{ij}^m\right) x_{ij}^{km} \qquad \forall i,j \in W, \forall k \in K, \forall m \in M \tag{23}$$

$$\tau_i^k \geq \mathrm{T}_{\mathrm{ij}}^{\mathrm{m}-1} x_{ij}^{km} \qquad \forall i,j \in W, \forall k \in K, \forall m \in M \tag{24}$$

$$\tau_i^k \leq \mathrm{T}_{\mathrm{ij}}^{\mathrm{m}} x_{ij}^{km} \qquad \forall i,j \in W, \forall k \in K, \forall m \in M \tag{25}$$

$$Q_0^k = Q_{2w+1}^k = 0 \qquad \forall k \in K(\tau) \tag{26}$$

$$Q_j^k \geq (Q_i^k + q_j) \sum_{m \in M} x_{ij}^{km} \qquad \forall i,j \in W, \forall k \in K, \tag{27}$$

$$max\{0, q_i\} \leq Q_i^k \leq min\{Q, Q + q_i\} \qquad \forall i,j \in W, \forall k \in K, \tag{28}$$

$$\mathrm{x}_{\mathrm{ij}}^{\mathrm{km}} \in \{0,1\} \qquad \forall i,j \in W, i \neq j, \forall k \in K, \forall m \in M \tag{29}$$

Note that constraints (23), (24), (25) and (27) are non-linear. Let B_1, B_2 and B_3 be large numbers, constraints (23) and (27) can be linearized as (Cordeau 2006), respectively:

$$\tau_j^k \geq \tau_i^k + c_{ij}^m - B_1(1 - x_{ij}^{km}) \qquad \forall i,j \in W, \forall k \in K, \forall m \in M \tag{30}$$

$$Q_j^k \geq Q_i^k + q_j - B_2(1 - \sum_{m \in M} x_{ij}^{km}) \qquad \forall i,j \in W, \forall k \in K, \tag{31}$$

and constraints (24) and (25) can be linearized as (Malandraki *et al.* 1992), respectively:

$$\tau_i^k \geq \mathrm{T}_{\mathrm{ij}}^{\mathrm{m}-1} - \mathrm{B}_3(1 - x_{ij}^{km}) \qquad \forall i,j \in W, \forall k \in K, \forall m \in M \tag{32}$$

$$\tau_i^k \leq \mathrm{T}_{\mathrm{ij}}^{\mathrm{m}} + \mathrm{B}_3(1 - x_{ij}^{km}) \qquad \forall i,j \in W, \forall k \in K, \forall m \in M \tag{33}$$

Constraint (5) imposes that every transportation request can only be served by a single vehicle. Constraints (6), (7), (8), (9), (10), (11) and (10) impose that routes start and end at the depot, the first route node must be a pickup node and that vehicles already on route must also return to the depot at the end of the routes. Constraint (13) imposes that the fleet size cannot be exceeded. Constraint (14) guarantees that every vehicle that enters a node leaves that node. Constraint (15) imposes that the same vehicle that does the pickup of a given must do the corresponding delivery, constraint (16) imposes that already accepted requests must be served, and constraint (17) guarantees that passengers already in a vehicle must be delivered by that vehicle. In every transportation request the delivery service must, of course, occur after the pickup service and every passenger must be picked up and delivered within the limits of the specified time windows – constraints (18), (19), (20) and (21). Constraint (22) ensures that the time at which a vehicle arrives/leaves a node must be later than the route planning and time consistency is guaranteed by constrain (30). Constraints (32) and (33) ensure that the proper link m is chosen between two nodes according to the departure time from the first node. Constraint (26) states that each vehicle must leave the depot empty and return to the depot empty, while constraints (28) and (31) state that the vehicles' capacity can never be exceeded and ensure its consistency along the route. Finally, constraint (29) defines x_{ij}^{km} as a binary variable.

4.4 Static Vehicle Routing for DRT services algorithms

The Dynamic Vehicle Routing approach for Demand Responsive Transportation (DVRDRT) is a NP-Complete, multi-objective, multi-criteria, strongly dynamic problem that requires good solutions to be obtained in useful time. For that purpose, heuristics are the only robust approach for real-life dimension problems. Heuristic approaches are well suited to solve extensions of the original Vehicle Routing Problem having time windows or simultaneous pickup and delivery constraints, like the problem at hand. Usually, heuristics are based upon simple ideas on how to search a good solution exploring the problem structure, reason why they tend to be specific for that problem. Meta-heuristics provide a structure and more general indications for the design of a heuristic that fits a particular problem.

Several heuristics have been proposed for the vehicle routing problem and its extensions. The classification of heuristics is neither easy nor consensual, but, according to (Cordeau *et al.* 2005), they can be grouped in constructive heuristics, improvement heuristics, population mechanisms heuristics and learning mechanism heuristics. Regarding the constructive heuristics, there are two main techniques: joining routes using savings criteria or gradually inserting nodes on an initially empty route based on an insertion cost. In this category, well known examples are the *savings algorithm* (Clarke *et al.* 1964), *cluster-first-route-second* methods (Gillett *et al.* 1974), (Fisher *et al.* 1981) or *route-first-cluster-second* methods (Beasley 1983). Constructive heuristics can also be classified in sequential or parallel. Many constructive procedures are followed by a more or less complex improvement phase, usually known as local search. Starting with an initial solution, small changes are applied to it to obtain different, hopefully better, solutions in its neighborhood. These improvements can be both intra and inter-routes. In the first case, intra-route improvements, an optimization procedure like λ-opt (Lin 1965) or Or-opt (Or 1976) exchanges can be applied to each route individually. The inter-route improvements are, usually, more complex, involving several routes in the solution route set, as in the cyclic transfers algorithm (Thompson *et al.* 1993), edge exchanges (Kindervater *et al.* 1997) or ejection chains (Glover 1996). Local search terminates when a better solution is found (first best approach), or no better solution can be found (hill climbing/descending) or the algorithm runs out of time. The basis for the population based heuristics is combination of solutions. Two well-known types of population based heuristics are the genetic algorithms (Reeves *et al.* 1993; Potvin 1996; Machado *et al.* 2002; Toth *et al.* 2002; Berger *et al.* 2004; Pankratz 2005), based on the analogy with the Evolution Theory by Charles Darwin, and the adaptive memory procedures (Taillard *et al.* 2001; Toth *et al.* 2002). As for the learning mechanism heuristics, neural networks (Reeves *et al.* 1993; Smith 1999; Toth *et al.* 2002) and ant colony optimization (Gambardella *et al.* 1999; Toth *et al.* 2002; Donati *et al.* 2003; Mazzeo *et al.* 2004; Favaretto *et al.* 2007; Yu *et al.* 2009) are two famous examples. Ant colony algorithms are based on the analogy with ants that leave a pheromone trail to learn the path to reach the food, with the best known discovered paths having a stronger trail of pheromones. Any ant that explores the path after that will, thus, find a stronger trail and it converges for, what soon becomes, a path with hundreds of ants.

In meta-heuristics, such as tabu search or simulated annealing, the improvements mechanisms are embedded in sophisticated neighborhood structures that allow momentarily worst solutions (maybe even infeasible ones) in order to escape local minima and, in the end, obtain better solutions. The main drawback of isolated use of local search procedures is that one can be stuck at a "local optimum" different from the aimed "global optimum". One possible way to overcome this situation would be to re-start the local search procedure multiple times with different random initial solutions. However, for large scale problems and complex neighborhood structures, the success rate of such method tends to be low (Toth *et al.* 2002). Meta-heuristics solve this problem orchestrating the interaction between local search procedures and high level strategies, to escape local optima and consistently search the solution space.

As in other meta-heuristics, the GRASP (Greedy Randomized Adaptive Search Procedure) (Feo *et al.* 1989), at each iteration constructs an initial solution (construction phase) and then performs local search procedures to improve that initial solution (local search phase). The difference to other meta-heuristic lies at the construction of the initial solution in a greedy, randomized and adaptative manner (and that's where its name comes from). The focus of this meta-heuristics is in the attempt to build the best possible initial solution and not so much in the local search phase. Figure 35 shows the GRASP pseudo-algorithm (Resende *et al.* 2003).

```
Parameters: Max_iter, seed
for k=1 to Max_iter do
       solution=Greedy_Random_Construction(seed);
       solution=LocalSearch(solution)
       Update_best_solution(solution,best_solution)
end-for
return best_solution
```

Figure 35 - GRASP pseudo-algorithm (source: (Resende *et al.* 2003))

The construction strategy is to evaluate the elements to be inserted in the solution at each iteration according to some criteria – it is useful to recall at the present point that the DVRDRT is a multi-criteria problem. These criteria adapts to the already built solution, such that the evaluation of the elements changes during the construction of the solution. At each iteration of this phase, a list of all elements that can be incorporated in the solution being constructed without destroying feasibility is created - the candidate list (CL). From this CL, a subset of the best elements is selected to form a restricted candidate list (RCL) - $RCL \subseteq CL$. The size of the RCL is defined by a parameter $\alpha \in [0,1]$ that sets either the numbers of elements or a threshold between the value of the best element of the CL and the value of the last element to be included in the RCL. The α parameter should be set to calibrate how random and greedy the construction process will be. By setting the α parameter to zero, only the best element from the CL is selected, in a "pure greedy" manner, while setting the parameter to 1 it will be completely random. The next step is to randomly select one element from the RCL and insert it in the solution being constructed. After this, the process is re-started, the CL is updated, the RCL is updated and a new element is randomly selected and inserted in the solution being constructed, and so on, until a complete solution is obtained. The found solution is then used in the local search phase. It is a multi-start meta-heuristic, so each GRASP iteration returns a solution with its cost. Only the best overall solution is kept as the final result of the GRASP.

In literature there is a number of enhancements that have been proposed for the basic GRASP presented so far. One of those enhancements is a memory scheme to learn the appropriate value for the α parameter that controls how random and greedy the construction process: Reactive GRASP (Resende *et al.* 2003). These authors tried to show that fixed values for the α parameter can hide good solutions that could be found with different α values. The Reactive GRASP reacts to solutions produced using different values for the α parameter and tries to adjust it to give the GRASP the "best" balance between greediness and randomness. At each GRASP iteration, the α parameter is chosen from a discrete set of values $\{\alpha_1, .., \alpha_m\}$. The probability of selecting a given α_i is $p(\alpha_k), k = 1, .., m$ and these probabilities are adjusted to favor α values that produce good solutions. Initially, we set equal probabilities to each α_k, i.e., $p(\alpha_k) = 1/m\ , k = 1, .., m$, then the probabilities are updated according to $p(\alpha_k) = q_k / \sum_{j=1}^{m} q_j$, where $q_k = F(S^*)/A_k$, being $F(S^*)$ the cost of the best solution found so far and A_k the average cost of the solutions found with α_k.

4.5 Algorithms for Dynamic Vehicle Routing for DRT services

As already mentioned, in practice, during service operation, several dynamic events occur, like vehicle breakdowns, road work, delays, traffic congestion, request cancelling, new requests, and so on.

In dynamic DRT scenarios, besides advanced requests (before operation start), there are immediate (real-time) requests, so part of the necessary information becomes available only during the operation period. The insertion of immediate requests into already planned routes is a complicated task. When a new request arrives at a given time instant, the route planning system must deal with it and, eventually, calculate new routes. Route sections already traversed until the arrival of the new request are, obviously, unchangeable. For problems with time windows constraints, the insertion of new requests in real-time is even more complex: sometimes these new requests have to be refused because it is not possible to neither include them in any route, nor have another vehicle to start a new route. Moreover, there's also the reaction time problem: more "immediate" requests may be denied service. In terms of quality of service, a fast response may lead to longer travel distances, thus conflicting with cost minimization objectives.

A traditional approach for the dynamic problem is to solve static scenarios when a new request arrives (Psaraftis 1995), i.e., each new request creates a new static scenario. Another approach is to improve the solution found for the initial static scenario taking advantage of (probabilistic) knowledge of the future (Powell 1988), but, in this case, the dynamic environment of real-world instances of on-line DRTs may lead to high computational times (Cordeau *et al.* 2005). Dynamic programming techniques are too slow for real-time performance and online programming techniques don't comply with time-windows complexity (Larsen *et al.* 2008). To overcome dynamic scenarios difficulties, some solutions were proposed:

- *a priori* methods: the idea is to pre-calculate several scenarios in an attempt to predict future requests;
- real-time optimization: constructs routes with the vehicles already in operation. However, the routing algorithm must be fast enough to (re)calculate a solution when new requests arrive in quick succession. (Attanasio et al. 2004), for instance, proposes the idea to take advantage of parallel processing capabilities to avoid overloading the algorithm when several requests arrive at the same time (or with a very short time interval between them).
- objective function modifications (Savelsbergh et al. 1998): sometimes, it is not interesting to minimize travel distance in the short term, for instance, in order to accommodate future requests. (Mitrovic-Minic et al. 2004a) uses the concept of double-horizon, where in the short-term, tries to minimize the total route travel distance and, in long-term, tries to maximize the slack time in order to accommodate new requests. The double-horizon concept descends from the rolling-horizon concept by (Psaraftis 1988): routes are planned for a certain time horizon that evolves as time elapses;
- waiting strategies: in dynamic contexts sometimes it is interesting to wait some time at a given node for new requests to arrive in the meantime, in order to maximize the number of requests accepted or minimize the travel distance;
- buffering strategies: the idea is to delay the answering to a new request, operating to route as planned in order to allow for more requests to arrive.

4.6 Heuristic approach

Given that a) exact algorithms can only solve very limited instances of the problem with extremely variable computation times (Toth *et al.* 2002), and b) population based and learning mechanisms based algorithms usually do not exhibit a performance level suitable for the real-time solution generation needs of the problem at hand (Voß 2001); we have designed a greedy randomized sequential constructive heuristic to obtain an initial route solution set, followed by an improvement phase. We chose to implement the Reactive-GRASP for its suitability for the problem at hand, its relative computational simplicity and the good results in terms of performance and solutions quality reported in literature using benchmark problem instances. One appealing characteristic of a GRASP implementation that we explored, mainly because our need of real time solutions, is that it can be trivially implemented in parallel, with each GRASP iteration being performed in parallel with only a single global variable required to store the best solution found over all processors. Our main effort was devoted to build the highest quality possible solutions in the construction phase, with the initial solution being constructed in a greedy random adaptative way. We also adopted real-time optimization for the immediate requests, mainly because we focused from the beginning in real-time performance for the algorithm and preliminary tests have shown that this was the case for static scenarios, so we solve static scenarios whenever a new request arrives. We re-optimize the remaining part of the initial solution after the insertion of the new request(s), taking in account that all the previous feasible requests are already in the on-going routes in one of these states: "not yet picked up" or "picked up but not delivered" (i.e., "picked up and delivered" are not considered in the re-optimization). The optimization of the performance of the algorithm to deal with higher degrees of dynamism was a major concern at all times.

Next, we present a detailed description of the construction and improvement phases of the heuristic approach.

4.6.1 CONSTRUCTION PHASE: NODE-RANKING FUNCTION

The construction strategy evaluates the elements to be inserted in the solution at each iteration according to some criteria. These criteria adapts to the already built solution, such that the evaluation of the elements changes during the construction of the solution.

Each transportation request is composed by an origin, a destination, as well as a pickup and a delivery time. Having a set of requests, the algorithm tries to find a set of trip sequences, called routes, optimizing the objective functions and respecting all problem constraints. A basic idea is to acknowledge that, in the limit, having enough available vehicles, every feasible request can be satisfied by a different vehicle - as in the initial step of the *savings algorithm* (Clarke *et al.* 1964) where each request is assigned to a different vehicle. The greedy constructive algorithm developed is called Node-Ranking Function

(NRF from now on) and tries at each iteration to find the next “best” node (bus stop) to be inserted in the route being constructed according to two perspectives:

- vehicle (or business) perspective – minimize travel cost and maximize number of satisfied requests;
- passenger (or human) perspective – minimize waiting time and minimize travel time.

In terms of the vehicle perspective, the major factors in the determination of the next node are the distance from the present position to all other nodes and the number of passengers at those nodes. From the passenger perspective, the major factors are the number of passengers already inside the vehicle having as destination a given node and the time windows (namely the lower time limits of pickup e_{i_p} and delivery e_{j_p}) at the remaining nodes. For each of these four factors, the decision maker defines a weight (α), in order to account for the different perspectives (multi-criteria decision making). Let α_d be the weight of the distance factor, α_p the weight of the number of passengers’ factor, α_v the weight of the delivery time window lower limit and, finally, α_t the weight of the lower limit of the pickup time window. Let $NW(\tau) = (W^+(\tau) \backslash W_{as}^+(\tau)) \cup W^-(\tau)$, then the Node-Ranking Function (NRF) is defined as:

$$\forall i \in NW(\tau), NRF[i] = \left(\alpha_d \times CRL[i] + \alpha_p \times NRL[i]\right) + (\alpha_v \times DRL[i] + \alpha_t TRL[i]) \quad (34)$$

where the first operand represents the vehicle perspective and the second represents the passenger perspective. CRL *(Cost Rank List)* is the ordered list of the normalized travel costs to each node, so $CRL[i]$ is the normalized cost from the present node to node i. NRL *(Number of passengers Rank List)* is the ordered list of the normalized load at each node, so $NRL[i]$ is the normalized load at node i. DRL (Delivery Time Rank List) is the list of normalized delivery lower time limit at each node, so $DRL[i]$ is the lower limit of the delivery time window associated to the node i. TRL *(Time-window Rank List)* is the list of normalized pickup lower time limit at each node, so $TRL[i]$ is the lower limit of the pickup time window at node i. The normalization of the values is obtained using $(Z_i^k)_N = \frac{Z_i^k - Z_{min}^k}{Z_{max}^k - Z_{min}^k}$ for maximization, and $(Z_i^k)_N = \frac{Z_{maxi}^k - Z_i^k}{Z_{max}^k - Z_{min}^k}$ for minimization.

Figure 36 presents the pseudo-code for the Node-Ranking Function algorithm.

```
Step 1:inicialize $S = \{\}$
While $NW \neq \emptyset \wedge num_{vehicles} \neq 0$
        Step 2:inicialize $R = \{\}$
        Step 3: start at the depot $R = \{0\}$
        Step 4: compute the NRF rank of all feasible nodes:
                Step 4.1:build the Cost Rank List (CRL) - sort all nodes
                by increasing distance from the current one, and normalize
                the values obtained, such the closest node is assigned
                with the highest value and so on;
                Step 4.2:build the Number of Passengers Rank List (NRL) –
                sort all nodes by decreasing order of the load and
                normalize.
                Step 4.3:build the Delivery time-window Rank List (DRL) –
                sort all nodes with delivery requests by increasing order
                of the closest delivery time associated to the node plus
                the trip time to that node and, finally, normalize so that
                the "earliest" gets the highest score and so on.
                Step 4.4:build the Time-window Rank List (TRL) - sort all
                nodes with pickup requests by increasing order of the
                closest pickup time associated to the node plus the trip
                time to that node and, finally, normalize so that the
                "earliest" gets the highest score and so on.
        Step 5:compute NRF for each node, such that
          $\forall i \in NW, NRF[i] = \left(\alpha_d \times CRL[i] + \alpha_p \times NRL[i]\right) + (\alpha_v \times DRL[i] + \alpha_t TRL[i])$

        Step 6: select the node with highest NRF that does not violate
                the constraints (feasible node) and add it to the route –
                $R = R \cup max(NRF[i])$;
        Step 7: update requests data, eventually removing the ones
                already satisfied (picked up and delivered), i.e.,$NW =
                NW \backslash max(NRF[i])$, and moving the unfeasible ones to a
                temporary list $U$
        Step 8:if $NW = \emptyset$ then add the depot node $(0)$ to the end of the
                route $R$ and add this route to the solution set $S$,
                i.e.,$S = S \cup R$;
        Step 9:if $U \neq \emptyset$ then
                        let $NW = U$ and $num_{vehicles} = num_{vehicles} - 1$
                        goto Step3;
                else goto next step;
end-while
return solution $S$
```

Figure 36 - Node-Ranking Function algorithm

The constructive, heuristic algorithm developed here allows for different weights for each factor to be set at the beginning of the process or, more interestingly, at each iteration (thus "changing" the neighborhood structure). Solutions are sensitive to both the weighs and the rank scale values used.

Figure 37 shows the route solution set obtained using the NRF algorithm in the hypothetical initial state for a static DVRDRT problem shown in Figure 34, setting the decision maker weight parameters to $\alpha_d = 0{,}20, \alpha_p = 0{,}15, \alpha_v = 0{,}55, \alpha_t = 0{,}10$.

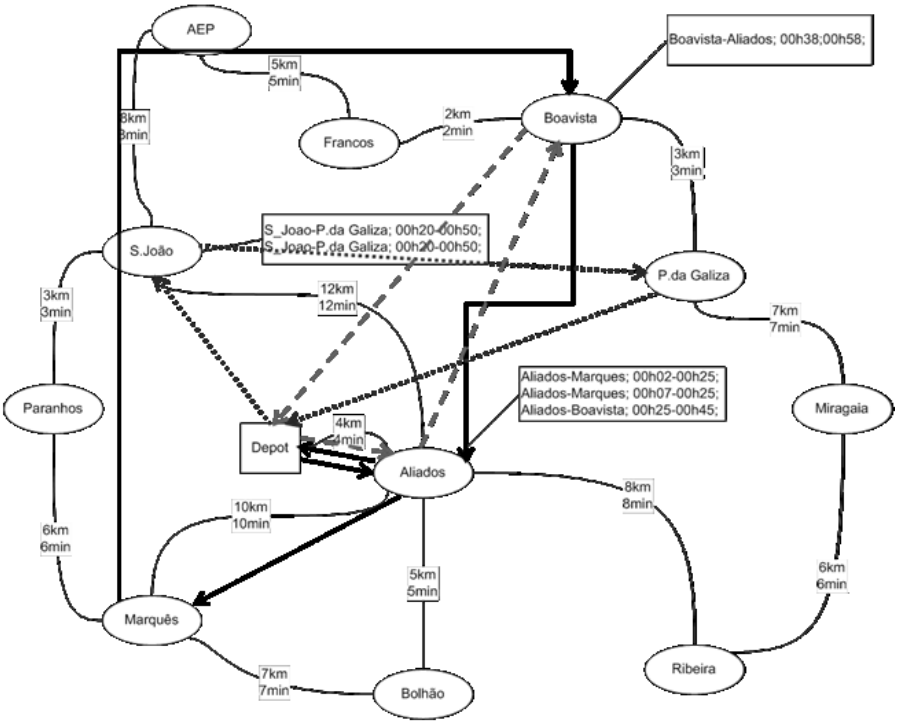


Figure 37 - NRF algorithm solution

The NRF algorithm solution for the hypothetical initial state depicted in Figure 34 for a static DVRDRT problem is a set of three routes:

- Depot->Aliados->Marquês->Boavista->Aliados->Depot (continuous line in Figure 37);
- Depot->S.João->P.da Galiza->Depot (less spaced dot line in Figure 37);
- Depot->Aliados->Boavista->Depot (more spaced dot line in Figure 37).

Looking at, for example, the first route (continuous line) one sees that the vehicle leaves the depot heading to stop “Aliados” with a trip time of 4 minutes. At “Aliados”, the vehicle picks up a passenger that was on the stop for 2 minutes and, waiting the defined time window (3 minutes), picks up a second passenger with the same destination as the first. Both passengers have defined the same delivery time (00h25m). Then, the vehicle heads to “Marquês”, arriving there at 00h17m, and drops the passengers that entered at “Aliados”. Notice that, on one hand, the decision maker defined a weight of 55% to the delivery time compliance and, on the other hand, passengers who are at “S.João” cannot be picked up by this vehicle because the trip time would violate the pickup time windows at that stop. From “Marquês”, the vehicle then heads to “Boavista”, where it arrives at 00h41m, picks up another passenger there and returns to “Aliados”. At this stop, the vehicles drops the passenger coming from “Boavista” and no one is waiting at the “Aliados” at this time because the other request made from this stop was either satisfied by another route (vehicle) or was requested for being unfeasible on this route. So, the vehicle returns to the depot and “closes” the route.

4.6.2 IMPROVEMENT PHASE

The solutions produced in the greedy randomized construction phase are not necessarily optimal. The following improvement phase tries to improve the constructed solution by moving iteratively to a neighborhood solution. This is only possible if a neighborhood structure is defined in the search space. With the purpose of understanding and discussing the added value of local search for the problem at hand, it is interesting at this point to recall the problem’s main differentiating characteristics:

- multiple vehicles with equal capacity;
- single depot where vehicle routes start and finish;
- simultaneous pickup and delivery;
- users specify transportation requests from anywhere to anywhere (many-to-many), at any time (dynamic);
- users specify pickup and delivery time-windows;
- multiple (possibly overlapping) time-windows at each stop;
- pickup time-windows must be respected (hard constraint);
- delivery time-windows can be violated at a penalty cost (soft constraint);
- variable travel times between network nodes.

In fact, DVRDRT is highly constrained. These characteristics and, more precisely, the combination of simultaneous pickup and delivery with the possibility of having multiple pickup and/or delivery time windows at each stop, increases significantly the complexity of possible local search procedures. The definition of neighborhood structures is non-trivial and their implementation is computationally complex – a good discussion on this issue can be found in (Kindervater *et al.* 1997). For instance, in (Psaraftis 1983), the author analyses the interchange procedure for the Travelling Salesman Problem (TSP) and shows that, in contrast to the TSP, where each individual interchange takes $O(1)$ time, checking whether each individual DARP interchange satisfies the origin-destination precedence constraints normally requires $O(n^2)$ time.

An interesting neighborhood structure is the ejection chains (Glover 1996) based on the idea of generating compound sequences of movements, allowing for a variable number of solutions components to be modified in a single local procedure iteration. In the vehicle routing problem, one possible ejection chain is obtained by ejecting a request from route 1 and inserting it at route 2, which, in turn, causes one request to be ejected from route 2 and to be inserted in route 3, and so forth, effectively creating a chain. The size of this ejection chain is bounded by the number of routes in the solution and can be cyclic or not. The core idea of the ejection chains is a reference structure which coordinates the kinds of movements (changes) that can be used in the local search procedure. A reference structure is a structure akin to, but different from, a problem's solution. Using a set of transition rules, the reference structure coordinates the generation of feasible movements from one solution to another - solutions are, thus, obtained from the reference structures (Sontrop *et al.* 2005). These authors propose a reference structure, called Constrained Doubly Rooted (CDR), for the vehicle routing problems with time windows (VRPTW) based on the Flower structure proposed by (Rego *et al.* 1996) with good results for the base vehicle routing problem.

Another neighborhood structure mentioned in the literature is a "parameterless" neighborhood called "zero split neighborhood" (Parragh *et al.* 2010). In each route complete sequences of requests – a kind of sub-routes – can be found. These complete sequences are found between two edges where the vehicle travels without passengers. Every route R_i in the route solution set S has at least two of these edges: from the depot to the first stop and from the last stop back to the depot. This is the core idea of the zero split neighborhoods in which a number of these sub-routes is removed from a route randomly chosen from the solution set. Then, all requests are inserted one by one into different routes chosen at random in the best way possible. However, using this idea on the studied dynamic problem is highly complex because: a) most of the times this sub-routes correspond to the entire route themselves and b) a given stop can be simultaneously the origin and destination of multiple request (these, in turn, coming from different origins) and so its later insertion at another route is far from trivial.

As a last example of interesting neighborhood structures, we briefly discuss the forward slack time (Savelsbergh 1992) – and later also in (Cordeau *et al.* 2003b) – that is based on the concepts defined in the Critical Path Method, CPM, (Kelley 1961) – or, if one considers, stochastic travel times between stops, the Program Evaluation and Review Technique (PERT) (Malcolm *et al.* 1959). The core idea is to "delay" the beginning of the service (pickup and/or delivery) at a given node without violating the time windows constraints. Consider a route $R = \{i_0 = 0, \ldots, i_q = 2w + 1\}$, v_i as the waiting time at node $i \in R$, τ_i as the time of service at node i, assuming zero service times, (Cordeau *et al.* 2003b) defines the "forward slack time" F_i at node $i \in W$ as $F_i = min_{i \leq j \leq q}\{\sum_{i<p\leq j} v_p + (l_j - \tau_j)\}$. Without violating the feasibility of the intermediate solutions during the local search procedure, the forward slack time represents the biggest increase in the time instant of the beginning of the service τ_i at node i that doesn't violate any time window. This slack can be used to, on one hand, try to delay the start of the route (thus reducing total travel time) and, on the other hand, to search the nearby stops for feasible requests that can be inserted in the slack between two stops in the original route.

In our GRASP approach for the DVRDRT we use a combination of three neighborhood structures in the improvement phase: the already mentioned forward slack time, a "nearby-stops" analysis, and a simple 2-exchange procedure. After calculating the forward slack time, the "nearby-stop" analysis takes each route in the solution set and "reproduces" its sequence of stops one-by-one trying to find in-between stops that would appear later in that route and can be served in the meantime. Suppose, for instance, that a vehicle has the following route [A,C,B,D], the "nearby-stop" analysis detects that B is in the physical path from A to C and when the vehicle leaves A heading to C it checks if it is possible to satisfy the request at B on route to C without destroying the time-windows and precedence constraints at any stop. The last improvement is a simple 2-exchange procedure based on the k-interchange procedure by (Psaraftis 1983), more specifically on a structure (a vector) that records the stop number at which each pick-up and drop-off occurs. This structure can be seen as the inverse of the route, indexed by event that gives the stop number of that event. For instance, the position i of that vector will be the stop number of the first delivery of a passenger who entered the vehicle at or after stop i. So, the swap must occur before the number at position vector's position i, or else the precedence constraints would be violated.

As a concluding remark, the definition of neighborhood structures for the dynamic vehicle routing for DRT problem is far from trivial and the implementation of such structures is highly complex, so most of our effort was devoted to build the highest quality possible solutions in the construction phase. The improvement phase in our approach is based on lightweight (in computational terms) neighborhood structures, to mitage the implementation complexity and the burden in the algorithm run-time (we need good solution in useful time) .

4.6.3 ORCHESTRATING THE TWO PHASES

The presented NRF algorithm was embedded in a GRASP-type metaheuristic. We chose to implement a Parallel Reactive-GRASP for its suitability for the problem at hand, its relative computational simplicity and its good results in terms of performance and solutions quality reported in literature using benchmark problem instances. One appealing characteristic of a GRASP implementation is that it can be easily implemented in parallel, with each GRASP iteration being performed in parallel with only a single global variable required to store the best solution found over all processors. The initial solution is constructed in a greedy random adaptative way using the NRF algorithm. This initial solution is then used in local improvements in a first-best procedure. These two phases are repeated a specified number of iterations in parallel. Figure 38 tries to capture the main idea behind the proposed heuristic approach.

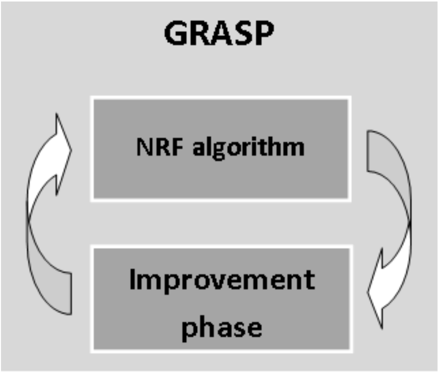


Figure 38 - DVRDRT heuristic approach

In the construction phase, a feasible solution (set of routes) is built by applying the NRF algorithm, adding to the each initially empty route one element at a time. The evaluation of each element according to the criteria is made by the already mentioned NRF function. Each NRF algorithm iteration constructs a candidate list (CL) of the elements to be inserted in the current route. From this CL, a number of its best elements are selected to form a restricted candidate list (RCL) - $RCL \subseteq CL$. The size of the RCL is defined by a parameter $\alpha \in [0,1]$ that sets either the numbers of elements or a threshold between the value of best element of the CL and the value of the last element to be included in the RCL. This last approach was considered the best for the DVRDRT problem because, being a very constrained problem and due to the adaptative nature of each iteration of the algorithm, the size of the CL varies and, sometimes, has very few elements. The α parameter should be set to calibrate how random and greedy the construction process will be. We implemented the Reactive GRASP, which reacts to solutions produced using different values for the α parameter and tries to adjust it to provide the "best" balance between greediness and randomness. At each GRASP iteration, the α parameter is chosen from a discrete set of values $\{\alpha_1, .., \alpha_m\}$. The probability of selecting a given α_i is $p(\alpha_k), k = 1, .., m$ and these probabilities are adjusted to favor α values that produce good solutions. Initially, we set equal probabilities to each α_k, i.e., $p(\alpha_k) = 1/m$, $k = 1, .., m$, then periodically, at every X GRASP iterations, the probabilities are updated according to $p(\alpha_k) = q_k / \sum_{j=1}^{m} q_j$, where $q_k = F(S^*)/A_k$, being $F(S^*)$ the cost of the best solution found so far and A_k the average cost of the solutions found with α_k. Being such a constrained problem, it comes as no surprise that in the DVRDRT problem, the best solutions are found with higher values for the α parameter, i.e., more randomness, giving the possibility to choose the next node from a larger list. The next step, is to randomly select one element from the RCL and to insert it in the route being constructed. When a route cannot satisfy any more transportation requests, the route is finished. If there are any unsatisfied feasible requests left and other vehicles available, a new route for another vehicle is started and built in the same manner. The process is repeated until there are no more feasible transportation requests left to satisfy or no more available vehicles (it is useful to recall at this stage that, if one has enough vehicles at hand, every feasible request can be satisfied assigning a "private" vehicle to it). The final solution is the resulting set of routes $S = \{R_1, \dots, R_n\}$ and the total cost is calculated. The found solution is then used in the local improvements phase until a better solution is found (first-best) or the available time for improvements runs out. For the improvements phase, we use a combination of three improvements: the already mentioned forward slack time, a "nearby-stops" analysis, and a simple 2-exchange procedure. It is a multi-start meta-heuristic, so each GRASP iteration returns a solution. Only the best overall solution is kept as the final result of the GRASP.

Figure 39 presents the high level pseudo-code of the Parallel Reactive-GRASP for the Dynamic Vehicle Routing for Demand Responsive Transport (DVRDRT) problem, where at every 200th iteration the probabilities of the GRASP the α parameter are updated.

```
Parameters:GRASP_max_iterations
while (num_iterations<GRASP_max_iterations)
        choose $\alpha_k$ parameter with probability $p(\alpha_k) = 1/m\ ,k = 1,..,m$
        initialize $S = \{\}$
        Construction phase:
                Calculate $S$ using NRF and $\alpha_k$ for the RCL
        If mod(num_iterations,200)==0 then $p(\alpha_k) = q_k/\sum_{j=1}^{m} q_j\ , k = 1, \dots, m$
        Calculate the solution cost  $F(S) = \left(\sum_{i=1}^{m} C(R_i) + \sum_{j=1}^{u} C(U_j)\right)$
        Improvement phase:
                using $S$ do:
                        forward slack time
                        nearby stops analysis
                        simple 2-exchange procedure
                until $F(S^{''}) < F(S)$ or elapsed_time>allowed_running_time
                if $F(S^{''}) < F(S)$  then $S = S'$
        update best solution found $S^*$: if $F(S) < F(S^*)$ then $S^* = S$
end-while
return best solution $S^*$
```

Figure 39 - Reactive-GRASP for DVRDRT pseudo-code

Figure 40 shows the route solution set obtained using the algorithm above in the hypothetical initial state for a static DVRDRT problem shown in Figure 34 of the present chapter, setting the decision maker weight parameters to $\alpha_d = 0{,}20, \alpha_p = 0{,}15, \alpha_v = 0{,}55, \alpha_t = 0{,}10$.

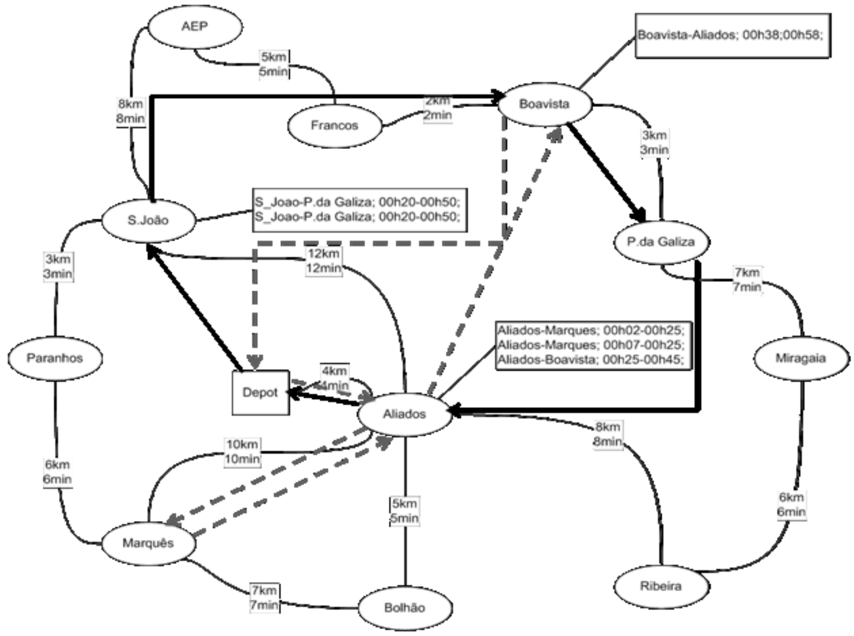


Figure 40 - Reactive GRASP algorithm solution

The algorithm solution for the hypothetical initial state for a static DVRDRT problem is a set of two routes with a significant smaller cost than the solution obtained with the "pure greedy" NRF algorithm (see Figure 37):

- Depot->S.João->Boavista->P.da Galiza->Aliados->Depot;
- Depot->Aliados->Marquês->Aliados->Boavista->Depot.

4.7 Heuristic approach assessment

4.7.1 BENCHMARKS

Being a problem with a new formulation, there are no "off-the-shelf" benchmark data bases to test the proposed heuristic approach for the DVRDRT, and to compare it with other published approaches. To the best of our knowledge, the most similar instances in the literature are the ones for the Capacitated VRP with Time Windows (CVRPTW) (Solomon 1987), the Capacitated VRP with Pick-up and Deliveries and Time Windows (CVRPPDTW) (Haibing *et al.* 2001) and the Dial-A-Ride-Problem (DARP) (Laporte *et al.*). The benchmark instances considered were:

- Capacitated VRP with Time Windows (CVRPTW)
    - (Laporte *et al.* ; Cordeau *et al.* 2001): set of various types of problems, with 100 customers and different number of vehicles. For each customer, we

    have the X,Y coordinates, service duration, demand, time windows and frequency of visit;

    - (Solomon 1987): Each costumer has a demand of X units, a delivery time window and a service time. These instances are divided into three categories: clustered customers, uniformly distributed customers and a mix of both previous categories; and have instances of 25, 50 and 100;

    - (Homberger *et al.* 1999): Extension of the (Solomon 1987) instance. The original contains 100 customers. Here is a large set of new instances with 200, 400, 600, 800 and 1000 customers.

- Capacitated VRP with Pick-up and Deliveries and Time Windows (CVRPPDTW)

    - (Breedam 2001): There are available two set of instances proposed by (Breedam 2001) for this problem. In both of them, the vehicle capacity is 100 and both have 60 VRP instances. The two benchmark differ in the quantities demanded by the customers (homogeneous quantities for one and non-homogeneous ones for the other. Each instance has a single depot, 100 stops, unlimited number of vehicles, time windows and mixed pickup and delivery;

    - VRPLIB (Vigo): The data format of the files is an extension of the TSPLIB data format (Reinelt 1991) for capacitated vehicle routing problems. The set is partitioned into six instances according to the size of the time windows. The format has information about the type of problem, a coordinate section, a demand section and time windows section. There are 200 customers and vehicles have different capacities;

    - (Haibing *et al.* 2001): this benchmark is the (Homberger *et al.* 1999) set, which in turn derives from the (Solomon 1987) set. These instances are divided into three categories: clustered customers, uniformly distributed customers and a mix of both previous categories; and can be classified according to the size of the time horizon: 1 - short time horizon, few customers per tour and 2 - long time horizon, many customers per tour. There are 10 instances of each class and some instances are more constrained in terms of time than others. We have information about X,Y coordinates of each costumer, its demand, time window and service time;

    - (Mitrovic-Minic *et al.* 2004a), (Mitrovic-Minic *et al.* 2004b): Although included in this category, vehicles don't have a limited capacity. This set of instances contains 90 instances with 100, 500 and 1000 requests. There are 30 instances for each problem size. Service period is 10 hours. Service area is 60 km x 60 km. Service time at each location is 0.

- DARP

    - (Cordone): This test set derives from the real-world street network of the Italian city of Verbania. Grouped by quality (medium or high), we have instances of 100, 200 or 300 passengers. The structure of the files has the number of passengers, the number of vehicles and their capacities, origin and destination of transportation requests and pickup time windows, but does not have spatial location of stops;

- (Pankratz 2005): This test set corresponds, in fact, to a Dynamic VRP with Pickup and Delivery with Time Windows. It is derived from the (Haibing *et al.* 2001) CVRPPDTW instances. It has a time stamp of arrival added to each request and varying degrees of urgency.

In order to use these datasets, we would have to convert the problems into DVRDRT instances. For example, a well-known CVRPTW instance is the one by (Solomon 1987): each costumer has a demand of X units, a delivery time window and a service time. In order to use this instance in the DVRDRT, one has to convert the X units demand into X different transportation requests (i.e., X different passengers) with the same delivery time window, assume that they all have the same origin stop – which is not "real" by the DVRDRT rules -, or some random stop, and, finally, ignore the service time.

Each of the other benchmark datasets poses similar problems, so, our decision was to use randomly generated instances for the city of Porto, Portugal. Being a proof of concept, we chose Porto because the needed data was readily available from several sources.

4.7.2 TEST INSTANCES

For the GRASP-type heuristic approach it is important to know:

- if the heuristic exhibits real-time performance;
- what are the major factors affecting the performance;
- what is the competitive ratio of the algorithm;
- what are the effects of assigning different weights to the decision criteria.

To this purpose we used randomly generated instances for the city of Porto, Portugal, with different number of stops, different number of requests and with different degrees of dynamism (DOD).

The service area for each test instance is a graph defined by a set of nodes, corresponding to the available stops, and links, corresponding to the roads connecting the stops. For the nodes, we used the stops of "Sociedade de Transportes Colectivos do Porto, S.A." (STCP) - bus operator for the municipality of Porto – network. For each stop, we use its real geographic coordinates and calculate the links lengths based on straight line distances between the stops. The depot is situated at "Francos" (a real STCP depot location).

For each test instance, the total number of generated requests is the sum of both advanced and real time requests. Advanced transportation requests have a number of attributes: desired pick-up time, pick-up location, desired delivery time and delivery location. Real-time requests have an additional attribute: request time. We used 15 minutes as the shortest time limit to place a request - as this was the shortest value found in the DRT survey in Chapter 2 - and randomly select request times with uniform probability between 15 to 60 minutes. The request arrival time to the service is modeled as a Poisson process, as this seems to be a general assumption for transportation related works (Larson *et al.* 1981), with parameter λ=0,3. Adding the request time limit to the request arrival time to the service, we have the user desired pickup time. For the users' "expected" travel time (i.e., to generate the desired delivery time), we use the normal distribution, with a mean of 35 minutes for Porto (according to Instituto Nacional de Estatística (INE) in 2001) and a standard deviation of 17 minutes (Melo 2002).

We generate origin and destination locations of the requests assuming that all nodes in the network have the same probability of being departure or destination points, i.e., assume that requests occur uniformly in any place of the service area.

Table 9 shows the dimension of the generated test instances, in terms of number of stops and requests. For each of these dimensions, as already mentioned, we tested also with different DODs: from 0% to 90% (we considered that all services had at least some requests in advance), with 10% increments.

Number of stops	10	25	50	100	250	500	750	1.000
Number of requests	5	10	20	50	75	100	250	500

Table 9 - Dimension of generated test instances

4.7.3 SOME RESULTS

Computational tests were done using an Intel Core Duo running at 1,66 GHz, with 2 GB RAM memory, and the adjustment of the α parameter that controls greediness/randomness level at every 100th algorithm iteration. The number of parallel threads running the algorithm is dynamically set to 8 (more details on this subject in Chapter 5).

In terms of performance, each 1000 iterations averages less than 1000ms, for 20 transportation requests in the Porto area. Another observation is the linear increase in running time with the number of iterations, the running time for each iteration being constant – this is in line with the literature results for GRASP-based algorithms.

The results obtained seem to highlight that the major factor affecting the algorithm running time is the number of passengers. Figure 41, obtained using 50 stops and 1000 algorithm iterations shows the effect of increasing the number of passengers (requests).

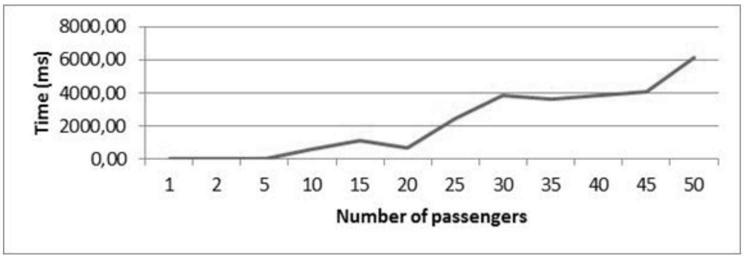


Figure 41 - Number of passengers' effect on the proposed heuristic algorithm

One common way to evaluate algorithmic approaches for Dynamic Vehicle Routing problems is to use the competitive analysis framework (Larsen *et al.* 2007). Our approach was to increase the degree of dynamism, in order to understand how the overall solution cost increases when compared to having all information in advance and, as such, provide an empirical estimate of the competitive ratio of the algorithm. For the scenarios tested with at least 20 passengers, the solution cost of a 90% degree of dynamism scenario with requests distributed evenly throughout the planning horizon, is around 45% higher than the static scenario with all information known *a priori* (0% degree of dynamism). Figure 42 shows the competitive analysis.

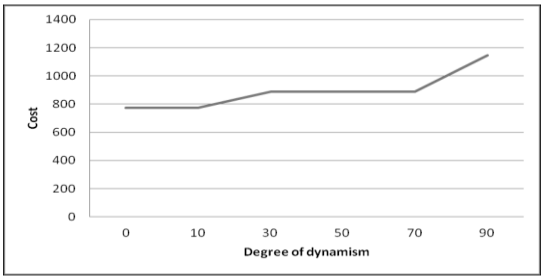


Figure 42 - Algorithm competitive analysis

Regarding the effects of assigning different weights to the decision criteria on the proposed heuristic algorithm, by increasing the weight of the vehicle's perspective criteria (minimization of distance and maximization of number of requests satisfied), the vehicles' travelled distance (cost) decreases, but the mean pickup delay increases. Increasing the weight of the passengers' criteria (minimization of waiting time and on-board ride time), the mean pickup delay decreases but the vehicles' travelled distance (cost) increases. Figure 43 shows a set of solutions obtained with different criteria weights where these effects are visible.

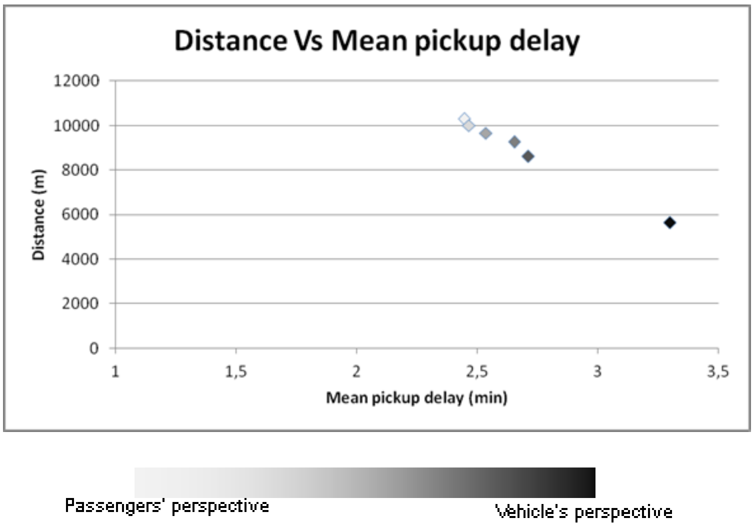


Figure 43 - Effects of assigning different weights to the decision criteria

The decision maker should use the decision support system described in the next chapter to analyze the trade-off level between cost reduction and quality of service to passengers for a given scenario.

4.8 Chapter summary

The problems of designing and operating DRT services are closely related to the Vehicle Routing Problem and, in particular, to the Dial-A-Ride Problem. Besides involving multi-objectives, DRT services can also be strongly dynamic, requiring the adaptation of solutions in real-time. In a dynamic environment, when a new request arrives at a given time instant, route planning system must deal with it and, eventually, calculate new routes. In problems with time windows constraints, the insertion of new request in real-time is more complex. Given the complexity of these problems, optimization methods are highly time-consuming, ruling out their usefulness in practice. Moreover when we consider multiple criteria, the "optimal" solution is in general meaningless because it is impossible to satisfy all (usually conflicting) objectives simultaneously.

The formulation presented in this chapter is intended to be flexible, easily allowing new constraints and variants of the problem, like a generic framework for the design of different multi-objective customizable algorithmic approaches for different kinds of DRT systems. For the dynamic routing, we followed a rolling horizon approach, which is to solve static scenarios when a new request arrives and/or the travel times change. There is an initial route schedule that incorporates all data currently known and this route schedule is adjusted only when required using the most recent data. We implemented a Parallel Reactive-GRASP-like heuristic for its suitability for the problem at hand, its relative computational simplicity and good results in terms of performance and solutions quality reported in literature. The initial solution is constructed in a greedy random adaptative way using a constructive algorithm (the NRF algorithm). This initial solution is then used in local improvements in a first-best procedure. These two phases are repeated a specified number of iterations in parallel.

To test the proposed heuristic approach, our decision was to use randomly generated instances for the city of Porto, Portugal. The results obtained seem to highlight that the major factor affecting the algorithm running time is the number of passengers. For the same problem, the solution cost of a 90% degree of dynamism scenario, with requests distributed evenly throughout the planning horizon, is around 45% higher than the static scenario with all information known *a priori* (0% degree of dynamism). Solutions are sensitive to the assignment of different weights to the decision criteria on the proposed heuristic algorithm.

4.9 Chapter highlights

Presentation of the Dynamic Vehicle Routing for Demand Responsive Transportation (DVRDRT) problem.

A mathematical formulation for the DVRDRT problem, flexible and allowing new constraints and variants of the problem, working as a generic modeling framework;

An efficient, customizable multi-objective algorithmic approach that deals with the combinatorial nature of the problem and with the multiple perspectives of its different stakeholders.

Algorithmic approach assessment.

Chapter 5

DECISION SUPPORT SYSTEM

5.1 Introduction

In order to involve the decision agents in the planning process, a prototype of a Decision Support System (DSS) has been developed. The system integrates the multi-objective heuristic and simulation, and has been used in testing and assessing the proposed integrated approach.

This chapter assumes that the reader is familiar with the Unified Modeling Language (UML) (OMG 2010). UML is the industry-standard language for specifying, visualizing, constructing and documenting the artifacts of software systems, as well as other non-software systems. UML provides both the structural views and behavioral views of the system.

5.2 Requirements analysis

The objective of this section is to present the functional and non-functional requirements of the DSS and describe the main functionalities of the system.

5.2.1 FUNCTIONAL REQUIREMENTS

Figure 44 shows the top level structure of the system.

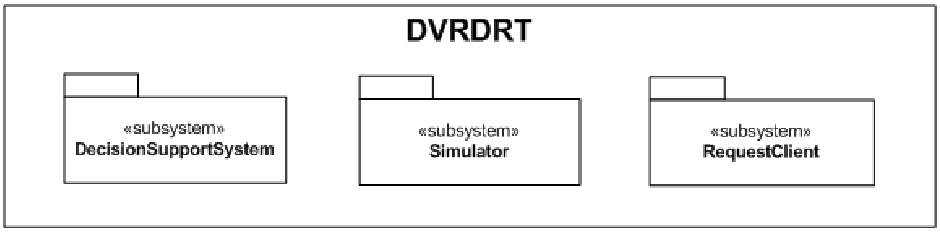


Figure 44 - Top level structure of the DVRDRT system

The top level structure diagram provides a vertical cut view into the system, showing its decomposition into subsystems. The DSS for DVDRT has three subsystems: the Decision Support System, the Simulator platform and the Request Client. The Use Case diagram for each of these subsystems follows. Use Case diagrams identify the functionality provided by the system, the users who interact with the system (the actors), and the association between the users and the functionality. Use Cases are used in the analysis phase of software development to articulate the high-level requirements of the system. The primary goals of Use Case diagrams include:

- providing a high-level view of what the system does;
- identifying the users ("actors") of the system;
- determining areas needing human-computer interfaces.

Decision Support System Use Case diagram

Figure 45 shows the Use Case diagram for the Decision Support System.

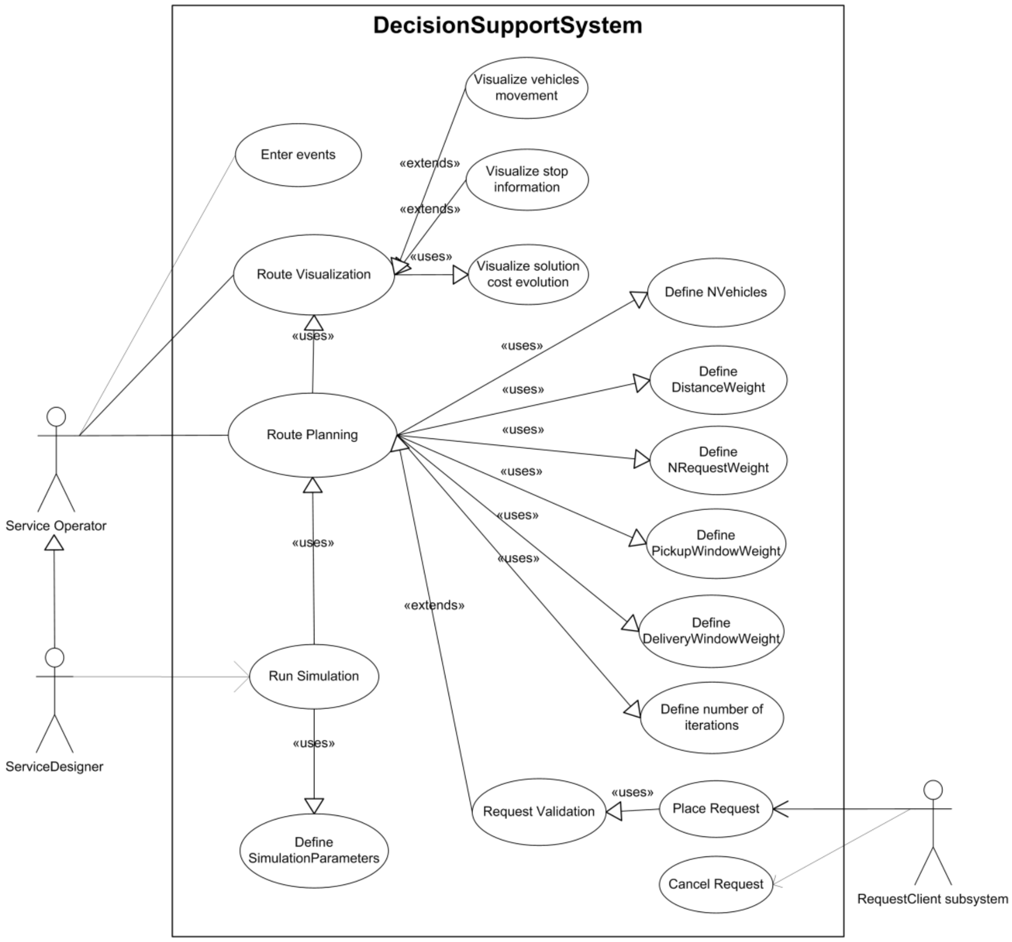


Figure 45 - Decision Support System Use Case diagram

Actors

ServiceOperator is the user that interacts with the Decision Support System for the route planning tasks of a designed DRT service.

ServiceDesigner is the user who interacts with the system with the main purpose of performing simulations in order to design the DRT service. He inherits the properties of the ServiceOperator actor (he can do all the tasks of the ServiceOperator plus the simulation).

RequestClient interacts with the Decision Support System with the objective of requesting the transportation service.

Main Use Cases

RoutePlanning

Route planning is the core use case of the system. It can be initiated at any time by service operator's request, but can also be performed automatically each time a new event arrives from the simulation model or a new transportation request arrives in real time. In the latter case, the request feasibility must be checked. Simulation events include customer-related events (new real-time requests, cancelations and no-shows) and vehicle related events (reaching a stop, breakdowns during service and delays).

The route planning requires the service operator to specify his/her perspectives/preferences, assigning weights to the different criteria: travel distance minimization, maximization of number of requests served, minimization of passenger waiting time and, finally, minimization of passenger on-board ride time. The service operator can also specify how many iterations the algorithm should perform. The service operator can also adopt default values for all the settings.

RouteVisualization

The service operator can at any time visualize the current route solution set. The routes are displayed on the map area and were defined by the route planning algorithm. The total solution cost is displayed. It is also possible to visualize the progress of the vehicles on the network performing the routes planned. The service operator can also check information available on the stops along the routes displayed on the map at a given time, such as the number of passengers waiting at the stop and the number of passengers who specified that stop as their destination.

EnterEvents

At any time, the service operator can enter (input) events that will change the data used in route planning, such as cancelation of requests, no-shows, vehicle breakdowns during service and delays. The user can then manually establish a new route planning or let the system automatically re-plan the routes.

PlaceRequest

The user (potential DRT passenger) intending to use the service must specify a request according to his transportation needs, using the Request Client subsystem.

CancelRequest

The user, having already specified a request according to his transportation needs, can cancel it for any reason, using for that purpose the Request Client subsystem.

Simulate

The service designer(s) can at any time perform simulations. To do so, he/she should define the simulation parameters, such as the vehicles' capacity or service time windows, for instance. The simulation model generates events that are processed by Decision Support System. The route planning algorithm embedded in Decision Support System subsystem uses data from the service area model and from the vehicle model and events generated by the simulation model to do the route planning. These events include customer-related events (new real-time requests, cancelations and no-shows) and vehicle related events (reaching a stop, breakdowns during service and delays).

Request Client Use Case diagram

Figure 46 shows the Use Case diagram for the Request Client.

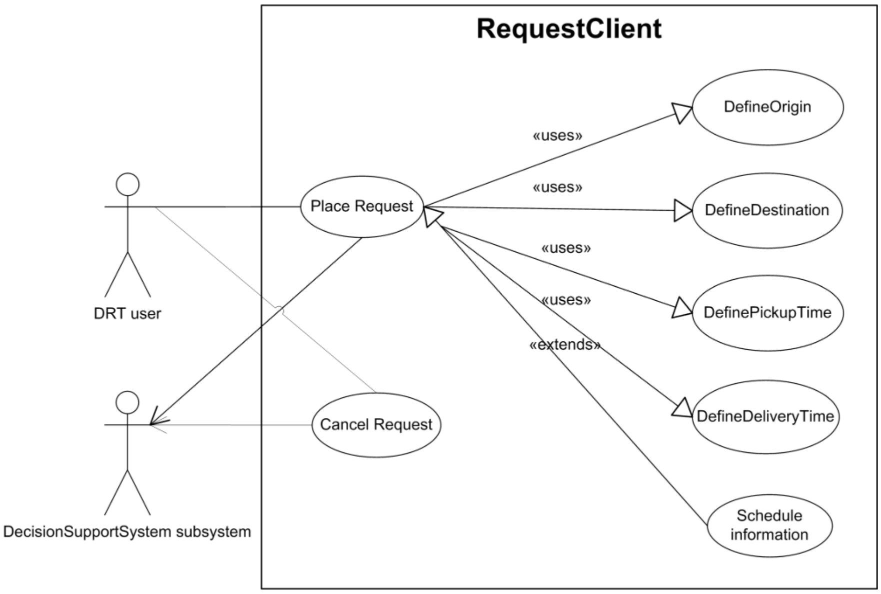


Figure 46 - Request Client Use Case diagram

Actors

DRT user: user who interacts with the Request Client system with the objective of requesting the transportation service or cancel an existing request.

DecisionSupportSystem: subsystem that receives new requests for transportation or the cancelation of transportation requests.

Main Use Cases

PlaceRequest

The user intending to use the DRT service must specify a request according to his transportation needs. To do so, he should define the origin, the destination, the pickup time and, finally, the delivery time according to his needs. This request is checked for feasibility and, afterwards, the user will be noticed about the result of the feasibility test and also on the proposed pickup and delivery times.

CancelRequest

The user can cancel the transportation service. The user can only cancel his last request made (i.e., his "active" transportation request).

5.2.2 NON-FUNCTIONAL REQUIREMENTS

First, and foremost, the system must have a performance level that allows the generation of good solutions in real-time to cope with the degree of dynamism degree. According to (Kopetz 1997), a real time computer system is a computer system in which the correctness of the system behavior depends not only on the logical results of the computations, but also on the physical instant at which these results are produced.

A number of measures should be implemented to enable a multi-tasking nature on the route planning interface. This is an important feature in terms of usability of the system: when the algorithm is taking longer than expected to perform the route planning, the interface should not hang, allowing the service operator to perform other tasks while the algorithm runs.

The system should also allow seamless data loading and access features so that the different data models (service area, vehicle and trip generation models) and advanced transportation requests can be easily incorporated and quickly accessed.

The architecture should allow for loosely coupled clients, such as the client application for placing transportations requests, to be developed, promoting interoperability between different technologies. The technology for the implementation of these client applications should not be restricted: it can be a web page, a web service, a desktop application, a mobile phone application, just to name a few.

In terms of usability, the implemented system, namely the Decision Support System application and the Client modules, should simple to use and have a smooth learning curve.

5.3 Logic architecture

This section details the design options for the system. The logic architecture and the corresponding object model is presented.

The developed system has a client-server logic architecture, based on the Three Tier Distribution Architecture pattern (Hirschfeld 1996), with a three-tier server and a thin client. This pattern is used to structure the distribution of the application functionality between distributed processing contexts, in order to optimize the usage of components and resources. The forces to be balanced are:

- if most of the application code is on the clients (fat-clients), they have to request and download all the data they need to do their tasks. This can be very inefficient and the network can become overloaded. Also, in this case, application performance is highly dependent on the platform supporting the client;
- more code on the clients means more specific-vendor dependency. We intend to support several different types of technology available for users to make their transportation requests (web pages, mobile applications, SMS services, and so on);
- distributing code between servers and clients makes the application scalable, but the system can become more difficult to maintain;
- if clients have direct access to data, this may require continuous checking of the server to detect changes and maintain consistency. This leads to network loads and some of the clients may become inconsistent.

The three-tier distribution architecture describes the partitioning of the application functionality into three tiers: front-end clients, application servers and a storage/data management server. The client implements only the presentation logic (thin-client). The business logic is implemented on application servers. Then, there is the back end component that provides users with access to services like database servers.

The vast majority, if not all, of the application logic is contained in the middle tier. It processes the clients' calls, eventually translating them into database queries, and the data from the database is simultaneously translated into client data. This effectively decouples components and allows for thin clients, i.e., clients that demand very few resources both from the platform supporting them and from the communication network between them and the server(s). The implementation of the clients in different technologies/platforms is also made possible with the positioning of the business logic on the server(s).

With the implementation of this architectural pattern we aimed at a flexible, evolutive, scalable architecture with support to the technological interoperability. As a disadvantage, it introduces another indirection level in the client-server communication – with possible consequences in terms of fault tolerance and communication network performance dependency. In order to reduce the network performance dependency, we chose to tight the coupling of the Decision Support System server: the three-tiers run on the same platform machine, although in different processes. The transportation requests client is still a thin-client running on any (world) location, on any platform and implemented on any technology. The simulator could also run in any world location as a stand-alone application, but due to the data requirements (data shared with the Decision Support System and intense load and access operations), we chose to integrate the Simulator on the Decision Support System: they share the same user interface, the same middle-tier (business tier) and the same data access tier – all in the same machine by the reasons already mentioned.

The UML Deployment diagram in Figure 47 tries to capture these ideas by showing the system high level components and their inter-relationships. The three-tier architecture of the Decision Support System is also highlighted.

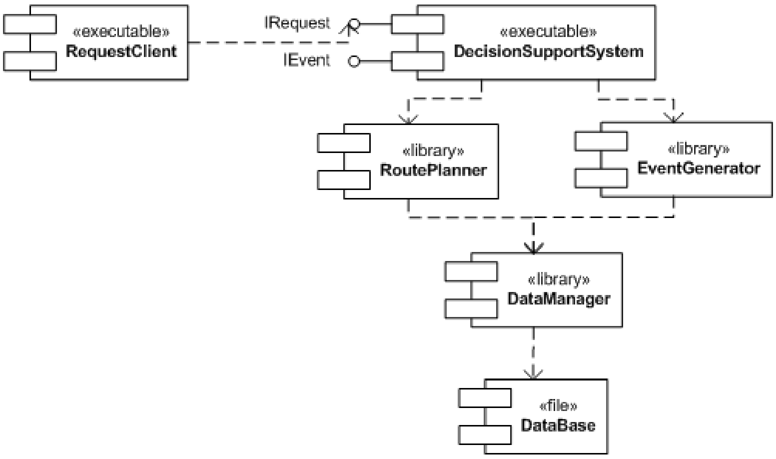


Figure 47 - Components UML diagram

As Figure 47 shows, the DecisionSupportSystem provides two external interfaces: one for requests (*IRequest*) and another for real-time events (*IEvents*). The former allows the developed client applications to insert new transportation requests and cancel requests. The later allows external systems to insert events for route re-planning: for instance. Vehicles or drivers can have systems that automatically send messages to the decision support system in case of a vehicle breakdown or if a passenger doesn't show (no-shows).

Figure 48 shows the high level logic architecture integration of the simulation system in the Decision Support System, highlighting the three-tier architecture.

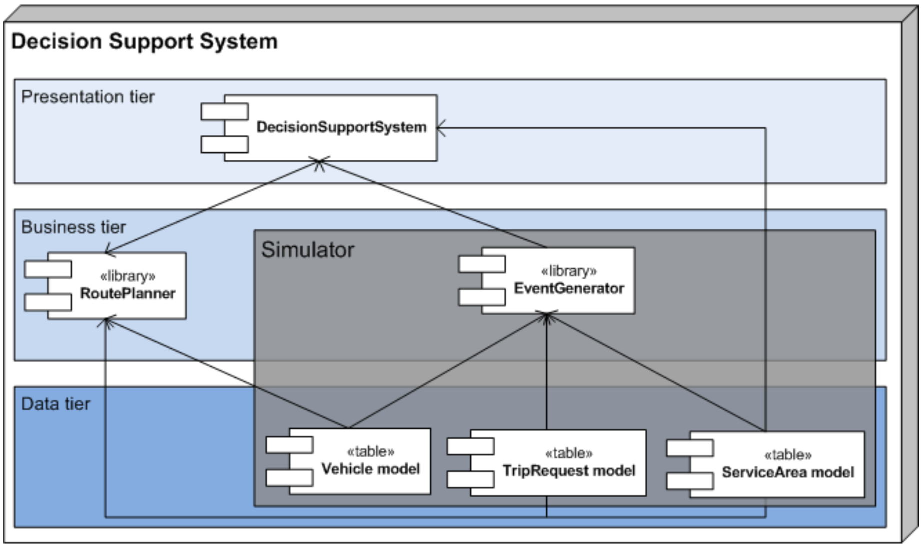


Figure 48 - System integration logic architecture

The simulator system generates time-ordered travel requests based on the trip request model. These requests are the inputs to the real-time multi-objective algorithmic approach that tries to satisfy each request by reference to a) the multiple perspectives of the different stakeholders stated via the Decision Support System's Graphical User Interface (GUI); b) a fleet of vehicles with their corresponding locations and other attributes (vehicle model) and c) the expected trip times (service area model). The dynamic routing algorithm is also responsible for updating the status of the vehicles and the corresponding set of data: assigned routes and schedules, visited stops, current network links being travelled, current speed, current position and eventual delays. The DSS Graphical User Interface (GUI) supports both the visualization of routes and the definition of the desired criteria weights by the stakeholders.

5.3.1 DECISION SUPPORT SYSTEM OBJECT MODEL

Next we present the object model of the “DecisionSupportSystem” component. The UML class diagram in Figure 49 describes the structure of a system by showing the system's classes, their attributes, operations (or methods), and the relationships among the classes, irrespective of time. Figure 49 provides a conceptual map of the DVRDRT problem.

It is important to note that, for styling commodity, in the UML class diagram presented the properties and methods for each class are omitted.

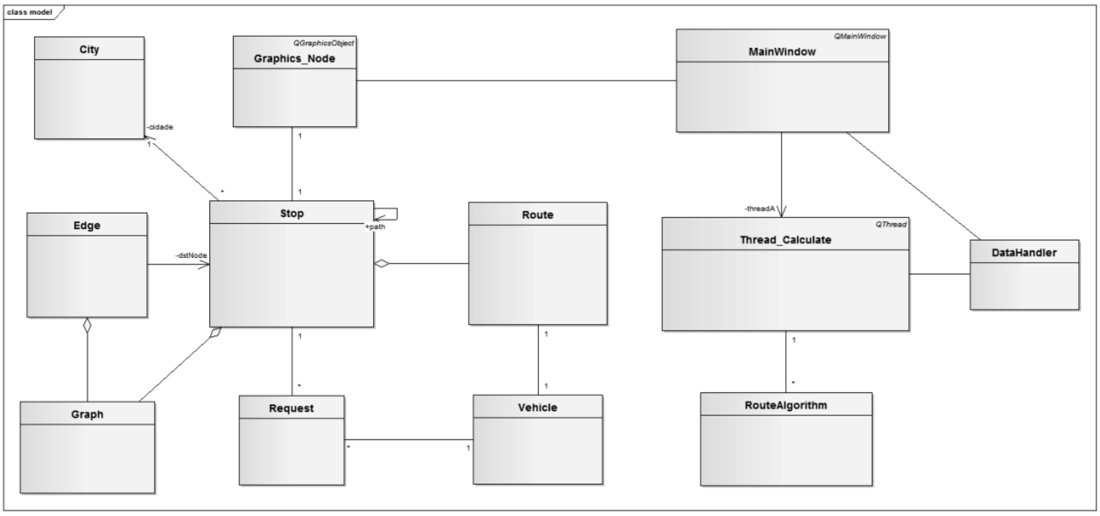


Figure 49 - System class diagram

Analyzing the relationships between the entities, we can see that a *City* (service area) is associated with several *Stop* points and, conversely, a given *Stop* point belongs to a single *City*. A *Stop* point can have several *Request*s, while a *Request* is associated with two *Stop* points (one for pickup and another for delivery). Two *Stop* points are linked by an *Edge*. The set of *Stop* points and the set of *Edge*s constitute a *Graph* (i.e., the road network graph). A *Route* is made by a sequence of *Stop* points and is always associated with a *Vehicle* – note that a vehicle may not be associated with any *Route*.

The Graphical User Interface (*MainWindow* object) is supported by thread multi-tasking, allowing the service operator to perform other tasks while the algorithm runs, and also acts as a TCP server for real-time events sent from external systems (client applications for transportation requests or vehicle on-board systems that report breakdowns, for instance). In terms of multi-thread operation, three threads are controlled by the

MainWindow object: *ThreadCalculate*, *Thread_Plot* and *Threat_Timer*. In broad terms, the first thread does the route planning, the second manages the display of data and the last manages all time-related events. The Routes are calculated by an independent thread – *ThreadCalculate* – which, in turn, is associated with one or several algorithms (*RouteAlgorithm*). This allows replacing the routing algorithm for another one easily and, so, trying new routing algorithm approaches is possible without having to re-code any other section of the Decision Support System. The *Thread_Plot* manages all data display operations, such as (re-)drawing routes on the maps or displaying information/notifications, independently of the main GUI window, thus allowing the Decision Support System user to perform other tasks on the interface and to receive real-time external events. Finally, *Thread_Timer* object manages all time related events, such as updating the vehicle positions on the map and, specially, manages the simulation. When simulation is requested, the *EventGenerator* generates simulation events (*Event*), using the service area, the trip demand and the vehicle models. These events can be of two types: *CustomerEvent* and *VehicleEvent*. The generated events are placed in a FIFO (First-In-First-Out) structure (*EventQueue*) which is accessed by the thread *Thread_Timer* thread to be processed.

5.3.2 EVENTGENERATOR OBJECT MODEL

Basically, it is a class used by the Decision Support System's *Thread_Timer* thread as a library to generate time ordered events.

5.3.3 ROUTEPLANNER OBJECT MODEL

It is a class used by the Decision Support System's *Thread_Calculate* thread as a library with the implemented algorithm.

5.4 Physical architecture

The UML Deployment diagram in Figure 50 depicts a static view of the run-time configuration of the processing nodes and the components that run on those nodes.

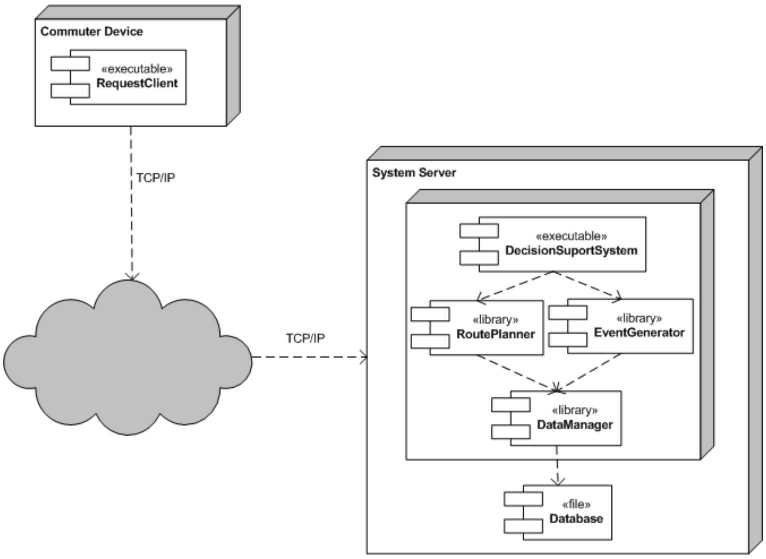


Figure 50 - System deployment diagram

We can clearly see from the diagram how the hardware is setup and which components should be in which machines.

5.5 System dynamic view

The UML Communication diagrams show the main interactions between objects using sequenced messages in a free-form arrangement. In the following subsections, each diagram corresponds to an identified use case.

5.5.1 ROUTE PLANNING

Figure 51 shows the route planning interactions.

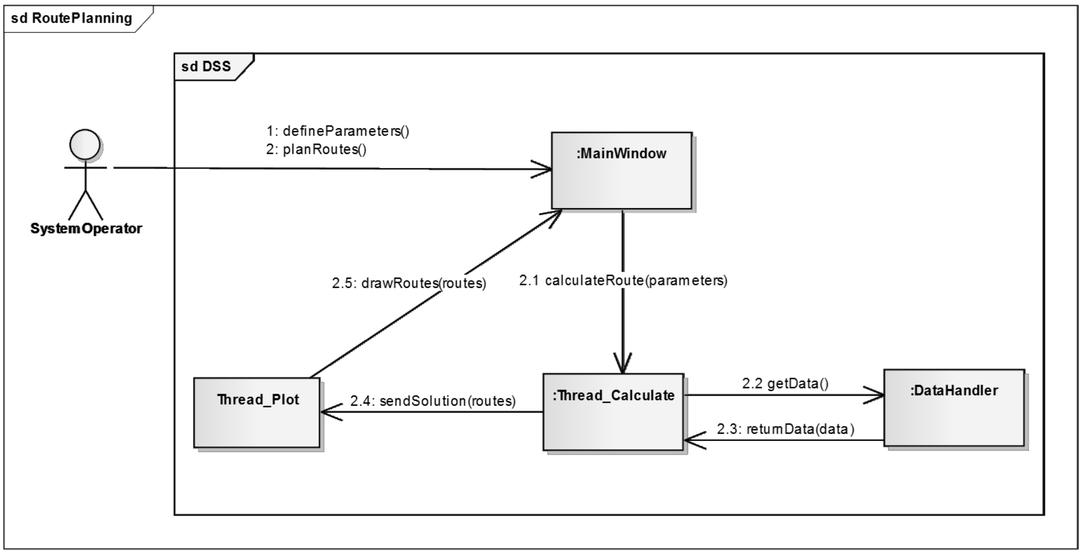


Figure 51 - Route planning in the DSS (communication diagram)

The route planning can be initiated at any time by service operator request but can also be performed automatically each time a new transportation request arrives in real time.

The route planning requires that the service operator specifies his perspectives/preferences, assigning weights to the different criteria: travel distance minimization, maximization of number of requests served, minimization of passenger waiting time and, finally, minimization of passenger on-board ride time. With these parameters, the *Thread_Calculate* object calculates the routes, accessing the data (requests, service area, vehicles fleet and their positions). The routes are then sent to the *Thread_Plot* object that is responsible for displaying all information on the main window (GUI).

5.5.2 SIMULATE

Figure 52 shows the interactions needed to perform a simulation.

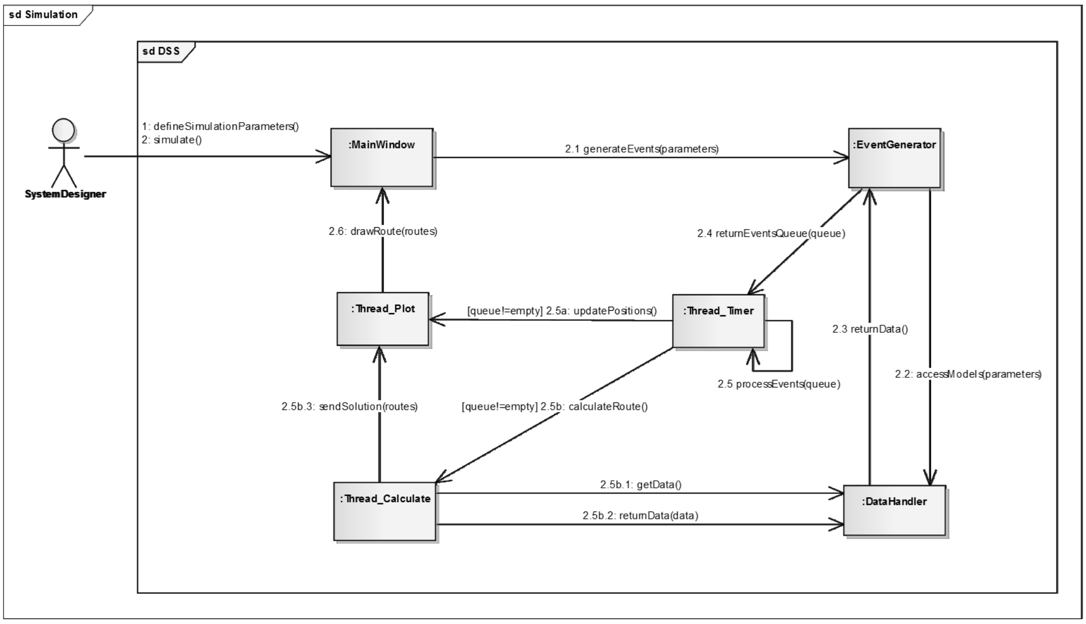


Figure 52 - Simulate in the DSS (communication diagram)

As described before, in order to perform simulation runs, it is necessary to define the some parameters, such as the service hours, for example. These parameters are then sent to the *EventGenerator* object, which generates events that include customer-related events (new real-time requests, cancelations and no-shows) and vehicle related events (reaching a stop, breakdowns during service and delays). The generated events are placed in an event queue (*EventQueue* object) that is processed by the *Thread_Timer* thread object, until there are no more events in the queue or the time available for simulation runs out. Each event process may require re-planning of routes.

5.5.3 ENTER EVENTS

Figure 53 shows the interactions to enter events. The service operator can at any time enter events that will change the data used in route planning. New events are stored in the system database by the *DataHandler* object.

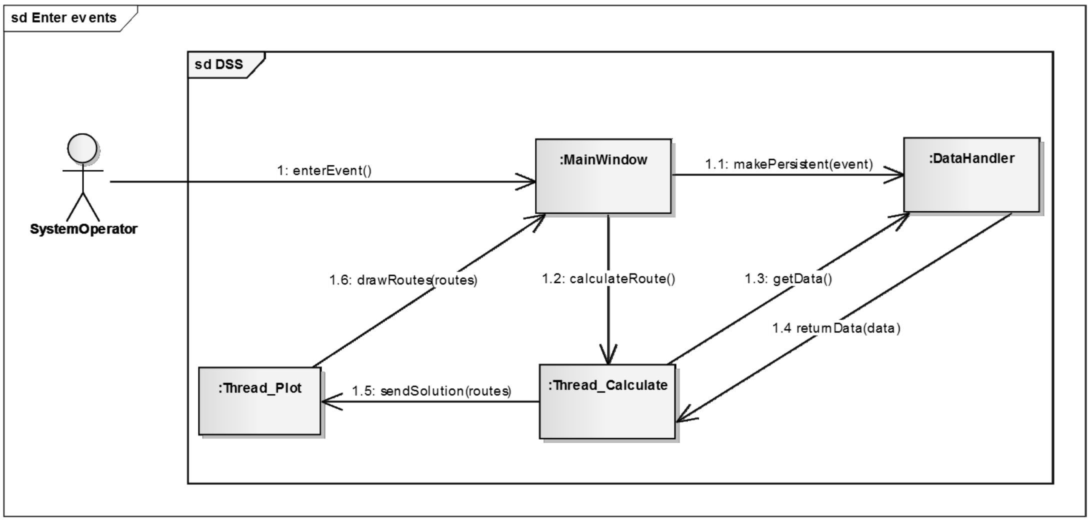


Figure 53 - Enter events in the DSS (communication diagram)

5.5.4 PLACE NEW REQUEST

The potential passenger (DRT user) intending to use the service must specify a request according to his transportation needs using the request client subsystem. Afterwards, the user will be noticed about the result of this feasibility test and also on the proposed pickup and delivery times. Figure 54 shows these interactions.

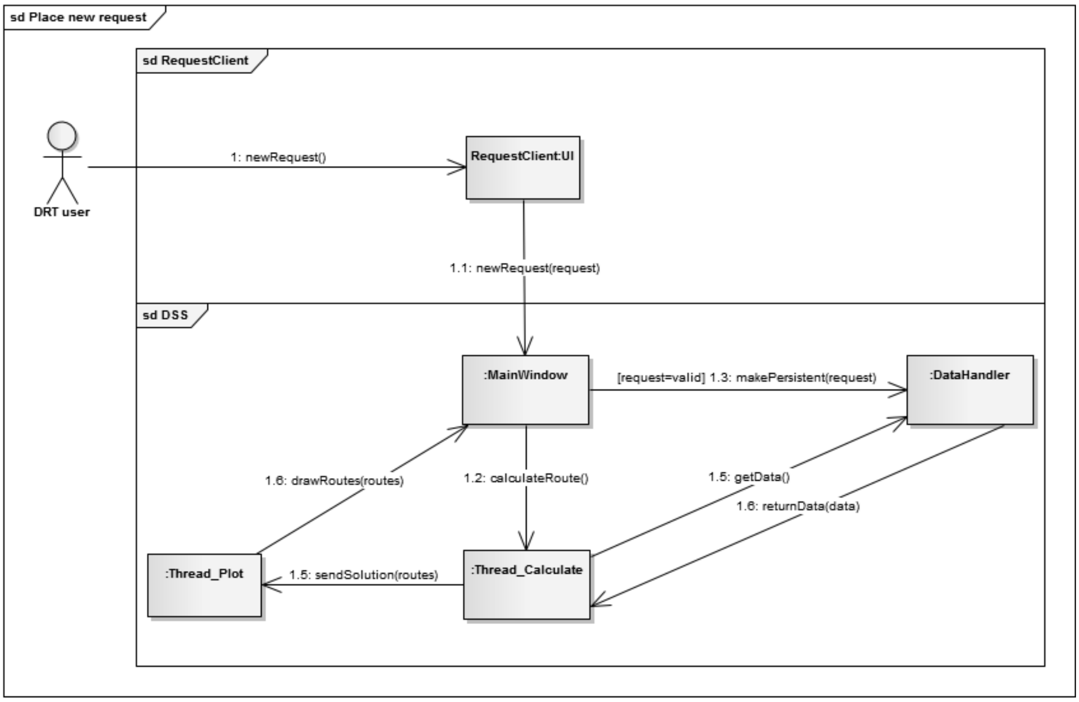


Figure 54 - Place new request (communication diagram)

5.5.5 CANCEL REQUEST

The DRT user can cancel the transportation service previously requested using the request client subsystem. On the DSS server side, this cancellation request is checked and deleted from the service database. Figure 55 shows these interactions.

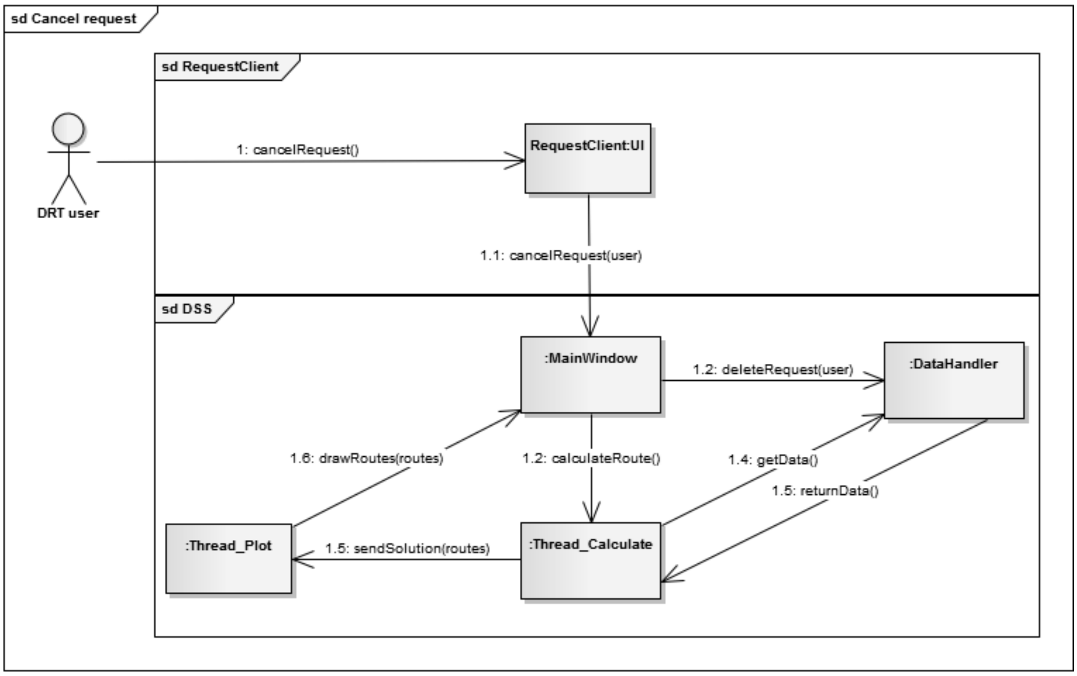


Figure 55 - Cancel request communication diagram

5.6 Implementation details

The system was implemented using the C++ programming language, in a notebook with an Intel Core2 Duo processor, 1,66 GHz, with 2 GB DDR2-667 memory, running Windows 7 Professional 32bits. The developed system is composed of:

- a Decision Support System application that includes the simulation platform;
- a desktop reservations client application;
- a mobile reservation client application.

The business and data access tiers were developed using Microsoft Visual Studio C++ 2008, with OpenMP support. For these tiers, 64bit versions were also developed in a second machine with a AMD Athlon 64 X2 Dual Core Processor 4600+, 2,44 GHz, with 4 GB DDR2-800 memory, running Windows 7 Professional 64bits. The user interface of both the Decision Support System and the two clients and also the networking and communications services were developed using Nokia QT 1.0. The mobile client was developed on a Nokia E71 mobile phone.

The Decision Support System server runs on Windows platform. The desktop reservations client runs on Windows platform, whereas the mobile reservations client runs on Symbian S60 3rd Edition.

Concerning the performance of routing algorithm, we can say that, in conjunction with its nature and structure, two other decisions contributed to the high performance of the heuristic presented, namely the adoption of the C++ Open Multi-Processing (OpenMP 2010) parallel programming API and the data pre-processing strategy using the Floyd-Warshall algorithm (Floyd 1962). A brief description of both factors and their integration on the heuristic approach proposed follows.

5.6.1 FLOYD-WARSHALL ALGORITHM

In the construction phase of the proposed heuristic approach, the evaluation of each element to add to the route being constructed is made by the NRF function. For that, at each iteration, it is necessary to calculate the distance from the present position to all other nodes – as is very often the case in many transportation problems, using the Djisktra's algorithm (Dijkstra 1959). But, besides being necessary to apply the algorithm many times during a route construction (in the worst case, as many times as the number of nodes), the procedure has to be repeated for the other routes in the (possible) route solution set and, even worse, all repeated as many times as iterations on the outer heuristic's loop.

The Floyd-Warshall algorithm (Floyd 1962) is an efficient dynamic programming algorithm to find all-pairs shortest paths on a graph. A single execution of the algorithm will find the lengths of the shortest paths between all pairs of vertices. As we needed to be able to re-construct the path, we implemented a small tweak in the algorithm o maintaining a record of the shortest paths – as in (Larson *et al.* 1981). The Floyd-Warshall Algorithm has a $O(n^3)$ complexity order, which is worse than the Djisktra's algorithm (for simple implementations, the Djisktra's algorithm has a $O(n^2)$ complexity order), but as it returns all all-pairs shortest paths on a graph and the respective path in a single algorithm run and this information is (highly) unlike to change in the course of the day, we run the algorithm only once at the boot of the system and the data will always be available to the proposed heuristic.

5.6.2 OPEN MULTI-PROCESSING

Open Multi-Processing (OpenMP 2010) is an Application Programming Interface (API) based on the multi-platform shared memory multiprocessing programming model. Jointly defined by a group of major computer hardware and software vendors, OpenMP is available in C, C++, and Fortran for several architectures. OpenMP implements multithreading parallelization (Chapman *et al.* 2007): a master thread "splits" (forks) a task into a specified number of slave threads. The threads then run concurrently, with the runtime environment allocating threads to different processors depending on usage, machine load and other factors. By default, each thread executes the parallelized section of code independently. After the execution of the parallelized code, the threads join back into the master thread, which then continues. Both task and data parallelism can be achieved using OpenMP.

The GRASP approach is very well suited for parallelization with each GRASP iteration being performed in parallel. Each thread performs one iteration of the Reactive GRASP-like algorithm. Ideally, each thread (iteration) would run on its own processor and the run time of any number of iterations would be constant and equal to the time one processor takes to do one iteration. But having that many processors is not cost-effective (nor feasible). So what we did was to dynamically fork the threads according to the number of cores on the platform hardware, taking care that the "thread splitting" process introduces overhead times and resources consumption. The same goes for the "thread joining" at the end. There needs to be a balance between the number of threads executing concurrently in a single machine and the resources available at the machine. After some testing, we came to the conclusion that, in the case of the proposed heuristic approach, the advisable number of threads on a single machine would be 4 times the number of processor cores and this "parameter" is set automatically - for instance, if the algorithm is run on a dual-core machine it will have 8 threads running the algorithm in parallel. All tests and preliminary results presented were obtained in a dual-core machine. It is expect to see performance gains running the algorithm in platforms with more cores.

5.7 User interface

5.7.1 DECISION SUPPORT SYSTEM

While building the Decision Support User interface special care was taken for its usability and response times. Each and every action that requires access to data or running the route planning algorithm is executed in background. This prevents user interface hang ups, leaving the user free to execute other tasks. This behavior is obtained using a multi-threading approach.

Figure 56 shows the interface of the Decision Support System prototype. In situation depicted, a simulation is being performed. The screen is divided in three columns and a bottom area:

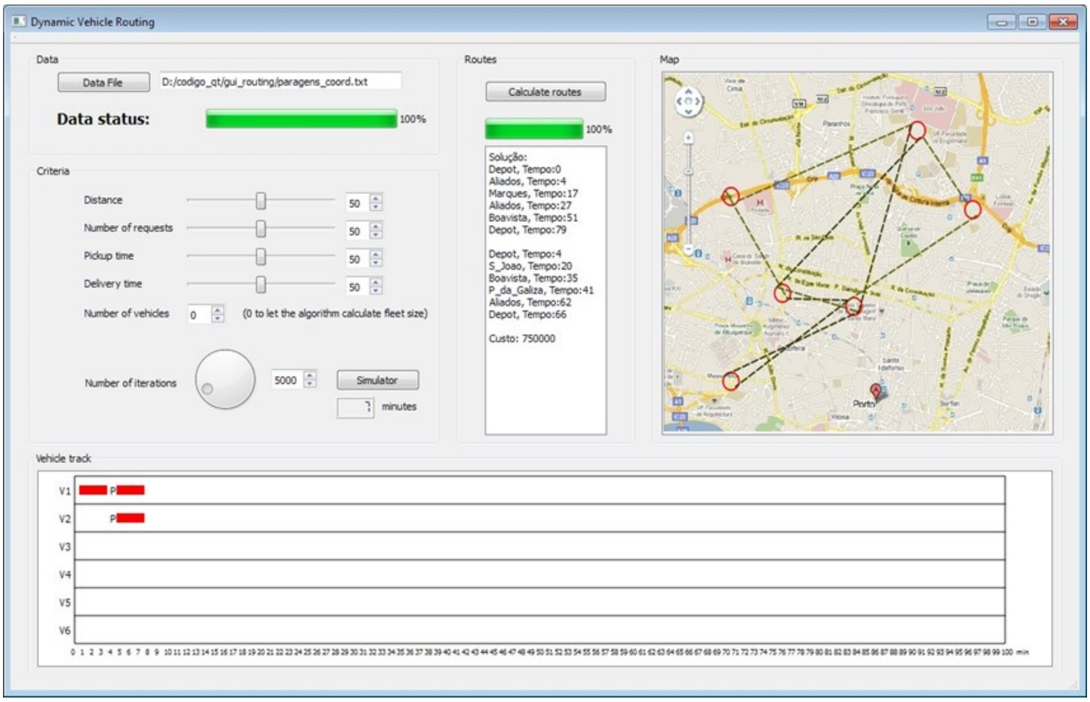
- on the left column, the service operator can load the route planning scenario data, chose the criteria weights and the number of iterations the algorithm should perform. The simulation start button is also placed in this area, together with the elapsed simulation time;

- on the middle column, we have the button to perform the route planning and, below it, an area where the routes solution set is presented in text form indicating, also, the order in which the stops are going to be visited;

- on the right column, the map of the service region is displayed and, each time the route planning is executed, the routes solutions set is drawn over the area map. On this map the service operator can also consult the information on the stops (passengers entering or leaving there);

- the bottom area is used mainly for simulation purposes. It is possible to see which vehicles are being used in performing the current route set, their position in real-time and the progress/delays as well as any vehicle related events. For instance, in Figure 56, vehicle 1 (v1) and vehicle 2 (v2) are executing their planned routes, having left the depot at time 0 minutes of simulation, in the case of v1, and at time

4 minutes, in the case of v2; more, the vehicle v1 has stopped two times for transportation related operations and v2 only one time.



Data File: D:/codigo_qt/gui_routing/paragens_coord.txt

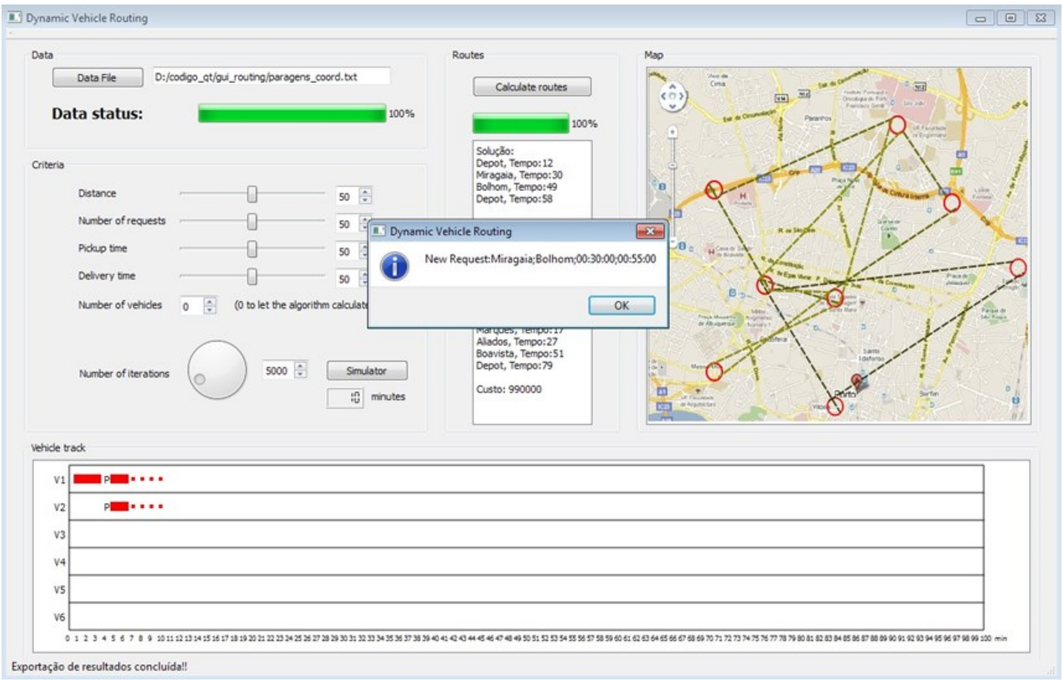
Distance: 50
Number of requests: 50
Pickup time: 50
Delivery time: 50
Number of vehicles: 0
Number of iterations: 5000

```
Solução:
Depot, Tempo:0
Aliados, Tempo:4
Marques, Tempo:17
Aliados, Tempo:27
Boavista, Tempo:51
Depot, Tempo:79

Depot, Tempo:4
S_Joao, Tempo:20
Boavista, Tempo:35
P_da_Galiza, Tempo:41
Aliados, Tempo:62
Depot, Tempo:66

Custo: 750000
```

Figure 56 - Decision Support System user interface during simulation



Data File: D:/codigo_qt/gui_routing/paragens_coord.txt

Distance: 50
Number of requests: 50
Pickup time: 50
Delivery time: 50
Number of vehicles: 0
Number of iterations: 5000

```
Solução:
Depot, Tempo:12
Miragaia, Tempo:30
Bolhom, Tempo:49
Depot, Tempo:58
```

```
Marques, Tempo:17
Aliados, Tempo:27
Boavista, Tempo:51
Depot, Tempo:79

Custo: 990000
```

New Request:Miragaia;Bolhom;00:30:00;00:55:00

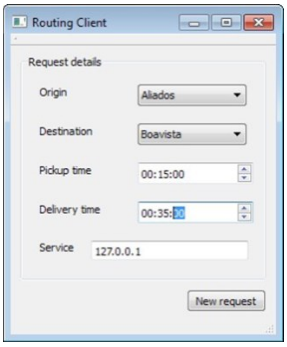
Exportação de resultados concluída!!

Figure 57 - Decision Support System user interface in real-time operation

Figure 57 shows a situation where a new transportation request arrives in real-time and the route re-planning is done automatically. The set of advanced requests is the same as the simulation situation depicted in the previous picture, but now it is possible to see on the map that, after the arrival of the new transportation request, the solution set of routes was changed (even includes a new route) to accommodate the new request.

5.7.2 DESKTOP REQUEST CLIENT

Figure 58 shows the interface of the Desktop Request client prototype. This is the application that the potential passengers use to make transportations requests. The user specifies the origin, the destination, the pickup time and the delivery time according to his needs. Note that this is a remote desktop client, so the user can be anywhere in the world but, as this is a preliminary prototype, he also should specify the web location where the server (Decision Support System) is running – in a final product this "location" can be the name of the DRT service the transport operator offers.



Origin: Aliados
Destination: Boavista
Pickup time: 00:15:00
Delivery time: 00:35:00
Service: 127.0.0.1

Figure 58 - Desktop Request client interface

5.7.3 MOBILE REQUEST CLIENT

Figure 59 shows the interface of the Mobile Request client prototype. It was captured directly from a Nokia E71 mobile phone. This is the application that the users use to make transportations requests using a mobile phone.

Paragem de Origem: Aliados
Paragem de Destinc: Boavista
Hora de Recolha: 00:00:00
Hora de Entrega: 00:00:00
Servidor: 127.0.0.1

Figure 59 - Mobile Request client interface

Figure 60 shows the mobile request client running on Nokia E71 mobile phone.

Paragem de Origem Aliados
Paragem de Destinc Boavista
Hora de Recolha 00:00:00
Hora de Entrega 00:00:00
Servidor 127.0.0.1

Figure 60 - Mobile Request client interface on a mobile phone

5.8 Chapter summary

In order to involve the experts in the planning process, a Decision Support System (DSS) has been developed. This system integrates the multi-objective algorithm and the simulation model proposed. The system exhibits a performance level that allows the generation of good solutions in real-time to cope with the degree of dynamism degree and also allows seamless data loading and access.

The developed system has a client-server logic architecture, based on the Three Tier Distribution Architecture pattern, with a three-tier server and a thin client. This pattern is used to structure the distribution of application functionality between distributed processing contexts, in order to optimize the usage of components and resources. As real-time performance was a strict requisite, we couldn't afford the risk of having network performance dependency and, so, we chose to tight the coupling of the Decision Support System server: the three-tiers are run on the same platform machine, although in different processes. The transportation requests client is a thin-client running on any (world) location, on any platform and implemented on any technology, promoting interoperability between different technologies: it can be a web page, a web service, a desktop application, a mobile phone application, or any other technology.

Summing up, the developed system is composed of:

- a Decision Support System prototype including the simulation platform;
- a desktop request reservations client prototype;
- a mobile request reservation client prototype.

The system was developed using the C++ programming language. The user interface of both the Decision Support System and the two request clients and also the networking and communications services were developed using Nokia QT 1.0. The mobile client was developed on a Nokia E71 mobile phone. The Decision Support System Graphical User Interface (GUI) supports both the visualization of routes and the definition of the desired criteria weights by the stakeholders. Route planning can be initiated at any time by the service operator, but can also be started automatically each time a new transportation request arrives in real time. The routes in the produced solution are displayed on the area map.

5.9 Chapter highlights

Decision Support Systems (DSS) requirements analysis.

Definition of the DSS logic and physical architectures.

DSS implementation details.

Presentation of the DSS user interface.

Chapter 6

CASE STUDIES

6.1 Introduction

The purpose of simulation is to obtain a better understanding of the behavior of a system in a given set of conditions, with uncertain events. The performance of the system can be determined by observing what happens in the network, during simulation, with different conditions. The results of the simulation runs also provide guidelines to help operators of public transport in the design of DRT services.

To test our approach we adopted a two-fold strategy:

- general simulation: analyze the behavior of an hypothetical DRT service in a given real geographic area, making some assumptions regarding the demand structure;
- case study: analyze a real DRT service (*Gato*), propose and assess a set of improvements to this service.

As mentioned in Chapter 4 of the present document, there are no "off-the-shelf" benchmark data bases to test our proposed approach. So, we have decided to use randomly generated instances for the city of Porto, Portugal. We chose Porto because the needed data was readily available from several sources. It is not in the scope of the present work to do an urban data gathering process, nor there were enough resources to do so. The idea was not to solve a real problem, but, rather, do a proof of concept. Nevertheless, the developed approach is independent of the scenario area and it is possible to use the developed Decision Support System and Simulation models for other areas.

6.2 General simulation

The Porto Metropolitan Area (AMP for short) is a large metropolitan area with its center in the city of Porto. Currently, what is known as the New Great Metropolitan Area is the country's second biggest metropolitan area and includes 16 municipalities: Arouca, Espinho, Gondomar, Maia, Matosinhos, Oliveira de Azeméis, Porto, Póvoa de Varzim, Santa Maria da Feira, Santo Tirso, São João da Madeira, Trofa, Vale de Cambra, Valongo, Vila do Conde e Vila Nova de Gaia. The municipalities of Oliveira de Azeméis and Vale de Cambra are the newest members (from 1 September 2008) of the New Great Metropolitan Area. According to the Instituto Nacional de Estatística (INE), in the last document produced for the AMP (AMP 2008), the area of the AMP is 1.885 km^2 and has a population of 1.672.994 inhabitants. Regarding the city of Porto itself, the main attraction zones are the downtown area (for commerce, tourism and services), the Boavista area (commerce, services and education) and the Asprela area (health care services and education). "Sociedade de Transportes Colectivos do Porto, S.A." (STCP) is the bus operator for the municipality of Porto and some other municipalities of AMP: in 2011, the network length was 522 km, with 2.651 stops in a total of 6 municipalities (Porto, Matosinhos, Vila Nova de Gaia, Maia, Gondomar and Valongo). Considering only the city of Porto, the bus network has around 1.000 different stops.

6.2.1 DRT SERVICE

We have simulated 2 hours of a DRT service that operates during the night time in the city of Porto. This service operates between 00h00 and 02h00 every day. Service booking is open during the day time to receive *a priori* requests to be served once the service starts at 00h00, and is open during service operation to receive real-time transportation requests. Passengers specify origins and destinations from a set of pre-defined possible stops, a pickup time, and a desired arrival time. The stops are STCP's bus network stops for the city of Porto (around 1.000 stops). Each possible route point, with the exception of the depot, can be a pickup point, a delivery point, or both. At a given pickup location, different passengers entering the vehicle can have different destinations (many-to-many). Several users can be simultaneously transported in one vehicle. The vehicles start and end their trips at a single depot and transportation requests can be received at any time, from any origin. Moreover, requests are to be served by a fleet of 3 owned vehicles of equal capacity (27 seats) and 2 sub-contracted vehicles (taxis). Using the terminology presented in Chapter 2, and summing up, this is a stand-alone service (N-SC1) with predefined stops only served on request (STP-3) in a service area (R-SC4), for general public (USR-2), with direct booking (B-SC2) and extendable vehicle allocation (V-SC2).

6.2.2 PARAMETERS

The developed Decision Support System integrates simulation supported by four models, as explained in Chapter 3: the service area model, the trip request model, the vehicle model and real-time events. Several simulation parameters are possible to define, both in terms of decisions and in terms of data that define these several simulation models. Table

10 presents the parameters and the example values used in this "base case" simulation runs.

Parameters			Example values
Decisions			
	Fleet size		3
	Vehicle capacity		27
	External Taxi vehicles		2
	Time window		10 min
	Fare		1 euro
	Distance minimization weight		0.2
	Requests maximization weight		0.15
	Pickup time weight		0.55
	Delivery time weight		0.1
Data			
	Vehicle		
		Vehicle commercial speed	16 km/h
		Vehicle cost per km	0,32 euro
		Fixed cost/vehicle	1.000 euro
		Taxi speed	30 km/h
		Taxi cost per km	0,60 euro
	Service area		
		Number of stops	974
		Mean travel time	35 min
		Standard deviation travel time	17 min
		Source zones (OD matrix)	9,8,6,4,1
		Sink zones (OD matrix)	7,6,5,3,2,1
	Requests		
		Number of advanced requests	100
		Degree of dynamism	10%
		New requests birth rate	Poisson (λ: 0,3)
		Cancelations statistical distribution law	Poisson (λ: 0,05)
		No-shows statistical distribution law	Poisson (λ: 0,01)

Table 10 - Parameters and example values used for "base case" simulation

A brief explanation of the most important simulation parameters follows.

Decisions

The simulation system deals with two types of vehicles: *owned fleet vehicles* and *subcontracted vehicles*. The owned fleet vehicles are homogeneous, all with the same capacity, fixed costs, operating costs and depot location, for the sake of simplicity (but it is easy to relax these restrictions to simulate also heterogeneous fleet services). As for subcontracted vehicles, they can represent taxis that the operator can contract if the fleet vehicles are not enough to satisfy extra transportation requests. These subcontracted vehicles have higher operating costs and different capacities. For the base case, we used 3 mini-buses with a *capacity* of 27 seats for the owned fleet, and 2 subcontracted taxis.

The default *time window* size is 10 minutes, for this is the smallest value found in the European DRT survey study (see Chapter 2). Naturally, the decision maker can set different values for the time-window size. The same goes for the fare price: the decision maker can try different fares. The default value is 1 euro.

Finally, the decision maker should specify his perspectives/preferences, assigning weights to the different criteria: travel distance minimization, maximization of the number of served requests, minimization of the passenger waiting time, and minimization of the passenger on-board ride time.

Data

Vehicles

In terms of data related to vehicles, it is possible to set the cost per kilometer of each vehicle type and the average commercial speed.

Service area

The simulated road network is a graph defined by a set of nodes, corresponding to the possible stops, and links, representing the roads connecting the stops. For nodes, we used the stops of the STCP network in the city of Porto: around 1.000. For each stop, we use its real geographic coordinates and calculate the link lengths based on straight line distances between the stops. The depot is situated at "Francos" (a real STCP depot location).

Requests

The simulation system generates two types of transportation requests: advanced transportation requests and real-time transportation requests. The common attributes of these requests types are: number of required seats, desired pick-up time, pick-up location, desired delivery time, and delivery location. Real-time requests have an additional attribute: the request time. The total number of generated requests is, thus, the sum of both advanced and real time requests.

One can define a degree of dynamism (DOD) as the ratio between the number of real-time requests over the number of advanced requests. Different instances can be generated with different DODs. We chose, as base case, a DOD for the city of Porto of 10%. Real-time transportation requests arrivals are modeled as a Poisson process, as this seems to be a general assumption for transportation (Larson *et al.* 1981), with parameter $\lambda = 0{,}3$.

Concerning the request time limit, it was found in the DRT survey made in the present thesis (Chapter 2) that the shortest time limit was 15 minutes, so we will also use 15 minutes as the shortest time limit, and randomly select request times with uniform probability between 15 to 60 minutes.

Adding the request time limit to the request arrival time to the system (given by the trip request arrival rate), we have the user desired pickup time. In order to simulate desired delivery times, we use the average trip time for Porto: according to Instituto Nacional de Estatística (INE) in 2001, the average trip time for a commuter using a public bus transportation system in Porto is 35 minutes. So, for the users' "expected" travel time (i.e., the time to simulate the desired delivery time) we use the normal distribution, with mean 35 minutes and standard deviation of 17 minutes (Melo 2002). Adding the user's "expected" travel time to the pickup time, we have the desired delivery time.

We generate origin and destination locations of the requests following the spatial distribution found in the OD matrices of Porto, as stated by the available mobility studies, namely, the OD matrix presented in (Oliveira *et al.* 2007) that divided Porto into 9 areas. From the OD matrix data, we identified the areas that generate more trips and those that capture more trips, and we have used this spatial distribution to generate the origins and destinations of the requests related to the structure of the demand.

Real-time events

The real time events in the system are essentially customer-related events. We do not consider vehicle related events, such as break-downs, for instance. Customer-related events include new real-time requests, cancelations and no-shows. The cancelation of requests and no-shows are assumed to be Poisson distributed, with $\lambda = 0{,}05$ and $\lambda = 0{,}01$, respectively, for the base case of Porto.

6.2.3 SIMULATION RESULTS

The results were analyzed to understand the impact of several factors on the DRT service, using, mostly, the performance indicators referred in Chapter 2. The factors considered were:

- the number of vehicles;

- the size of the vehicles;
- the time window;
- the vehicles' mean operating speed;
- the number of requests canceled (cancelations);
- the number of users that do not show at the origin of their requests (no-shows);
- the total number of requests;
- the degree-of-dynamism.

The following subsections detail the findings for each of these factors.

Impact of the number of vehicles on the DRT service

The number of satisfied/unsatisfied requests is highly sensitive to the number of vehicles in the fleet: the number of requests satisfied seems to grow linearly in direct proportion with the number of vehicles (naturally, the number of un-satisfied requests drops linearly with the number of vehicles).

The *passenger trips per revenue hour* performance indicator (that equals the *total passenger trips / total revenue hours*) tries to capture the ability of the DRT system to schedule and serve passenger trips. This indicator grows linearly with the increase of the number of vehicles, but the same is true for the *operating cost per revenue hour*, which means that the *operating cost per passenger trip* remains rather constant. The *trip denial rate* drops linearly with the number of vehicles increase. But, as more trips are served and eventually aggregated, the *mean delivery delay* increases.

With 5 or 6 or more vehicles, there are almost no refused real-time requests, but the (fixed) cost of these vehicles is usually high and, as such, the operator might not have as many vehicles as he would need to satisfy all real-time requests. Therefore, the operator might consider between 4 and 7 fixed vehicles and subcontract external taxis to cope with the un-satisfied real-time requests, depending on the budget for the fleet fixed costs.

Impact of the vehicle size on the DRT service

The *passenger trips per revenue hour* performance indicator remains stable with the increase of the vehicles capacity, but, as the fixed cost grows with the size of the vehicle, the *operating cost per revenue hour* grows, which, in turn, means that the *operating cost per passenger trip* grows with the size of the vehicle.

There is almost no effect of the vehicle size, both on the satisfied and unsatisfied requests, for sizes between 12 and 90 seats. Very small vehicles, like vans with 9 or 10 seats, do not seem appropriate because, although having a lower fixed cost, the number of satisfied requests is also smaller. A full size bus may have a lower average commercial speed than, say, a minibus and so the number of refused real-time requests grows. The sweet spot seems to be between 12 and 18 places. Lower than 12 and the operator might miss many requests, higher than 18 might result in low occupancy rates and higher fixed costs. Vehicles with 10 and 12 seats are the ones with lower fixed costs. Table 11 presents some of the results from simulation according to the vehicle size (note that this table presents average values and that a small number of requests do not fall into columns 3 and 4 – due to cancelations and no-shows that occur with a given probability, defined in the simulation parameters).

Vehicle size (seats)	Cost (€)	Satisfied requests	Unsatisfied requests	No-shows/cancelations
10 seats	229,0	9,4	83,9	6,7
12 seats	231,6	12,7	80,4	6,9
14 seats	306,9	19,1	73,3	7,6
16 seats	305,8	15,7	76,6	7,7
18 seats	305,6	15,5	76,1	8,4
20 seats	305,6	14,5	77,8	7,7
22 seats	307,3	13,0	80,3	6,7
24 seats	304,1	12,5	80,6	6,9
28 seats	306,5	14,3	78,2	7,5
90 seats	455,8	14,3	78,8	6,9

Table 11 - Vehicle size impact on the DRT service

Impact of the time window on the DRT service

The *passenger trips per revenue hour* performance indicator increases linearly with the time window size and, as the size of the fleet remains fixed, the *operating cost per passenger trip* drops linearly with the time windows size. The *trip denial rate* drops slightly as the time windows size increases. With larger time-windows there is a linear increase in the *mean pickup delay* (waiting time) and a slight increase in the *mean delivery delay*.

Naturally, customers prefer small time-windows. However, to maintain small time-windows, operators may have to decrease the ridesharing and increase their fleet size, thus increasing costs and lowering productivity. The setting of the time-window size needs to balance customer service quality with the impact on productivity and costs.

The sweet spot for the time-window size seems to be between 10 and 14 minutes. Besides the already mentioned equilibrium between user and operator preferences, for time-window sizes smaller than 10 minutes there are more requests not satisfied. For time window sizes larger than 14 minutes, more requests might be aggregated, leading to a slight increase in the *mean delivery delay*. Table 12 presents some of the results from simulation according to the time window size (note that this table presents average values and that a small number of requests do not fall into columns 3 and 4 – due to cancelations and no-shows that occur with a given probability, defined in the simulation parameters).

Time-window (min)	Cost (€)	Satisfied requests	Unsatisfied requests	No-shows/ cancelations	Pickup delay (min)
2	303,9	5,5	89,4	5,1	0,5
4	303,2	6,1	89,1	4,8	0,5
6	304,8	10,9	81,8	7,3	1,9
8	305,6	12,1	81,6	6,3	1,7
10	306,8	13,6	79,4	7,0	3,2
12	305,3	17,0	76,6	6,4	3,2
14	306,2	14,3	78,8	6,9	4,0
16	306,0	20,0	73,0	7,0	5,7
18	306,9	24,3	75,3	0,4	6,3
20	309,0	22,1	71,2	6,7	8,4

Table 12 - Time window impact on the DRT service

Simulation results suggested the existence of linear relationships between operating practices and performance measures:

- for each 4 minutes increase in time-window size, the number of satisfied requests increases by 3;
- for each 5 minutes increase in time-window size, there is an increase of 2 minutes in the mean pickup delay.

Planners should use the developed Decision Support System to test the "best" time-window size for the problem scenario at hand.

Impact of the vehilce speed (traffic) on the DRT service

The *passenger trips per revenue hour* performance indicator increases as the average commercial speed increases and, as the size of the fleet remains fixed, the *operating cost per passenger trip* drops linearly with the increase in vehicle commercial speed. Also, the *trip denial rate* drops slightly as the vehicle commercial speed increases. With the increase of commercial speed, there is a slight decrease in the mean pickup delay and a big drop in terms of the mean delivery delay.

As the vehicle speed increases, the number of accepted requests increases, as expected, but at a slower rate if compared to, for instance, the increase of the number of available vehicles. This is understandable, because a vehicle cannot be in two places simultaneously, so even if the speed increases, more requests can be accepted but not as much as having extra vehicles. There is a compromise, though, because extra vehicles mean extra fixed costs. The speed variations are analogous to traffic congestion, in the sense that congested network links mean lower average speeds, so it can be said that when traffic congestion builds up, the number of satisfied requests drops. Traffic congestion also plays an important part, as simulation results point that every 2,5 km/h drop in the mean vehicle's speed corresponds to one less request satisfied.

Planners should use the decision support system taking the traffic values and expected number of requests for a given scenario, to understand which is the number of vehicles the service should have available, or the size of the time window, to achieve the envisaged service quality level.

Impact of cancelations on the DRT service

As noted by (Nuworsoo 2011), the most common causes for disruption of service schedules are late trip cancellations or no-shows.

When a passenger cancels a request either: a) the vehicle that was heading to pick up that request "looses" the trip portion already made but has a "slack" to accommodate new requests; or b) the vehicle was not heading to the request yet(i.e., the request was far ahead in the vehicle route) and it does not lose anything in terms of distance cost and has a new slack to accommodate new requests, thus, eventually, avoiding the need to send a new vehicle (if available) to serve these new requests. In both cases, the "slack" time to accommodate new requests is larger than in the no-shows case. The slight decrease in *trip denial rate* as cancelations increase indicates precisely this effect.

Simulation results seem to point out that cancelations have a big impact in the *operating cost per passenger trip* indicator: this indicator grows steadily with the increase in cancelations, and when more than 80% of the requests are canceled, the *operating cost per passenger trip* grows sharply.

Impact of no-shows on the DRT service

No-shows have a very similar effect to cancelations. In fact, no-shows can be regarded as (extremely) late cancelations. However, unlike cancelations, no-shows also have an impact in the overall profit of the service: as no-shows increase, the profit decreases. The reason for this difference is that in the no-shows case, the vehicle has to do the full trip to the request origin just to find that the passenger did not show up, whereas in the cancelations case, the cancelation can be made before the trip beginning time and, as such, either the vehicle only does part of the pickup trip, or does not have to do the pickup trip at all. When the vehicle travels to pick up a request and the passenger does not show up, the travel distance and time of the corresponding delivery trip already planned into the route becomes available and it can represent a cost reduction (total distance travelled) – compared to the initial plan cost -, or an opportunity to serve new real-time requests. Naturally, this is true for services with some degree of dynamism – for services that only accept advanced requests, a no-show always represents a cost of making the trip without the revenue associated to the fare, plus the cost of the "empty" trip to serve the next request on the planned route.

Finally, there seems to be a consistent increase in *operating cost per passenger trip*, at a slight higher rate when compared to the impact of cancelations on this indicator. At around 50% to 60% of no-shows, the *operating cost per passenger trip* increases more rapidly, and at between 90% and 100% of no-shows, this indicator increases sharply.

The decision support system would help to understand the impact of no-shows on the service, for the estimated degree of dynamism, in a given scenario. A careful analysis of the simulation results should be carried out, especially in scenarios where a high number of no-shows is expected.

Impact of the number of requests on the DRT service

The *passenger trips per revenue hour* performance indicator (*total passenger trips / total revenue hours*) grows linearly with the increase of the number of requests, but the operating cost per revenue hour grows at a higher rate. Keeping a fixed fleet size, the trip denial rate grows linearly as the number of requests increases.

The number of requests has a major impact in the profit of the DRT service. The profitability of the DRT system with a fixed number of buses drops very quickly when the number of requests increases, with around 30% less profit for each 20 requests more.

Increasing demand leads to more and more rejected requests which, associated with higher costs (more traveled distance), means less profit. Associating a monetary cost to the loss of opportunity of not accepting a request, the effect is even more significant.

Planners should use the decision support system to define the size of the fleet and/or number of subcontracted vehicles to cope with the demand forecasted in a given scenario. A trade off in terms of fleet costs and the number of rejected requests should be achieved.

Impact of the degree-of-dynamism on the DRT service

The *passenger trips per revenue hour* performance decreases with the increase of the degree of dynamism, but the *operating cost per revenue hour* increases, which means that the *operating cost per passenger trip* also increases. So, there are fewer requests satisfied per revenue hour and at a higher cost. The trip denial rate drops linearly with the degree of dynamism.

The increase of the degree of dynamism has a big impact on the number of unsatisfied requests: the higher the DOD, the higher the number of unsatisfied requests (keeping fleet size constant). Also, the overall cost increases. However the profit does not seem to be very affected if the operator has refused (real-time) requests (because of reaction time) and, as such, the vehicle does not travel to those locations, and so there is only the distance costs associated with the already accepted requests which, in turn, tend to be less as DOD grows. This also means that if the cost of not satisfying requests is high, the overall cost grows accordingly and the profit quickly decreases.

6.2.4 CONCLUDING REMARKS AND GUIDELINES

The developed Decision Support System can be very helpful to find the best combination of the decision parameters to design DRT services that meet the envisaged cost level and quality of service. For example, for a given demand structure, decision makers should experiment with different time window sizes, different number of vehicles and capacities, and different number of subcontracted taxis, because these parameters directly influence indicators such as fixed costs, the total distance travelled, the number of requests satisfied/unsatisfied and the mean pickup delay. Moreover, different criteria weights result in different cost structures and service quality and, as such, should be analyzed using the Decision Support System. These factors should also take into account the available budget: for example, the budget limits the number of fixed vehicles assigned to the service and so, decision makers should try different time-window sizes or a different number of subcontracted vehicles to meet the envisaged service quality level or target operational cost constraints.

In the case of Porto, with the DRT service and demand structure presented, the operator might consider between 4 and 7 fixed vehicles, with a capacity between 12 and 18 seats, subcontract external taxis to cope with the un-satisfied real-time requests and the time-window should be set between 10 and 15 minutes. Note that, although external taxis can have two types of costs (a fixed cost, representing their availability, and a variable cost, representing the cost of providing the service), we only considered the cost of providing the service. If the demand changes significantly, in terms of the number of requests, or degree-of-dynamism, and/or the traffic conditions, the operator might tune the parameters to better understand the behavior of the DRT service in these conditions. Keeping a fixed fleet size, the profitability of the DRT service drops very quickly with the increase of the number of requests but, as also noted by (Noda *et al.* 2003), increasing the number of buses proportionally to the demand, the profitability of the DRT system improves significantly. In the simulated Porto scenario, typically, a new vehicle in the fleet means 6 new requests satisfied but this new vehicle has a fixed cost that must be analyzed, comparing it to the available budget and the cost of subcontracted vehicles. On the other hand, for each 4 minutes increase in the time-window size, the number of satisfied requests increases by 3, but there is an increase of roughly 2 minutes in the mean pickup delay – and this must be taken into account in terms of the envisaged quality of service and the corresponding public perception, that might deteriorate with the increasing delays. Several combinations of number of vehicles, vehicle size and time-windows should be analyzed: for instance, increasing time-windows might be a "cheap" way to cope with increased demand, but it depends on the growth rate of the demand. In fact, if there is a big increase in demand, as a vehicle cannot be in two places simultaneously, even having bigger time-windows does not allow to satisfy as many requests as having more vehicles. Figure 61 shows these effects.

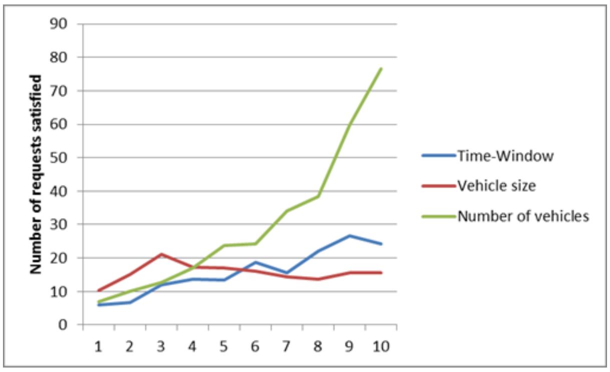


Figure 61 - Effect of increasing the time-window size, vehicle capacity and number of vehicles on the number of requests satisfied

Figure 61 also shows that the number of satisfied requests grows quicker than the number of vehicles. This seems to point out that having a higher number of vehicles gives a higher flexibility and the requests can be better aggregated.

Traffic congestion also plays an important role. Simulation results point out that every 2,5 km/h drop in average vehicle speed corresponds to one less request satisfied. Therefore, for congested areas or ate some periods of the day, the decision maker might adjust the time-window size or subcontract another vehicle to cope with these peaks. The addition of new vehicles to the owned fleet does not seem to be a good choice, because the number of satisfied requests increases more with a new vehicle than with the vehicle speed increase, meaning that acquiring a new vehicle to face a peak traffic situation would mean a low occupancy rate for this vehicle and the operator would also incur in a "unrecoverable" fixed cost at other periods.

Finally, the operator must take extra care in the analysis of the expected degree-of-dynamism (DOD). On one hand, with the increase of DOD there are fewer requests satisfied per revenue hour, at a higher cost and, on the other hand, for very low DODs, no-shows and cancelations have a big impact in the costs and revenues of the service. Planners should use the developed Decision Support System to understand the relationship between: a) having more vehicles to serve more requests with the increase of DOD or bigger time-windows for more "reaction" time for real-time requests; and b) the cost of no-shows/cancelations in low DOD scenarios.

6.3 Case study: *Gato* DRT service

6.3.1 PORTO BUS OPERATOR

“Sociedade de Transportes Colectivos do Porto, S.A.” (STCP) is the bus operator for the municipality of Porto and some other municipalities of AMP: in 2011 the network length was 522 km, with 2.651 stops in a total of 6 municipalities (Porto, Matosinhos, Vila Nova de Gaia, Maia, Gondomar and Valongo). STCP also operates three tram lines. The service provided by STCP has 81 lines using around 470 buses, 54% of them powered by natural gas. From these 81 lines, 11 are operated during night time (1 a.m. to 5 a.m.) and the rest during the day time (6 a.m. to 9 p.m.). Roughly, the day time bus service is divided in 8 main groups (bus lines starting with numbers 200, 300, 400, 500, 600, 700, 800 and 900), where the first digit in the line number corresponds to the destination geographic area according to Figure 62, and 4 other lines using lower capacity buses serve low demand zones (ZL - Zona Lordelo, ZM - Zona Massarelos, ZR Zona Rio and ZF - Zona Francelos). The night time network is identified by the letter “M”.

Figure 62 - STCP zoning numbers

In 2011, STCP served 108 million passengers, 59% unimodal and 41% intermodal passengers, covering a total of 29 million kilometers, with a global occupancy rate of around 15%. The mean number of kilometers for each passenger was 3,55 km. Around 9,5 million kilometers were covered for social service (as defined by *Decreto-lei nº 167/2008*) representing 33% of the total distance covered by STCP services, with a total cost of 24 million euros in 2011 (STCP 2011). For calculation purposes, the company’s annual report considers as social service the number of kilometers covered in the night-time service, during weekends and holidays, and also in the lines serving low demand zones (Z).

Night-time bus network

The night time bus network serves the municipalities of Porto, Gaia, Matosinhos, Valongo, Gondomar and Maia, being the only public transport mode operating between 1 a.m. and 6 a.m. When it was first set up in 2005, the objectives were to serve the demand of passengers that used the public transportation during night time in the city: young people going to or from night leisure areas, students returning to student residential areas, social areas residents and access to the main hospitals. In June 2011, the night time network was re-adjusted. Figure 63 shows the night time network in June 2011.

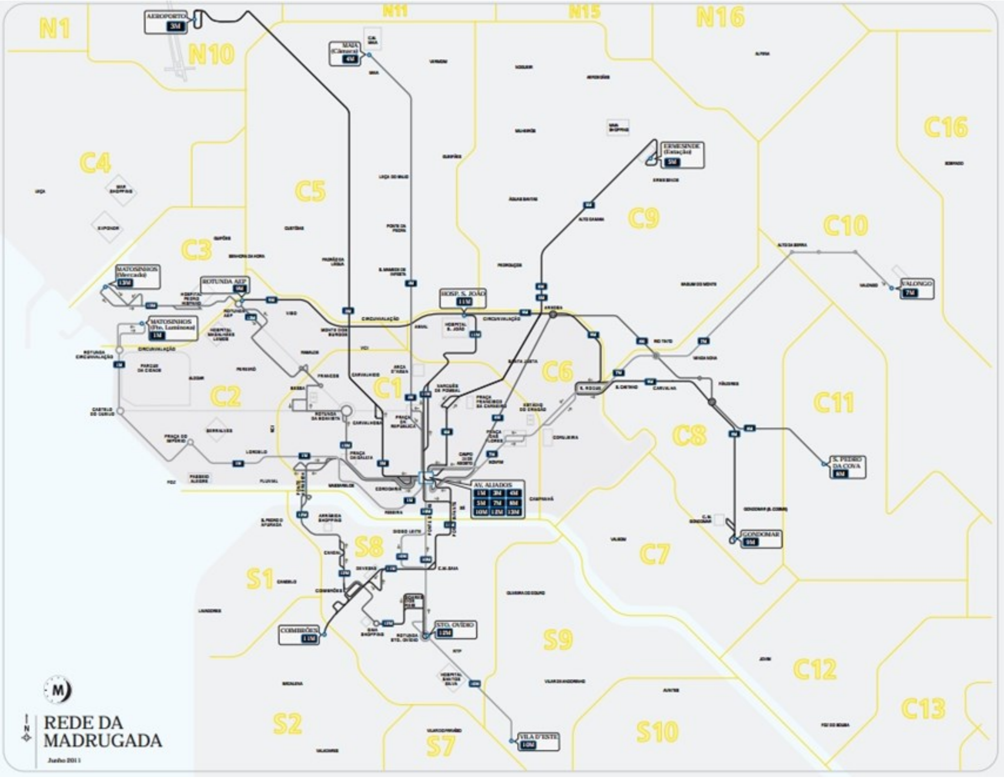


Figure 63 - STCP night time network in June 2011 (source: (STCP 2011))

As already mentioned, the night time network has 11 lines, essentially connecting the city center (Aliados) to the city's main outskirts points (see Table 13). The average trip length during night time is around 13 km.

Line	Origin	Destination	Trip time
1M	Av. dos Aliados	Matosinhos (Câmara)	23min
3M	Av. dos Aliados	Aeroporto	28min
4M	Av. dos Aliados	Maia(Câmara)	25min
5M	Av. dos Aliados	Ermesinde(Estação)	28min
7M	Av. dos Aliados	Valongo	28min
8M	Av. dos Aliados	S. Pedro da Cova (via Areosa)	28min
9M	Rotunda AEP	Gondomar (via H.S.João)	28min
10M	Av. dos Aliados	Vila d'Este	25min
11M	H.S.João	Coimbrões (via Pte. Infante)	28min
12M	Av. dos Aliados	Sto.Ovídio (via Pte. Arrábida)	28min
13M	Av. dos Aliados	Matosinhos (Mercado)	28min

Table 13 - STCP night time network lines

From Table 13, we can see that the total trip times are very short, allowing the use of a single vehicle to service each of the lines.

Service offer

The night time STCP service has a fleet of 11 vehicles (1 per each line), assuring an hourly frequency at the serviced stops, with a hub at Aliados where vehicles leave at 1 a.m., 2.a.m, 3a.m., 4a.m and 5a.m. At the final destinations, buses heading to Aliados leave at 1:30a.m., 2:30a.m., 3:30a.m, 4:30a.m and 5:30a.m., with the exception of lines 1M (the return is five minutes earlier), 11M (the first trip stars 15 minutes earlier) and 13M (the first trip is a return trip to Aliados half an hour earlier). The total number of trips during the night time is 111 and the lines are operated using regular sized buses and mini-buses (in some lines, during weekdays).

Demand

According to (STCP 2011), 545.000 passengers used the night time network in 2011, whereas in 2010 the number was 507.000 (+8%). The average number of passengers per day in 2011 was around 1.490 passengers, which represents a mean demand of around 13 passengers/trip for the night time network. This demand leads to very low vehicle occupancy rates and it is the main reason why STCP is using evermore mini-buses for the night time service (the average capacity for a full size STCP bus is around 90 places and for a mini bus is around 27 places).

Costs

In terms of costs, we focused the present analysis on two aspects: fuel costs and drivers costs.

The vehicles used for the night time service run on compressed natural gas (CNG) and have a consumption of 67,66 m^3/100 km (STCP 2011). According to STCP the average cost per kilometer of a natural gas vehicle is 0,319 euro (Palma-Ferreira 2010). Since the total covered distance in the night time network in 2011 was around 620.000 kilometers, the total fuel cost was around 200.000 euro. This value corresponds to an average of 50 euro per line, per day, in fuel costs.

As for the drivers cost, (STCP 2011) states the value 7,2 euro/hour for a driver's extra time work, so we can use such value as an upper bound for the cost per hour for the driver's cost per hour, as we do not have the real figure for regular (no extra-time) working hours. This value is just indicative, since it represents the net value and not the total amount STPC pays for salaries, deductions and social security systems. However, taking into account this value and the number of hours (5) for each night time service line, the drivers cost per day per line, would be at most around 7,2 euro/hour * 5 hours=36 euro. Thus, the total drivers cost of the night time service (11 lines) could reach 396 euro per day.

Table 14 presents the operational cost structure of the night time service (without fixed costs):

Cost	**Euro**	**%**
Total fuel cost per day	550	58%
Total drivers cost per day	396	42%
Total cost per day	946	100%

Table 14 - Cost structure of the STCP night time service

On December, 15th, 2011, STCP launched the *Gato* service. STCP presented *Gato* as an urban night flexible service, "targeting university students that like to go out and have fun on the nights of Thursday, Friday and Saturday". The service was operated in experimental regime, financed by the European Union in the framework of the CIVITAS-ELAN project (EuropeanUnion 2011).

6.3.2 GATO SERVICE DESCRIPTION

Figure 64 shows a brochure used in the *Gato* night time service by STCP in the city of Porto (in Portuguese *Gato* means “cat”).

Figure 64 - Brochure from *Gato* service (source: (STCP-GATO 2011))

The *Gato* brochure clearly states the type of users the service wishes to capture (“festas” in Portuguese means both “party” and “caress”), the operating period of the service, the service area, the frequency, the booking method and the web URL for more information. The “cat” picture tries to captivate the user telling him that this is a night service with a somehow “mysterious” path.

The service was free until January, 8th, 2011, and was used by around 300 passengers during this period (Pereira 2012) – more or less 25 passengers/day. From that date on, the service was no longer free. By the end of the service in April, 29th, 2012, STCP reported that about 1.100 users with an average age of little more than 20 years were transported during the 4 months of service operation.

The service operated in a scenario of predefined stops in a corridor (see Chapter 2), that were served on request, with two fixed stops – the end points – at which the vehicle arrived at a predefined time. The passing times at the requested stops were calculated in order to structure the service. The calculation of these predefined passing times is a very important aspect for the design of this type of services, since it will determine its flexibility: in general, more time between two stops with predefined passing times will allow serving more intermediates stops, but will slow down the service. Figure 65 illustrates the *Gato* routes.

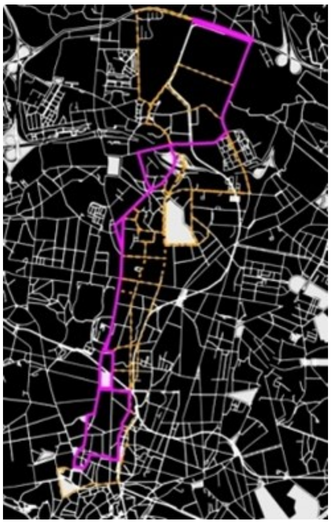


Figure 65 - *Gato* service routes (source: (STCP-GATO 2011))

In this service, there was no fixed timetable. Only stops on demand were served and the structure of the service was completely defined by the requests. Users had to book the service 1h30 before its operation start - and could be informed later of the expected departure and arrival time -, so that more requests could be combined in one service journey. It was possible to hail-and-ride (use the service without reservation) but only at the served stops.

In terms of service hours, *Gato* was a night time service provided between 0:30 a.m. and 5:00 a.m. from Thursday to Saturday. It was available to everyone. No handicapped/special groups' service was available.

The service was oriented towards young citizens, specifically "targeting university students that like to go out and have fun". Addressing this target market also had, mostly likely, the objective of potentially increasing traffic safety levels, by promoting the usage of public transportation instead of driving home late hours after having fun and drinking with friends.

Regarding the operation, the service was operated using a regular bus, with routes that started at every hour. To request the service, the passengers could use the Internet or the telephone, booking the trips until 1h30 before the start of the service, specifying both origin and destination. The service provided the pickup and delivery time to the user.

The trip fare price for *Gato* was 2 euro. Group discounts were available: 1,60 euro/pax for a group of 10 to 29 people; 1,40 euro/pax for groups of 30 or more people.

6.3.3 SERVICE ANALYSIS

By the end of the service on April, 29th, 2012, STCP reported that about 1100 users had been transported during the 4 months of service operation. The service operated 3 days a week (Thursday, Friday and Saturday), meaning a total of 48 operation days, corresponding to 22 users per day. Since there were 10 trips per operation day (5 in each direction), this gives a low mean figure of around 2 users per trip. And, as the *Gato* used a regular sized bus, the occupancy rate was very low. The trip length was around 8km and the driver worked for 5h30, so using the figures presented above for fuel and driver costs the *Gato* service would have a driver cost of 7,2 euro/hour × 5,5 hours = 39,6 euro, and a fuel cost of 0,319 euro/km × 8 km × 10 = 25,5 euro, so the total cost per operation day was roughly 65 euro. Having had an average of 22 users per day, even with a price of 2 euro per user, the ticket revenue would only pay 68% of the costs. For these calculations, we used the driver's cost per hour based on the extra-time cost, because, as already mentioned, we do not have the real figure for regular (no extra-time) working hours. The actual value should be lower and, as such, the ticket revenue should cover a higher percentage of the costs.

As mentioned in Chapter 3, (Brake *et al.* 2007) identified three general market niches where DRT could be efficient. Unfortunately, the *Gato* service failed to fall in any of these three market niches:

- in the first niche, low-tech, low-quality, small-scale simple DRT are directed to captive users, but captive users can only pay low fares, and the *Gato* fare (2 euro) is not a low fare price. Price is a very important issue for captive users, but less so for choice users (Enoch *et al.* 2004);
- in the second niche, DRT operators target choice users who appreciate luxury and are prepared to pay a premium for a service that is far away from a bus, with small scale, simple to operate systems, but *Gato* is not far away from a bus, neither from a physical nor luxury point of view, and students (the target users) do not assign so much utility value to luxury, and are not prepared to pay a premium. Comfort and image is far more important for choice users than for captive users (Brake *et al.* 2007). The target user group was defined with population interview techniques;
- finally, *Gato* is not a large-scale, complex network DRT system and does not provide savings in terms of substituting even more expensive specialist transport trips.

It is recognized that the fare setting is often constrained by the need to make a certain level of revenue, in order for the service to become commercially viable, or, at least, to be provided at an acceptable level of subsidy. However, serving appropriate markets combined with proper fare pricing is essential. *Gato* fare was set to 2 euro. This was a very high price. To put things into perspective, a 2 zone Andante costs 1,10 euro, and an equivalent T1 STCP bus ticket costs 1,45 euro when bought on the bus. A group of 4 students (the *Gato* target users) sharing a taxi from and to any stop points of the *Gato* service would pay roughly the same 2 euro each, or even less – (0,80 euro phone call fee + 2,5 euro initial fee + 0,54 euro/km × 8 km)/4 pax=1,9 euro/pax (LojadaMobilidade 2008) - , without the need to book the service at least 1h30min before - and this booking overhead seemed to be a critical aspect as STCP recognized that "(these young) passengers didn't want to commit with a schedule, preferring to see how the night evolved, and also for most the route did not matter much as they traveled between terminus stops" (STCP-GATO 2011). The Gato service was designed with support of the CIVITAS-ELAN European project team (EuropeanUnion), but the price was set by the operator (STCP).

In Europe, the survey from Chapter 2 showed that 45% of the services have a fare equal to the regular public transportation service, 40% have higher fares than the regular public transportation service, and 15% are free. In North America, according to (Potts *et al.* 2010), 70% of the operators charge the same fare for the DRT service as for the fixed-route service. From the operators that charge a different fare for DRT, more than a half, around 60%, charge a higher fare for the DRT service than for a normal scheduled service.

(Enoch *et al.* 2004) classified the DRTs financial performance according to four groups:

- commercially viable DRT: services that are either profitable, or operate within a commercial context (for example, a non profitable service is compensated by its positive effects on a service network as a whole);
- acceptable subsidy DRT: services that require only the same (or less) subsidy than other comparable services;
- justifiable higher subsidy DRT: services for which a subsidy above that comparable to tendered services can be justified. This may be due to the operational area (e.g. deep rural areas) or other factors;
- financially unsustainable DRT.

Due to the low occupancy rate observed and the cost involved, *Gato* could only be classified either as a justifiable higher subsidy DRT or a financially unsustainable DRT. But, it is difficult to justify higher subsidies for students commuting to and from leisure zones, especially when there are alternatives. So, *Gato* could be classified as financially unsustainable.

Naturally, and as already mentioned, the viability of a service is highly dependent on the relationship between revenues and costs. The combination of an addressed niche market, the fare structure and the operation framework, was the reason for the financial unsustainability of the service. One of the main problems with *Gato* was the fare price set by the operator: 2 euro, was set too high. But even with such a high fare, and the sponsorship of a well know beer brand, the revenue of the service did not make up for the operational costs.

6.3.4 SOME IMPROVEMENT IDEAS

As (Brake *et al.* 2007) pointed out, when a gap between revenues and costs persists during the lifetime of the service, there should be an analysis whether costs can be reduced or revenues can be increased. In order to do so, we have used the guidelines from Table 3 (actions to overcome some DRT problems) and have proposed some actions on all dimensions of the service:

- service planning - for better demand aggregation;
- vehicle fleet - with smaller vehicles;
- operator model - with cooperation with private taxi firms;
- dispatching - with more automation;
- reservation - with new reservation channels;
- marketing - with new vehicle colors;
- pricing - with a new pricing scheme integrated into the existing operator's system;
- travel dispatch center - opened not only a couple of hours before the service start but also during all service operation time, for real-time requests reservation.

These actions can be roughly grouped in cost reduction actions and revenue increase actions.

Costs

Costs could have been lowered, for instance, by using a mini bus instead of a regular bus, as a regular size bus has a higher fixed cost than a mini bus. In the European survey presented in Chapter 2, the data shows that around 20% of the surveyed DRT services had a heterogeneous fleet. The most commonly used vehicles are adapted mini buses (50% of the services use them). Regular mini buses are used by 39% of the services, taxis (eventually shared) are used by 26% of the services, and adapted vans by 10%. In (Potts *et al.* 2010) nearly half of the North American operators (46%) used small buses, while 28% used vans to operate the service.

Also, by changing the *Gato* model to a more demand responsive one, could allow cost reductions in terms of the driver costs: for instance, instead of operating continuously between 0:30 a.m. and 5:00 a.m., the service could have operated only when demand occurs.

Revenues

Typically, changing fare levels will induce changes in the level of demand for public transport. In broad terms, all other things being equal, an increase in fares will reduce patronage, whilst a decrease in fares will increase patronage. The size and direction of the change in demand, following a change in fares, can be expressed in terms of fare elasticity. A high elasticity value indicates that a good is price-sensitive; that is, a relatively small change in price causes a relatively large change in consumption. A low elasticity value means that prices have relatively little effect on consumption. The fare elasticity is therefore a measure of the price sensitivity of bus passengers.

A wide range of factors influence the fare elasticity, and whilst these factors can be discussed in isolation, it is likely that more than one of them will exert an influence at the same time. For instance, price changes may have relatively little impact on ridership for a public transport system that primarily serves captive users. However, if the transport system wants to attract significantly more users and reduce automobile usage levels, fares will need to decline and service quality improve to attract more choice users (Litman 2004). It is not in the scope of the present work to understand in detail all the factors involved in fare price setting and their influence in DRT services in general, and in *Gato* in particular. However, we are interested in having a shallow model to link the change in fare price in *Gato* and the expected demand level and, so, some of these factors should be taken into account, namely user type and trip type. Captive users are generally less price sensitive than choice users (Litman 2004) and certain demographic groups, such as the target users of *Gato*, i.e. university students, tend to be more public transport dependent (Litman 2004). Some studies also point out that elasticities are lower for passengers with lower incomes and for younger people (Gillen 1994). As for the trip type factor, non-commute trips, such as the ones in *Gato* service, tend to be more price sensitive than commute trips. Also, elasticities for off-peak period are typically higher than those for peak periods, partially because of the trip types associated with the mentioned periods.

A general rule-of-thumb - *Simpson–Curtin rule* (Curtin 1968) - is that the elasticity of demand with respect to price for public transportation is -0,33, i.e., a 3 percent fare increase reduces ridership by about 1 percent. This can be useful for a rough analysis, but it is too simplistic and outdated for detailed planning and modeling (Cervero 1990). Nevertheless, it would serve our purpose of using a shallow model to link the change in fare price in *Gato* and the expected demand level - for an in depth discussion of elasticities for public transportation see, for instance, (Litman 2004) and (Hensher *et al.* 2007). However, recent works, such as (Paulley *et al.* 2006), point out that bus fare elasticity averages around -0.4 in the short run, in the UK, for peak periods. Off-peak elasticities tend to be higher, and the bus fare elasticity in this conditions was found to be -0,48, in the UK, and -0,51 outside the UK. Using the -0,51 elasticity figure, taking the fare price in isolation, and assuming the elasticity relationship is bidirectional, 1% decrease in the fare price represents a 0,51% increase in demand. So, if the *Gato* fare price is reduced by 45%, from 2 euro to the *Andante* integrated fare price of 1,10 euro, an increase of 23% in demand could be expected. This means that, from the original 1.100 users during the 4 months operation period, *Gato* would have had 1.353 users, or roughly 29 users per operation day (instead of 22).

Moreover, unless users are aware of a new initiative, revenues will be lower than they could be. In the case of DRT services, this awareness is even more critical, as they require an understanding of how their operational principles differ from conventional bus services, with many schemes requiring pre-booking and/or having flexible route and/or flexible timetables. In *Gato*, the STCP system-wide integrated ticket was not accepted and social passes were not accepted either. In order to mitigate the "understanding gap" between *Gato* and the regular service, the integrated ticket system should have been used.

For this type of services, (Brake *et al.* 2007) identified a number of critical marketing factors such as the visibility of the DRT services themselves and the options available for promotion to service operators and to end users. Paradoxally, the more flexible the service becomes the less visible it is to the end user. For example, a sign placed on a bus stop where a DRT service does not necessarily stop can give regular public transport users wrong ideas about the service. Also, the more clearly branded the vehicle is, the more quickly it becomes recognized by the general public. Ideally, DRT needs to get away from having a bus type image. The *Gato* used a regular bus painted in black: although the black color differentiated itself from the STCP regular offer, it is still open to debate if it was the best color choice for a night service. Perhaps a better choice would have been to use a mini bus with a bright color, more clearly branded and further away from a regular bus image. Figure 66 shows a *Gato* vehicle.

Figure 66 - A *Gato* vehicle

Another idea would have been to offer financial incentives to passengers that booked ahead – a method used very successfully by the low cost airlines, as the service also allowed hail and ride. The “improved” *Gato* service could be more dynamic, not only accepting advanced requests but also real-time requests, with origin and destination at the service assigned stops during service operation time. The reason for the proposal of this improvement is to deal with the booking overhead, pointed out as being responsible for the bad performance of the “original” *Gato* service: the booking overhead seemed to be a critical aspect as STCP recognized that “(these young) passengers didn’t want to commit with a schedule, preferring to see how the night evolved, and also for most the route didn’t matter much as they traveled between terminus stops” (STCP-GATO 2011).

There is less evidence on the demand impacts of service improvement variables, such as the integrated ticket system or a more clearly branded vehicle or the waiting environment or even personal security (it is assumed that a vehicle with higher occupancy rate feels more secure for the passenger), than that of fares (Paulley *et al.* 2006). Anyhow, the valuation of a service attribute can be used to infer that service attribute elasticity. Having said this, it is expected that more clearly branded vehicles, an integrated ticket system, and financial incentives to passengers that book ahead, all contribute for a higher level of demand. Therefore, instead of the 29 users per operation day pointed out earlier, we will use 32 per operation day (which, in turn, would mean 1.500 users in 4 months).

Using the rough calculations presented at the beginning of this section, *Gato*'s trip length was around 8km and the driver worked for 5h30m, so the service would have a driver cost of 7,2 euro/hour × 5,5 hours = 39,6 euro, and a fuel cost of 0,319 euro/km × 8 km × 10= 25,5 euro, and total cost per operation day was roughly 65 euro. It is straightforward to see that, with a fare price of 2 euro per user, we would need to have around 33 passengers for the break even between cost and revenue. At the proposed integrated fare price of 1,10 euro, around 60 users per operation day would be needed to balance cost and revenues, using the same *Gato* service with 5h30 operating time and 10 trips of 8 km length each. But the improved *Gato* service is more dynamic, with variable trip length and service duration (i.e., the vehicle only goes to "where" and "when" it is necessary) and, as such, besides a smaller sized vehicle, both driver's and fuel costs, and also fixed costs, should be smaller than those of the original *Gato*.

Table 15 presents the design differences between the original *Gato* service and the improved *Gato* service using the terminology presented Chapter 2.

Concept	**Original *Gato***	**Improved *Gato***
Stops	Predefined stops, only served on request (STP-3)	Predefined stops, only served on request (STP-3)
Users	General public (USR-2)	General public (USR-2)
Route and time	Predefined stops in a corridor (R-SC3)	Predefined stops in a corridor (R-SC3)
Booking	Collecting requests – defining service (B-SC4)	Direct booking (B-SC2)
Booking Technology	Internet (BT-5)	Operator (BT-1) and Internet (BT-5)
Network	Stand-alone service (N-SC1)	Stand-alone service (N-SC1)
Vehicle allocation	Fixed vehicle allocation (V-SC1)	Extendable vehicle allocation (V-SC2)

Table 15 - *Gato* and improved *Gato* service design concepts

6.3.5 SIMULATION

The "original" *Gato* service data (namely, the demand structure, the predefined stops, fuel and driver costs, and, finally, the trip fare price) was used in the developed simulation environment to better understand and analyze the service operation and, also, propose and analyze the impact of some improvement ideas. The main characteristic of the simulation environment for the *Gato* service were:

- the simulated road network is a graph defined by a set of nodes, representing the available stops, and links, representing the roads connecting the stops. The stops considered were the ones used by the original *Gato* service (roughly 38 stops);
- the *Gato* service used one "full size" bus (90 passengers). We simulated the service with this vehicle and for the "improved" *Gato* service considering the possibility of two types of vehicles: fleet vehicles and subcontracted vehicles. Fleet vehicles are operator-owned vehicles affected to the service. We have used a medium size mini-bus of 27 places with a lower fixed cost and a bit higher mean commercial speed than a full size bus;
- the trip request model generated trip requests with a structure consistent with the studied area and the road network within which the service operated.
    - the "original" *Gato* service allowed only advanced reservation. For the "improved" *Gato* service two types of trips were considered: advance reservation trips, which are requested before service starts, and real-time trips, which are requested after service started and needs to be serviced immediately. We did not considered the possibility of hail-and-ride;
    - as reported by STCP for the *Gato* service, we started with 22 users per day, and gradually changed this number according to a price elasticity model for the fare price;
    - for the "improved" *Gato* service, we simulated different degrees of dynamism – DOD. Real-time requests arrivals were modeled as a Poisson process, as it is usual in transportation studies (Larson et al. 1981), with parameter $\lambda = 0{,}3$. The time between each pair of consecutive real-time requests follows a negative exponential distribution. The request time limit for real-time requests was randomly selected with uniform probability between 15 to 60 minutes;
    - the default time window size was 15 minutes;
    - for the users' "expected" travel time (i.e., to simulate the desired delivery time) we used the normal distribution, with a mean of 35 minutes, and a standard deviation of 17 minutes - as found by mobility studies for the city of Porto (see Chapter 2);

    - in terms of spatial distribution of the transportation requests, we could simply assume that all nodes in the network have the same probability of being departure or destination points, but there are two sets of stops that, clearly, have special meaning in terms of the *Gato* service: the stops near Aliados are the only destinations and the stops near Hospital de São João are the strongest origins - although demand can occur in all other stops;

- the real-time operational events considered in this work were new requests, no-shows and request cancelations. No-shows and request cancelations were modeled as a Poisson process with parameters $\lambda = 0{,}01$ and $\lambda = 0{,}05$, respectively. We were interested in knowing how these disruptions would affect the "original" *Gato* service and the "new" *Gato* service.

Table 16 sums up and compares the simulation parameters for the "original" *Gato* service and the "improved" *Gato* service:

Parameters				**Original *Gato***	**Improved *Gato***
	Decisions				
		Fleet size		1	1
		Vehicle capacity		90	27
		External Taxi vehicles		0	1
		Time window		Service defined pickup time	15 minutes
		Fare		2 euro	1,1 euro
	Data				
		Vehicle			
			Vehicle commercial speed	16 km/h	20 km/h
			Vehicle cost per km	0,32 euro	0,32 euro
			Fixed cost/vehicle	1.500 euro	1.000 euro
			Taxi speed	30km/h	30km/h
			Taxi cost per km	0,60 euro	0,60 euro
		Service area			
			Number of stops	38	38
			Mean travel time	35 min	35 min
			Standard deviation travel time	17 min	17 min
			Source zones (OD matrix)	mainly Asprela	mainly Asprela
			Sink zones (OD matrix)	mainly Aliados	mainly Aliados
		Requests			
			Mean number of requests	22	32
			Degree of dynamism	0%	50%
			Cancelations statistical distribution law	Poisson (λ: 0,05)	Poisson (λ: 0,05)
			No-shows statistical distribution law	Poisson (λ: 0,01)	Poisson (λ: 0,01)

Table 16 - *Gato* service simulation parameters

According to Table 16, we considered that smaller vehicles may have a higher mean commercial speed than regular sized vehicles due to, essentially, having less weight and, as a consequence, better acceleration and braking abilities.

Simulation Results

In terms of average *profit per operation day*, both services (*Gato* and "improved" *Gato*) present a negative value, but for the "improved" *Gato* this value is higher when compared to the "original" *Gato* by around 25%. The same is true for the average *operating cost per revenue hour*: "improved" *Gato* has a better (lower) *operating cost per revenue hour* by around 30%, when compared to the "original" *Gato* service. The *mean operating cost per passenger trip* for the "improved" *Gato* is around 17% of the *mean operating cost per passenger trip* for the "original" *Gato* (lower, therefore), which means that not only the "improved" *Gato* has a lower *operating cost per revenue hour*, but it seems it uses this cost in a much better way that the "original" *Gato* (i.e., it has a better productivity). Table 17 shows the simulation results for these indicators (mean values), although the analysis of the relative values seems more interesting than looking to absolute figures.

	profit/day	operating cost/revenue hour	operating cost/passenger trip
"original" *Gato*	- 61,21euro	754,62 euro	327,73 euro
"improved" *Gato*	- 46,36 euro	516,30 euro	55,57 euro

Table 17 - Mean simulation results

Simulation results seem to point out that the "improved" *Gato* service is more robust in terms of service disruptions, such as cancelations and no-shows. In both services, the *operating cost per passenger trip* grows with the increase of the number of request cancelations. However, above 50% of requests canceled, the *operating cost per passenger trip* in the "original" *Gato* grows sharply: this cost increases 250% between 50% and 100% of requests canceled in the "original" *Gato*. For the "improved" *Gato*, this increase of the *operating cost per passenger trip* is more pronounced above 80% of requests canceled, but, even so, the increase is not as steep as for the "original" *Gato* (around 75% in cost increase). Figure 67 illustrates these findings.

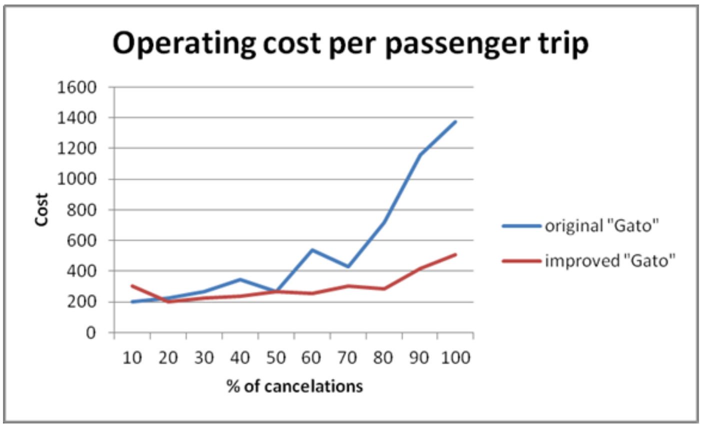


Figure 67 - Operating cost per passenger trip VS requests cancelation

Regarding no-shows, the behavior is similar for both services: there seems to be a consistent increase in *operating cost per passenger trip* (bigger for the "original" *Gato*) with an increase in the number of no-shows and a bigger increase in the *operating cost per passenger trip* at 50% of no-shows. However, between 90% and 100% of no-shows in both services, the *operating cost per passenger trip* increases sharply (500% to 600%).

The widening of the service area could bring more demand into the service and it might be pointed out as an interesting idea to bring into the simulation for further research, in order to understand its impact in the cost/revenues structure of the *Gato* service to, along with the improvements proposed, try to bring the service into a financial sustainable zone.

6.4 Chapter summary

To test the presented integrated approach, we adopted a two-fold strategy:

- general simulation: analyze the behavior of an hypothetical DRT service in a given real geographic area, making some assumptions regarding the demand structure;
- case study: analyze a real DRT service (*Gato*), propose and assess a set of improvements to this service.

The results of the simulation runs also give guidelines to help operators of public transport to design DRT services.

For the analysis of the behavior of a hypothetical DRT service in a given real geographic area, our decision was to use randomly generated instances for the city of Porto, Portugal. The developed approach is independent of the scenario area and, as such, it would be extremely easy, once in possession of the data, to use the developed Decision Support System and simulation models for other areas.

In the city of Porto scenario, with the DRT service and simulated demand structure, the operator should consider between 4 and 7 fixed vehicles, depending on the budget for the fleet fixed costs, with a capacity between 12 and 18 seats, subcontract external taxis to cope with the un-satisfied real-time requests and set a time-window between 10 and 15 minutes. If demand structure changes significantly, in terms of the number of requests, or degree-of-dynamism, and/or the traffic conditions change significantly, the operator should use the developed Decision Support System to better understand the behavior of the DRT service in these conditions and decide on a new owned fleet size, number of subcontracted vehicles and/or the size of the time-windows. We can say that there are combinations of number of vehicles, vehicle size and time-windows size that should be analyzed. Traffic congestion also plays an important part, as simulation results points that every 2,5km/h drop in mean vehicle's speed corresponds to one less request satisfied. So, for congested areas or some periods of the day, the decision maker might adjust the time-window size or subcontract another vehicle to cope with these picks. Simulation results for Porto also show that the number of satisfied requests grows quicker than the number of vehicles. This seems to point that having a higher number of vehicles gives a higher flexibility and the requests can be better aggregated. Finally, operator must take extra care analyzing the expected degree-of-dynamism (DOD). Decision makers should use the developed Decision Support System to understand the relationship between a) having more vehicles to serve more requests with the increase of DOD or bigger time-windows for more "reaction" time for real-time requests; and b) the cost of no-shows/cancelations in low DOD scenarios.

STCP presented *Gato* as an urban night flexible service, "targeting university students that like to go out and have fun on the nights of Thursday, Friday and Saturday". By the end of the service, STCP reported that about 1.100 users were transported during the 4 months of service operation. With such a sub-optimal performance, an analysis whether costs can be reduced or revenues can be grown needed to be done. In order to do so, we proposed some actions to overcome problems on all dimensions of the service. The "original" *Gato* service data was used in the developed simulation environment to, on one hand, better understand and analyze the service operation and, on the other hand, analyze the impact of the proposed actions on the service ("improved" *Gato*). In terms of mean profit per operation day, both "original" *Gato* and "improved" *Gato* services present a negative value but "improved" *Gato* has a higher profit by around 30%. The same is true for the mean operating cost per revenue hour: “improved” *Gato* has a better (lower) operating cost per revenue hour by around 30% compared to the “original” *Gato* service. Simulation results seem to point out that the “improved” *Gato* service is more robust in terms of service disruptions, such as cancelations and no-shows. The widening of the service area could bring more demand into the service and can be pointed as an interesting idea to bring into the simulation for further research, in order to understand its impact in the cost/revenues structure of the *Gato* service to, along with the improvements proposed, try to bring the service into a financially sustainable zone.

6.5 Chapter highlights

Assessment of the proposed integrated approach.

General simulation details and results: behavior of an hypothetical DRT service in a given real geographic area, making some assumptions regarding the demand structure.

Case study: analysis of a real DRT service, propose and assess a set of improvements to this service.

Chapter 7

CONCLUSIONS

7.1 Main contributions of the thesis

A first goal of this doctoral project was to better understand and characterize a set of issues related to Demand Responsive Transportation (DRT) services, in particular by identifying their various types and features, and their scope for practical implementation. Having set the context and the problem, the next goal was to develop a simulation model to design and assess DRT services and analyze how different ways of operating the service affect customers and operators. Finally, a "methodology" to support decision-making in the design and operation of DRT services was developed.

A generic solution strategy was developed for efficiently solving the dynamic vehicle routing for DRT systems problem. This strategy is based on a multi-objective heuristics to deal with the combinatorial nature of the problem and with the multiple perspectives of its different stakeholders, as an innovative approach to cope with these systems.

In order to "involve" the experts in the planning process, a prototype of a Decision Support System was developed. This system integrates the multi-objective algorithm and simulation model developed and was used in testing and assessing the approach.

The simulation experiments have shown the potential and importance of the approach for designing and managing DRT services. Decision makers should use the developed Decision Support System to find the best combination of the decision parameters to design DRT services that meet envisaged cost level and quality of service. For a given demand, planners may experiment different time window sizes, different number of vehicles and capacities, and number of subcontracted vehicles. Also, setting different criteria weights result in different cost structures and service quality and, as such, should be analyzed using the developed Decision Support System.

The main contributions of this dissertation are:

- a framework for the analysis of DRT services operation;
- a survey addressing 25 existing DRT services from different European countries using the proposed framework;

- a development process for DRT services, with a sequence of activities for services designers to follow;
- a review of the literature on simulation for DRT services;
- a simulation model for dynamic DRT services;
- a set of DRT design patterns categorized by service type and service area;
- a dynamic vehicle routing formulation for Demand Responsive Transportation, to be used as a generic modeling framework for the design of different multi-objective customizable algorithmic approaches for DRT services;
- an efficient, customizable multi-objective algorithmic approach that deals with the combinatorial nature of the problem and with the multiple perspectives of its different stakeholders;
- a prototype of a Decision Support System, integrating optimization and simulation, to "involve" the experts in the planning process, and 2 request reservation applications (one mobile application, and one desktop application).

7.2 Future research opportunities

The simulation model and Decision Support System tool proposed in this work can be used to understand and study how different service designs and different ways to operate a DRT service affect its performance and efficiency in very concrete scenarios. As such, it could be used in DRT design and implementation projects. In that sense, it would also be interesting to have the possibility of developing a DRT service using the proposed WinWin Spiral Model, with the 4 cycles through the spiral. To the best of our knowledge, the Spiral Model, and particularly, the WinWin Spiral Model, was never used for DRT services development.

The integration of Demand Responsive Transport services into the public traditional transportation systems may be an effective way, in terms of cost, of improving both quality and public mobility systems coverage as a whole. The sound and effective improvement of public transport may lead to an important modal shift from the private vehicle to the public transport, reducing traffic levels, energetic consumption levels and environmental pollution levels. These are some of the objectives for European Union transport policies objectives, along with the provision of equal mobility opportunities for all the citizens. It would be interesting to develop new research lines, to answer some questions regarding the integration of DRTs in the public traditional service offer:

- what might be the appropriate mix of DRT with other forms of public transport?

- when (or where) should DRT replace buses?
- in what circumstances might it be better to have DRT as a service to support/complement demand for conventional buses?

In fact, a M.Sc. dissertation project at Faculdade de Engenharia da Universidade do Porto as just started, as a follow up of the present dissertation to contribute to answer these questions. The objectives of the project are to use a set of software tools for the design, management and effective operation of integrated Demand Responsive Transport services, given the operations dimension and complexity when considering the complete network. The key project objectives are:

- the characterization of the several types of DRT services;
- use simulation tools to characterize and analyze different public transportation options for a given area/scenario: "traditional" public transportation, DRT services, or a combination of both;
- the development of an integrated transport service model.

Given the large spectrum of possible DRT service designs, it is important, in a first stage, to characterize the most influential design aspects and clearly understand how DRTs can be integrated in the traditional public transportation network in an efficient way in terms of cost, minimizing the disruption on operating services, seeking to improve both quality and public transports network coverage as one whole.

Another possible usage for the simulation model and Decision Support System tool proposed is to study the effects on the solution (service) produced by different heuristics and algorithms for computing routing plans. The developed integrated tool works as a framework in which the routing and scheduling algorithm is a black box and, thus, can be easily replaced by other algorithms. This way, we should be able to assess the performance and to try different routing and scheduling strategies for a given scenario.

As already mentioned, being a "new" problem, there are no "off-the-shelf" benchmark data bases for the DVRDRT. To the best of our knowledge, the most similar instances in the literature are the ones for the Capacitated VRP with Time Windows, the Capacitated VRP with Pick-up and Deliveries and Time Windows and the Dial-A-Ride-Problem. In that sense, the test instances generated to test our approach, with different number of requests, and different spatial and temporal (birth rates and pickup/delivery times) request distributions, can be useful and used to test different routing and scheduling algorithms.

To standardize and to make these test instances available to the scientific community, surely deserves future research. Also, the simulation results can be used for mobility studies, using data visualization and data mining techniques.

Another natural future development concerns the assessment and enhancement of the usability of the Decision Support System GUI and the implementation of possible improvements. The idea is to take a strong step towards a production ready version of the DSS and, eventually in a near future, implement it at transport operator and/or transport engineering consultancy agencies.

Finally, it would be important to extend this work to study and design a financial framework for the proposed integrated approach, effectively framing it, and assessing its impacts for operators. This financial framework should define a set of guidelines for pricing strategies, according to the possible DRT system designs, and understand how management information systems can be used for that.

Demand Responsive Transportation systems are a good way to bridge the gap between individual transport and scheduled conventional transport: there is a large spectrum of possible DRT systems, from the most "rigid", to the most flexible. Therefore, DRT systems offer a huge opportunity to design new, innovative services, to be part of broader mobility systems. For some user groups, DRTs may have a significant impact in terms of life quality.

"Eu não parti de um porto conhecido. Nem hoje sei que porto era, porque ainda nunca lá estive. Também, igualmente, o propósito ritual da minha viagem era ir em demanda de portos inexistentes — portos que fossem apenas o entrar-para-portos; enseadas esquecidas de rios, estreitos entre cidades irrepreensivelmente irreais."

Fernando Pessoa, *O Livro do Desassossego*

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ANNEX A: DRT SURVEY DATA

Data summary

The data of the DRT services studied in the survey is summarized in Table 18. This table adopts for clear understanding both terminologies and respective codes presented in (Nelson 2004) and (López 2010), augmented with the analysis of other service aspects, such: as the existence of pickup/delivery time windows, operation time period, the type of vehicles used for providing the system, the fare or the time limit for the user to book the service. In this table:

- column 1 is the service name;
- column 2 is route scenario as per (Nelson 2004);
- column 3 is the service role as per (Nelson 2004);
- column 4 is the service operating period (D- day; N- night; 24h – all day);
- column 5 is the type of users entitled to use the service as per (López 2010);
- column 6 is the type of stops (Nelson 2004);
- column 7 is the time window defined for the service pickup or delivery time;
- column 8 is the booking scenario (Nelson 2004);
- column 9 is the booking technology (Nelson 2004);
- column 10 the time limit for the user to book the service;
- column 11 is the type of vehicles used by the service (MB – mini bus; T – taxi; ST – shared taxi; SP – shared private vehicle; AMB – adapted mini bus; AV – adapted van);
- column 12 is the information required from the user to book the trip (P – Pickup point; D – delivery point; PT – pickup time; DT – delivery time);
- column 13 indicates whether the service requires a monthly pass, or not;
- column 14 is the fare of the service.

information not available is grayed-out.

Service Name	Country	Route scenario	Role	Service hours			Users	Stops	Timewindow	Booking	Technology	Booking time				Vehicles						Information provided					Pass	Trip price
				D	N	24H						<1h	1h	1h<=2h	1 day	MB	T	ST	SP	AMB	AV	P	D	PT	DT	NP		
Allo Lexo	France	R-SC3	N-SC1			X	USR-2	STP-3	-	B-SC2	BT-1		X			X						X	X	X			0.0€	regular bus
AST Shared Taxi	Austria	R-SC3 / R-SC4	N-SC3	X	X		USR-2	STP-2 / STP-3	-	B-SC2	BT-1		X					X				X	X	X		X	0.0€	3.2-5.6€
Belbus	Belgium	R-SC4	N-SC3	X	X		USR-1 / USR-2	STP-3	15 min	B-SC2	BT-1			X						X		X	X	X			11.0€	0.85€
CallConnect	England	R-SC4 / R-SC5	N-SC1	X			USR-1 / USR-2	STP-3 / STP-4	-	B-SC2	BT-1		X			X						-	-	-	-	-	-	-
Cambridge Dial-a-Ride	England	R-SC5	N-SC1	X			USR-1	STP-4	-	B-SC2	BT-1	-	-	-	-					X		-	-	-	-	-	0.0€	4.0-5.0€
Cango	England	R-SC4	N-SC1	X	X		USR-2	STP-3 / STP-4	-	B-SC2	BT-1		X			X						-	-	-	-	-	-	-
Collecto	Belgium	R-SC4	N-SC1		X		USR-2	STP-3	10 min	B-SC2	BT-1	X						X				X	X	X		X	0.0€	6.0€
DrinBus	Italy	R-SC4	N-SC1	X			USR-2	STP-2	-	B-SC1 / B-SC2	BT-1	X				X						-	-	-	-	-	0.0€	regular bus
Flexibus	Portugal	R-SC3	N-SC1	X			USR-2	STP-3	-	B-SC1	None	X				X							X				0.0€	0.5-1.0€
Flexiline	Sweden	R-SC3	N-SC1	X			USR-1	STP-3	30 min	B-SC2	BT-1	X				X						-	-	-	-	-	0.0€	regular bus
London Dial-a-Ride	England	R-SC5	N-SC1	X			USR-1	STP-4	15 min	B-SC4	BT-1				X					X		-	-	-	-	-	0.0€	0.0€
PersonalBus	Italy	R-SC4 / R-SC5	N-SC3	X			USR-1 / USR-2	STP-3	-	B-SC4	BT-1				X	X				X		X	X	X	X		0.0€	regular bus
Provibus	Italy	R-SC3	N-SC1	X			USR-2	STP-3	-	B-SC4	BT-1				X	X						X	X	X			0.0€	1.0-2.0€
Proxitan	France	R-SC4 / R-SC5	N-SC2	X	X		USR-1 / USR-2	STP-2 / STP-4	-	B-SC4	BT-1				X	-	-	-	-	-	-	-	-	-	-	-	0.0€	regular bus
Pti'Bus	France	R-SC3	N-SC2	X			USR-2	STP-2	-	B-SC2	BT-1	X				-	-	-	-	-	-	-	-	-	-	-	0.0€	regular bus
PubliCar	Switzerland	R-SC2 / R-SC4 / R-SC5	N-SC3	X	X		USR-1 / USR-2	STP-1 / STP-4	-	B-SC4	BT-1				X					X		X	X	X			0.0€	regular bus (2€ door-to-door)
RegioTaxi	Netherlands	R-SC5	N-SC1	X			USR-1 / USR-2	STP-4	10-15 min	B-SC2	BT-1	X								X		-	-	-	-	-	0.0€	regular bus(U-1 users) 4xregular bus(U-2 users)
Ring and Ride	England	R-RC5	N-SC1	X			USR-1	STP-4	-	B-SC2	BT-1			X						X		-	-	-	-	-	0.0€	regular bus
Rural Lift	Ireland	R-SC2	N-SC1	X			USR-1 / USR-2	STP-3 / STP-4	-	B-SC4	BT-1				X			X	X	X		-	-	-	-	-	-	-
SPT Dial-a-Bus	Scotland	R-SC5	N-SC1	-	-	-	USR-1	STP-4	20 min	B-SC2	BT-1	-	-	-	-					X		X	X	X			0.0€	0.0€
STS	Sweden	R-SC5	N-SC1	X			USR-1	STP-4	-	B-SC2	BT-1	X				X	X				X	-	-	-	-	-	0.0€	2xtaxi
TaxiTub	France	R-SC4	N-SC2			X	USR-2	STP-2	-	B-SC2	BT-1		X					X				X	X	X		X	-	-
Telebus	Germany	R-SC5	N-SC1			X	USR-1	STP-4	-	B-SC2	BT-1				X					X		X	X	X			-	-
Trambus Abile	Italy	R-SC5	N-SC1	X			USR-1	STP-4	-	B-SC4	BT-1				X				X		X	X	X	X	X		0.0€	0.0€
TAD Castilla y León	Spain	R-SC2	N-SC1	X			USR-2	STP-1 / STP-3	-	B-SC2	BT-1 / BT-4 / BT-5	-	-	-	-		X		X	X		-	-	-	-	-	0.0€	1.0€

Table 18 - Survey data summarized

Raw data

The analyzed services are presented in a per country structure in the following pages, using the framework proposed in Chapter 2.

COUNTRY: AUSTRIA

Service Name:	AST Shared Taxi
City:	Linz
Description/Route scenario	Almost door-to-door service. Stand-alone night time service and daytime feeder service.
Role	DRT with multiple roles
Service hours:	Night service every day of the week between 8 p.m. and 5 a.m. Daytime service provided between 5:40 a.m. and 7:40 p.m. to feed the train service.
Passengers:	Available to everyone. No handicapped/elderly special service available.
Operation:	
Vehicles:	Shared taxi cabs.
Service points:	For the night service the passengers are picked up at one of 275 predefined points. Delivery is made in any address inside the limits of the service area. The day time service works only between train stations.
Time window:	No information was found.
Service frequency:	Routes start at every 30 minutes.
Service request:	
Booking	Direct booking
Technology:	Trip request are made by telephone call.
Request time:	Trip request must be made at least 1 hour before the desired pickup time.
Information provided:	Desired pickup time, destination and number of passengers.
Price:	Inside the boundaries of Linz the price is between 3,20€ and 5,60€.

Service Name:	Belbus
City:	Many
Description/Route scenario	Predefined stops in an area scenario service connecting 31 rural areas but also operates as a feeder service in some areas. No schedule.
Role	DRT with multiple roles
Service hours:	Every day of the week between 11 p.m. and 6 a.m.
Passengers:	Available to everyone, including handicapped/elderly.
Operation:	
Vehicles:	10-12 seats capacity adapted minibuses. The trip service can be provided by public operator or by a subcontractor (e.g. a local taxi company).
Service points:	Predefined points.
Time window:	15 minutes before the agreed pickup time.
Service frequency:	No information was found.
Service request:	
Booking	Direct booking
Technology:	Trip request are made by telephone call.
Request time:	Trip request must be made at least 2 hours (just 1 hour in some areas) before the desired pickup time. Working days from 6:30 a.m. to 7 p.m. On Saturday, Sunday and holidays from 8 a.m. to 7 p.m.
Information provided:	The date and desired time of pickup, the municipality and the entry and exit stops and whether the trip connects to the train service or not. The operator then provides the pickup time.
Price:	Subscription of the service costs 11€/year and then each trip costs 0,85€.

Service Name:	Collecto
City:	Brussels
Description/Route scenario	Predefined stops in an area scenario service
Role	Stand-alone DRT service
Service hours:	Every day of the week between 11 p.m. and 6 a.m
Passengers:	Available to everyone. No handicapped/elderly special service available.
Operation:	
Vehicles:	Shared taxi cabs.
Service points:	Passengers are picked up at one of 200 predefined points (which correspond to bus stops) and delivered at the service stop point nearest to the address specified by the passenger.
Time window:	The passenger must be at the pickup stop at the specified pickup stop, but there is a 10 minutes time window for the vehicle arrival.
Service frequency:	Routes start at every 30 minutes.
Service request:	
Booking	Direct booking
Technology:	Trip request are made by telephone call.
Request time:	Trip request must be made at least 20 minutes before the desired pickup time.
Information provided:	Desired origin, pickup time, desired destination address and number of passengers.
Price:	6€/pax (5€/pax for passengers with public transportation monthly travel cards).

Service Name:	CallConnect
City:	Many (Lincolnshire)
Description/Route scenario	Flexible route with a set of predefined stops but it is possible to go to handicapped or elderly passengers home address. No fixed timetable.
Role	Stand-alone DRT service
Service hours:	From Monday to Saturday between 7 a.m. to 7 p.m.
Passengers:	Available to everyone.
Operation:	
Vehicles:	Shared taxi cabs.
Service points:	Set of predefined stops but with possibility to go to handicapped or elderly passengers home address.
Time window:	No information found.
Service frequency:	No information.
Service request:	
Booking	Direct booking
Technology:	Trip request are made by telephone call.
Request time:	Trip request must be made at least 1 hour before the desired pickup time.
Information provided:	No information found.
Price:	No information found.

Service Name:	Cango
City:	Hampshire County
Description/Route scenario	Predefined stops in an area scenario. Non-fixed lines with at least a fixed stop and a set of demand driven predefined stops. Non-predefined stops can be negotiated.
Role	Stand-alone DRT service
Service hours:	Workdays from 8 a.m. to 5 p.m. and on Saturdays from 8 a.m. to 4:30 p.m.
Passengers:	Available to everyone. No handicapped/elderly service information found.
Operation:	
Vehicles:	Minibuses
Service points:	Fixed and predefined stops with possibility to negotiate non-predefined stops.
Time window:	No information found.
Service frequency:	No information.
Service request:	
Booking	Direct booking
Technology:	Trip request are made by telephone call.
Request time:	Trip request must be made at least 1 hour before the desired pickup time.
Information provided:	No information found.
Price:	No information found.

Service Name:	Cambridge Dial-a-Ride
City:	Cambridge
Description/Route scenario	Door-to-door service. Cambridge Dial-a-Ride is a charitable organization which offers this service on week days in the City of Cambridge and the villages immediately bordering the city and on specified week days from neighboring villages in South and East Cambridgeshire.
Role	Stand-alone DRT service
Service hours:	In the City of Cambridge and in the villages included in the City Service, the service is available in each day of the working week. In the villages where Cambridge Dial-a-Ride offers its County Service, the service is available on a specified day. No other information about the hours was found.
Passengers:	Anyone over 16 years old with reduce mobility.
Operation:	
Vehicles:	Adapted minibuses
Service points:	Door-to-door.
Time window:	No information found.
Service frequency:	No information.
Service request:	
Booking	Direct booking
Technology:	Trip request are made by telephone call.
Request time:	The order should be place as soon as possible to allow the service to guarantee the ride as requested; later requests are serviced as possible. From Monday to Friday 9 a.m. 3 p. m. Outside these times you will find an answer-phone for your booking requests.
Information provided:	No information found.
Price:	There is an annual membership fee and fixed fare for each single or return journey. City fares: 3,5£ per trip; County fares: 4£ per trip.

COUNTRY: ENGLAND

Service Name:	London Dial-a-Ride
City:	London
Description/Route scenario	Dial-a-Ride is a free door-to-door service for disabled people who can't use buses, trains or the Tube. It can be used for all sorts of journeys such as shopping, visiting friends, attending meetings, doctors or dentists appointments. However it cannot be used to attend hospital appointments or local authority day centers.
Role	Stand-alone DRT service
Service hours:	Every day from 6 a.m. to midnight.
Passengers:	Anyone with reduce mobility and elderly.
Operation:	
Vehicles:	Adapted minibuses
Service points:	Door-to-door.
Time window:	15 minutes
Service frequency:	No information.
Service request:	
Booking	Collecting requests (defining service)
Technology:	Trip request are made by telephone call.
Request time:	For next day bookings, Monday to Friday from 9 a.m. to 4 p.m. For same day bookings, Weekdays: from 8 a.m. 7 p.m. Saturday and Sunday: 8 a.m. to 4 p.m.
Information provided:	No information found.
Price:	Free.

Service Name:	Ring and Ride
City:	Many (West Midlands urban boroughs)
Description/Route scenario	Door-to-door bus service for people with reduced mobility. Points in an area scenario serviced with non-predefined stops: the stops are negotiated between the operator and the passengers. No-fixed lines. It is a standalone DRT service connecting rural areas and nearby city centers and services.
Role	Stand-alone DRT service
Service hours:	Available from 8 a.m. to 11 p.m. daily.
Passengers:	People with reduced mobility.
Operation:	
Vehicles:	Adapted minibuses
Service points:	Door-to-door.
Time window:	No information found.
Service frequency:	No information.
Service request:	
Booking	Direct booking
Technology:	Trip request are made by telephone call.
Request time:	Trip request must be made at least 2 hours before the desired pickup time. There is also an advanced booking facility aimed at enabling passengers to make bookings for special events or important appointments where they want to guarantee their journey.
Information provided:	Passenger registration number, destination and desired pickup time. If they are able to accommodate your request they will confirm it there and then. If one or more parts of the journey cannot be provided at the time requested then alternative times will be offered and/or just one of the legs of the trip.
Price:	A number of social passes are accepted. In the event that no pass is held, a cash fare equivalent to a local bus fare will be charged.

Service Name:	Allo Lexo
City:	Lisieux
Description/Route scenario	This service operates in a predefined stops scenario, where the stops are the same as the public transportation bus service, but the timetables are not fixed.
Role	Stand-alone DRT service
Service hours:	24 hours per day, every day.
Passengers:	Available to everyone, no information was found about reduced mobility passengers.
Operation:	
Vehicles:	Adapted minibuses
Service points:	Predefined stops.
Time window:	No information found.
Service frequency:	No information.
Service request:	
Booking	Direct booking
Technology:	Trip request are made by telephone call
Request time:	Trip request must be made at least 1 hour before the desired pickup time. From 9 a.m. to 12 a.m. and then from 1:30 p.m. to 6 p.m. on working days and Saturdays.
Information provided:	Desired pickup time, pickup and delivery stops number.
Price:	The same as the public transportation service.

Service Name:	TaxiTub
City:	Many
Description/Route scenario	Demand driven feeder service. Serves city zones and blocks with low density/demand where a regular bus line is not cost effective, with predefined stop and timetables connecting to the main bus lines.
Role	DRT feeder service
Service hours:	24 hours per day, every day.
Passengers:	Available to everyone, no information was found about reduced mobility passengers.
Operation:	
Vehicles:	Taxicabs.
Service points:	Predefined stops.
Time window:	Not applicable.
Service frequency:	Not applicable.
Service request:	
Booking	Direct booking
Technology:	Trip request are made by telephone call
Request time:	Trip request must be made at least 1 hour before the desired pickup time.
Information provided:	Number of passengers, desired pickup time, pickup and delivery stops number.
Price:	No information found.

Service Name:	Proxitan
City:	Nantes
Description/Route scenario	Demand driven feeder service. Serves city zones and blocks with low density or demand where a regular fixed bus line is not cost effective, with predefined stop and timetables connecting to the main bus lines.
Role	DRT feeder service
Service hours:	Depends on the line, but typically, service operates from 9 a.m. to 4:15 and then from 7 p.m. to 10 p.m. from Monday to Friday, from 7:50 a.m. to 11:30 p.m. on Saturday and from 9:30 a.m. to 8:45 p.m. on Sunday.
Passengers:	Available to everyone, including reduced mobility passengers (in this case is a door-to-door service).
Operation:	
Vehicles:	No information found.
Service points:	Predefined stops.
Time window:	Not applicable.
Service frequency:	Not applicable.
Service request:	
Booking	Collecting requests (defining service)
Technology:	Trip request are made by telephone call
Request time:	Reservations are made from Monday to Friday 8:15 a.m. to 4 p.m. Trip request must be made at least 16 hours before the desired pickup time.
Information provided:	Information provided:
Price:	Equal to the public transportation service.

Country: France

Service Name:	Pti'Bus
City:	Poitiers
Description/Route scenario	Demand driven feeder service. Serves city zones and blocks with low density or demand where a regular fixed bus line is not cost effective, with predefined stop and timetables connecting to the main bus lines. The service operates a total of 33 demand driven lines.
Role	DRT feeder service
Service hours:	9:30 a.m. to 6:30 p.m., every day.
Passengers:	Available to everyone. No information was found about reduced mobility passengers.
Operation:	
Vehicles:	No information found.
Service points:	Predefined stops.
Time window:	Not applicable.
Service frequency:	Not applicable.
Service request:	
Booking	Direct booking
Technology:	Trip request are made by telephone call
Request time:	Information provided:
Information provided:	No information found.
Price:	Equal to the public transportation service.

Service Name:	Telebus
City:	Berlin
Description/Route scenario	Door-to-door dial-a-ride system with aid at the pick-up and the target point for handicapped people that cannot use the public transportation system.
Role	Stand-alone DRT service
Service hours:	Available every day from 5 a.m. in the morning to 1 a.m. at night.
Passengers:	Available to reduced mobility passengers.
Operation:	
Vehicles:	About 100 different capacity mini-buses rented on demand from charitable organizations and commercial companies. There are 5 different vehicle types, being that the vehicle type determines its capacity.
Service points:	Door-to-door.
Time window:	There is a time window, but it was not possible to find its dimension.
Service frequency:	Not applicable.
Service request:	
Booking	Direct booking
Technology:	Trip request are made by telephone call. Every entitled user (currently about 25,000 people) can order up to 50 rides per month
Request time:	If the order is placed one day in advance, service guarantees the ride as requested; later requests are serviced as possible.
Information provided:	Pickup and delivery location and desired pickup time.
Price:	No information found.

COUNTRY: IRELAND

Service Name:	Rural Lift
City:	Leitrim, West Cavan and Bundoran/Ballyshannon district
Description/Route scenario	Semi-flexible route DRT service connecting on rural regions.
Role	Stand-alone DRT service
Service hours:	From 8 a.m. to 6 p.m., every day.
Passengers:	Available to everyone, including handicapped/elderly.
Operation:	
Vehicles:	Minibuses, taxis and individual voluntary vehicles.
Service points:	Predefined points along main routes, but with the possibility to diverge to non-defined points.
Time window:	No information was found.
Service frequency:	No information was found.
Service request:	
Booking	Collecting requests (defining service)
Technology:	Trip request are made by telephone call.
Request time:	Trip request must be made on the previous day between 9 a.m. and 4 p.m.
Information provided:	No information was found.
Price:	Price varies according to distance travelled.

Service Name:	DrinBus
City:	Genoa
Description/Route scenario	Predefined stops in an area DRT service. The service covers an area with predefined stops. The structure of the service is defined by the demand. Each stop has a predefined passing time. The service operates 3 lines.
Role	Stand-alone DRT service
Service hours:	The service operates Monday to Saturday (excluding holidays) from 7 a.m. to 8 p.m.
Passengers:	Available to everyone but handicapped/elderly (there is a specific service for this demographic group).
Operation:	
Vehicles:	Minibuses.
Service points:	Predefined points.
Time window:	Predefined passing times.
Service frequency:	No information was found.
Service request:	
Booking	Non pre-booked trips/ Direct booking
Technology:	Trip request are made by telephone call.
Request time:	The booking can be made from Monday to Saturday from 6 a.m. to 7:30 p.m. Trips can be booked for the same day with at least 30 minutes before the desired pickup time, or for future days. Even when the passenger has not booked the trip, he can get on board if there are still seats not assigned and he agrees to share the route already planned.
Information provided:	Pickup and delivery stops, departure and arrival time.
Price:	Price equals to public transport services.

Service Name:	PersonalBus
City:	Florence (Calenzano, Campi Bisenzio, Sesto Fiorentino, Porta Romana)
Description/Route scenario	This service operates in a predefined stops scenario but the timetables are not fixed. Operates also as feeder service.
Role	DRT with multiplr roles
Service hours:	The service operates every working day (including Saturday) from 6:30 a.m to 7:30 p.m.
Passengers:	Available to everyone. For reduced mobility passengers there is a special door-to-door service.
Operation:	
Vehicles:	Different minibuses from different operators.
Service points:	Predefined points.
Time window:	No information found.
Service frequency:	No information was found.
Service request:	
Booking	Collecting requests (defining service)
Technology:	Trip request are made by telephone call.
Request time:	Trips can be booked up to 30 minutes before the bus departure from the terminal. Call centre works every working day (including Saturday) from 6 a.m. to 8 p.m.
Information provided:	Desired pickup time OR delivery time, pickup and delivery stops. The result of the negotiation phase is the acceptance/refusal by the users of one of the proposed trips.
Price:	Price equals to public transport services.

COUNTRY: ITALY

Service Name:	Provibus
City:	Province of Turin
Description/Route scenario	This service operates in a predefined stops scenario, where the stops are the same as the public transportation bus service, but the timetables are not fixed.
Role	Stand-alone DRT service
Service hours:	9 a.m. to 12 a.m. and from 2 p.m. to 4:30 p.m., Monday to Friday.
Passengers:	Available to everyone, no information was found about reduced mobility passengers.
Operation:	
Vehicles:	8-seat capacity minibuses.
Service points:	Predefined stops.
Time window:	Not applicable.
Service frequency:	No information was found.
Service request:	
Booking	Collecting requests (defining service)
Technology:	Trip request are made by telephone call.
Request time:	It is advised to book the trip the day before. Call centre works Monday to Friday from 9 a.m. to 12 a.m. and from 2 p.m. to 4 p.m.
Information provided:	Desired pickup time, pickup and delivery stops.
Price:	Between 1,10€ and 2€.

COUNTRY: ITALY

Service Name:	Trambus Abile
City:	Rome
Description/Route scenario	Door-to-door service for reduce mobility citizens. It is the largest DRT service for disabled and elderly people in Italy. The service was established 14 years ago.
Role	Stand-alone DRT service
Service hours:	The service operates on weekdays from 6 a.m. to 10 p.m.
Passengers:	Handicapped and elderly.
Operation:	
Vehicles:	100 vehicles: 75 vans equipped with lifting platform, and 25 cars.
Service points:	Door-to-door.
Time window:	Not applicable.
Service frequency:	No information was found.
Service request:	
Booking	Collecting requests (defining service)
Technology:	Trip request are made by telephone call.
Request time:	The booking can be made from Monday to Friday from 8 a.m. to 1 p.m. the day before the desired trip.
Information provided:	Pickup and delivery stops, departure and arrival time.
Price:	Free.

COUNTRY: NETHERLANDS

Service Name:	RegioTaxi
City:	Many
Description/Route scenario	Demand responsive door-to-door shared taxi. Focus on rural regions.
Role	Stand-alone DRT service
Service hours:	From 6 a.m. to 1 a.m.
Passengers:	Available to everyone, including handicapped/elderly.
Operation:	
Vehicles:	About 600 adapted minibuses from 5 main contractors and 25 sub-contractors.
Service points:	Door-to-door.
Time window:	10 or 15 minutes (depending on the region) around desired pickup time.
Service frequency:	No information was found.
Service request:	
Booking	Direct booking
Technology:	Trip request are made by telephone call.
Request time:	Trip request must be made at least 30 minutes or 1 hour (depending on the region) before the desired pickup time.
Information provided:	No information was found.
Price:	For passengers with reduced mobility the price is the same as the public transport system. For all other passengers the price is 3 or 4 times (depending on the region) the price of the public transportation system.

Service Name:	Flexibus
City:	Almada
Description/Route scenario	Flexible route with a set of predefined stops but it is possible to make on-demand detours go to the address of social aid institutions in the service area. No fixed timetable. The service is oriented towards senior and young citizens.
Role	Stand-alone DRT service
Service hours:	Daytime service provided between 7:00 a.m. and 7:00 p.m. from Monday to Friday. On Saturday the service operates from 8:00 a.m to 1:00 p.m.
Passengers:	Available to everyone. No handicapped service available.
Operation:	
Vehicles:	2 electric mini buses.
Service points:	Predefined points and social aid institutions.
Time window:	No information was found.
Service frequency:	Routes start at every 20 minutes.
Service request:	
Booking	Non pre-booked trips
Technology:	Directly to the driver (hail-and-ride).
Request time:	Directly to the driver (hail-and-ride).
Information provided:	Destination.
Price:	0,50€ for senior and young citizens, 1,0€ for general public. It is possible to buy trip packs with a big discount.

COUNTRY: SCOTLAND

Service Name:	SPT Dial-a-Bus
City:	Many
Description/Route scenario	SPT Dial-a-Bus is a free door-to-door service for disabled people who can't use the public transportation system. It can be used for all sorts of journeys such as shopping, visiting friends, attending meetings, doctors or dentists appointments. However it cannot be used to attend hospital appointments or local authority day centers.
Role	Stand-alone DRT service
Service hours:	No information found.
Passengers:	Anyone with reduce mobility and elderly.
Operation:	
Vehicles:	Adapted minibuses.
Service points:	Door-to-door.
Time window:	20 minutes.
Service frequency:	No information found.
Service request:	
Booking	Direct booking
Technology:	Trip request are made by telephone call.
Request time:	No information found.
Information provided:	Pickup and delivery location, as well as desired pickup time.
Price:	Free.

Service Name:	Transporte a la Demanda Castilla y León
City:	Many (rural localities from Castilla and León)
Description/Route scenario	Semi-flexible route scenario service. There is a set of fixed stops and predefined passing times, but in addition the vehicle can deviate from the route to serve predefined stops on request. The service operates around 700 routes connecting rural areas to major cities and services, corresponding to almost 1.000.000 potential passengers.
Role	Stand-alone DRT service
Service hours:	The service operates 3 or 5 days per week, depending on the region. Outgoing trips are between 8 a.m. and 9 a.m. and the return trips between 11:30 a.m. and 1 p.m.
Passengers:	Available to everyone. No information was found about reduced mobility passengers.
Operation:	
Vehicles:	Around 400 adapted minibuses, taxis and 4x4 vehicles, according to the terrain.
Service points:	Fixed stops plus a set of predefined stops.
Time window:	Real-time information provided at each stop.
Service frequency:	No information found.
Service request:	
Booking	Direct booking
Technology:	Trip request are made by telephone call, SMS message or Internet.
Request time:	Trip request are received in real time by the driver of the vehicle from the central reservation service.
Information provided:	No information was found.
Price:	1€ per total trip (outgoing and return).

Service Name:	STS
City:	Gothenburg
Description/Route scenario	Door-to-door vehicle sharing service for citizens with reduced mobility.
Role	Stand-alone DRT service
Service hours:	Working days from 6h a.m. to 11h p.m. weekends and official holidays from 9 a.m. to 23 p.m.
Passengers:	Only for local citizens with reduced mobility.
Operation:	
Vehicles:	Adapted vehicles, minibuses, and taxi cabs. The operator doesn't own any vehicles – they are operated by private companies.
Service points:	Door-to-door.
Time window:	No information found.
Service frequency:	Not applicable.
Service request:	
Booking	Direct booking
Technology:	Trip request are made by telephone call or Internet.
Request time:	Trip request must be made at least 15 minutes before the desired pickup time.
Information provided:	No information was found.
Price:	Twice the equivalent taxi ride.

Service Name:	Flexiline
City:	Gothenburg
Description/Route scenario	Predefined stops in an area scenario service with a set of 100 demand driven predefined stops. The service operates 10 lines.
Role	Stand-alone DRT service
Service hours:	Working days from 9 a.m. to 5 p.m.
Passengers:	Only for local elders who are not eligible for the STS service.
Operation:	
Vehicles:	30 minibuses with 10-12 seats capacity.
Service points:	100 demand driven predefined stops.
Time window:	The service operator calls the passenger 15 minutes before his desired pickup time to notify that the vehicle will arrive on time or not. In the latter case there is 30 minutes time window.
Service frequency:	No information found.
Service request:	
Booking	Direct booking
Technology:	Trip request are made by telephone call or Internet.
Request time:	Trip request must be made at least 15 minutes before the desired pickup time. If in the next hour there is no flexibus passing by the desired stop, the service redirects the request for the STS service.
Information provided:	No information was found.
Price:	The same of the public transportation service.

COUNTRY: SWITZERLAND

Service Name:	PubliCar
City:	Many
Description/Route scenario	PubliCar is a flexible demand-driven door-to-door bus service started in 1995. Operates in a "points in a region" scenario, but, depending on the region, can have fixed stops. It also provides a link with traditional transportation systems. Currently the service operates in 28 zones inside the federal territory, with various types of service and timetables, managed by a national centre. The success was instantaneous, having to turn away customers, unfortunately, from the very opening of the service.
Role	DRT with multiple roles
Service hours:	Depends on the zone, but, typically from Monday till Thursday operates between 8 a.m. and 6 p.m.; on Friday and Saturday, operates between 8a.m. and 8 p.m. and from 10.30 p.m. to 1.30 a.m.; on Sunday and national holidays from 8 a.m. to 8 p.m.
Passengers:	Available to everyone, including handicapped and elderly.
Operation:	
Vehicles:	Minibuses. Each mini bus can offer up to 18 places and are equipped with seats and ramps for people with reduced mobility. Each vehicle will stay and operate in its allocated zone. Each zone currently has about 2 to 3 vehicles.
Service points:	Door-to-door or fixed points (depending on regions).
Time window:	No information found.
Service frequency:	No information found.
Service request:	
Booking	Collecting requests (defining service)
Technology:	Trip request are made by telephone call.
Request time:	Reservations should be made 24 hours in advance, however last minute bookings are accommodated as much as possible. Call center is open during the week between 7 a.m. and 7 p.m. On Saturdays between 7 a.m. and 3 p.m. If calls are made outside of these hours (including Sundays) but during PubliCar operating hours, the calls are diverted to the driver.
Information provided:	Time and place of departure, destination and possible constraints (e.g. correspondence with bus or train departure). If the proposed trip proposed by the user is not possible, PubliCar will ask that the user changes his/her departure time. The user does not in this case have a choice and will need to take the new proposed time. The driver then instantly receives a new itinerary via SMS messaging.
Price:	Similar to conventional public transport, with only a small additional surcharge 2 € in the case of the door-to-door service.