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Doctoral Thesis

Combination of Vehicle Routing Models and Dynamic Traffic Simulation for City Logistics Applications

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To my family: mom, dad, Kasia, Gracjan and Gérald

Mojej rodzinie: mamie, tacie, Kasi, Gracjanowi i Geraldowi

Para mi familia: mama, papa, Kasia, Gracjan y Gérald

Abstract

The urban network is a highly dynamic system. Thus, a modern and efficient fleet management in urban areas should account for dynamics of traffic conditions, variability in travel times, changes in demand and fleet availability. All these factors significantly affect the distribution of goods and the provision of services. As a consequence, the freight operations optimizing approaches should be based on the time-dependent travel time estimates rather than on the average static values commonly employed as input data.

Proficient dynamic fleet management decisions need to take into consideration all the factors conditioning the addressed problem. Hence, the customers' requests and service conditions (demands, time windows, etc.), operational conditions of the employed fleet (vehicles' availability, status, positions, current occupancy of the carriage space, etc.) and traffic conditions need to be reckoned with. This information can be provided in the real-time fashion and at an affordable price by the ICT applications and tools such as: ATIS, GPS, GPRS or other.

Instead of relying exclusively on the experience of a dispatcher, it is effective to base the freight management decisions on information provided by a professional Decision Support System facilitating the consideration of all the factors conditioning the addressed issue.

The objective of the present thesis is to propose, implement and computationally test, on the basis of a simulation, the architecture of a Decision Support System for real-time freight management able of accounting for all the dynamic factors mentioned above. Its design is based on integration of a selected pickup and delivery vehicle routing model and dynamic traffic simulation models, whose purpose is to carefully emulate the evolving traffic conditions. The optimal dynamic routing and scheduling of a vehicle fleet is obtained due to dynamic modifications of the current routing and scheduling plan on the basis of the recently revealed information conditioning the addressed problem.

The obtained results of computational experiments show that the performance of freight fleet strongly depends on the traffic information used to create the routing and scheduling plan. Due to the special character of transport operations performed in metropolitan areas it is possible that not all the scheduled customers would be served, although a feasible initial solution is created on the basis of the historical travel times' data. Hence, there is a need to implement real-time rerouting strategies allowing modifications of the original routes in order to feasibly fulfil the routing tasks. In addition, the tighter the constraints specifying the customers' time windows and the higher the number of dynamically appearing requests, the higher the cost of the performance and the level of utilization of the freight fleet.

Streszczenie

Sieć miejska jest systemem niezwykle dynamicznym. Tak więc, nowoczesne i skuteczne zarządzanie flotą pojazdów w obszarach miejskich powinno brać pod uwagę dynamikę warunków ruchu, zmienność czasu podróży oraz zmiany dotyczące popytu i dostępności floty, ponieważ czynniki te znacząco wpływają na dystrybucję towarów i jakość świadczonych usług. W związku z tym, metody optymalizacyjne dla miejskich przewozów towarowych powinny być oparte na danych reprezentujących czas podróży w zależności od momentu jej rozpoczęcia, a nie na średnich wartościach statycznych, które są powszechnie wykorzystywane jako dane wejściowe.

Aby podjąć sprawne i dynamiczne decyzje w zarządzaniu flotą należy wziąć pod uwagę wszystkie czynniki warunkujące badany problem. Należy uwzględnić: zamówienia klientów wraz z warunkami określającymi charakter świadczonych usług (wielkość zamówienia, okna czasowe, itp.), operacyjność poszczególnych pojazdów z zatrudnionej floty (dostępność, status, lokalizacja, ilość aktualne przewożonego towaru, itp.) oraz warunki ruchu. Te informacje mogą być dostarczone w czasie rzeczywistym i po przystępnej cenie dzięki aplikacjom i narzędziom Technologii Informacyjnych i Telekomunikacyjnych, takich jak: zaawansowany system informacji o ruchu drogowym (ATIS), GPS, GPRS lub inne.

Zamiast opierać się wyłącznie na doświadczeniu dyspozytora, przy podejmowaniu decyzji dotyczących zarządzania flotą warto wykorzystać informacje dostarczone przez profesjonalny system wspomagania podejmowania decyzji, który ułatwia analizę wszystkich czynników warunkujących rozwiązywany problem.

Celem niniejszej pracy jest zaproponowanie, wykonanie i przetestowanie na podstawie symulacji architektury systemu wspomagania decyzji dla zarządzania transportem towarów w czasie rzeczywistym uwzględniającego wszystkie wymienione czynniki dynamiczne. Jego konstrukcja opiera się na integracji wybranego modelu określającego trasy dla pojazdów przy uwzględnieniu odbioru i dostawy poszczególnych przesyłek i dynamicznego modelu symulującego ruch uliczny, którego celem jest staranne naśladowanie zmieniających się warunków ruchu. Optymalne i dynamiczne wykonanie planowanych tras uzyskano dzięki dynamicznej zmianie obecnego planu trasy i zaplanowanie nowego na podstawie nowych informacji warunkujących badany problem.

Z uzyskanych wyników eksperymentów obliczeniowych wynika, że wydajność floty w dużym stopniu zależy od informacji o ruchu ulicznym wykorzystanych do zaprojektowania tras i harmonogramu dostaw. Ze względu na szczególny charakter przewozów realizowanych w obszarach miejskich, choć początkowe rozwiązanie zbudowane na podstawie danych historycznych jest poprawne i możliwe, może się zdarzyć, że nie wszyscy klienci będą obsłużeni. A zatem, istnieje potrzeba wdrożenia strategii przekierowujących pozwalających na modyfikacje pierwotnej trasy w czasie rzeczywistym, aby pomyślnie wypełnić oryginalne zadania transportowe. Ponadto, zaostrzenie ograniczeń określających okna czasowe serwisu klientów, jak również większa liczba dynamicznie pojawiających się zamówień sprawia, że wyższy jest koszt transportu i stopień wykorzystania floty.

Resumen

La red urbana es un sistema altamente dinámico. Por lo tanto, la gestión moderna y eficiente de la flota en las zonas urbanas debe tener en cuenta la dinámica de las condiciones del tráfico, la variabilidad en los tiempos de viaje y los cambios en la disponibilidad de la demanda y de la flota, ya que afectan de manera significativa en la distribución de bienes y la prestación de servicios. Como consecuencia, los enfoques para optimizar las operaciones de carga deben basarse en las estimaciones de los tiempos de viaje dependientes del tiempo y no en los valores medios estáticos comúnmente empleados como datos de entrada.

Las decisiones competentes de gestión dinámica de las flotas necesitan tener en cuenta todos los factores que condicionan el problema abordado. Por lo tanto, hay que considerar las características de las peticiones y las condiciones de servicio de los clientes (demanda, ventanas de tiempo, etc.), las condiciones operacionales de la flota empleada (disponibilidad de los vehículos, estatus, ubicación, ocupación actual del espacio de transporte, etc.) y las condiciones de tráfico. Esta información puede ser proporcionada en tiempo real a un precio asequible por las aplicaciones de las TIC y herramientas tales como: ATIS, GPS, GPRS u otros.

En lugar de confiar exclusivamente en la experiencia de un distribuidor, también sería correcto basar las decisiones de gestión de transporte de mercancías en la información proporcionada por un sistema profesional de apoyo a la toma de decisiones que facilita la consideración de todos los factores que condicionan el problema abordado.

El objetivo de esta tesis es proponer, implementar y validar computacionalmente en base a la simulación, la arquitectura de un Sistema de Apoyo a la Toma de Decisiones para la gestión de transporte de mercancías en tiempo real capaz de considerar todos los factores dinámicos previamente mencionados. Su diseño se basa en la integración de un modelo seleccionado de rutas de vehículos con recogida y entrega y modelos de simulación de tráfico dinámicos cuyo propósito es emular detalladamente las condiciones de tráfico que cambian con el paso del tiempo. Las rutas y los horarios dinámicos óptimos para una flota de vehículos que transporta mercancías se obtienen de las modificaciones dinámicas de un plan actual de rutas y horarios en base a la nueva información recibida que condiciona el problema abordado.

Los resultados obtenidos de los experimentos computacionales demuestran que el rendimiento de la flota de transporte de mercancías depende en gran medida de la información de tráfico utilizada para crear el plan de rutas y los horarios. Debido al carácter especial de las operaciones de transporte realizadas en las áreas metropolitanas, a pesar de una solución inicial factible que se crea sobre la base de los datos históricos de los tiempos de viaje, es posible que no todos los clientes sean servidos. Por lo tanto, hay una necesidad de implementar estrategias de cambios de rutas en tiempo real, que permiten modificar las rutas originales con el fin de cumplir las tareas de enrutamiento viables. Además, más estrictas son las limitaciones que especifican las ventanas del tiempo de los clientes y más alto es el número de solicitudes de servicio que aparecen de forma dinámica, mayor será el coste final de las prestaciones del servicio y el nivel de utilización de la flota de transporte de mercancías.

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Figures

Tables

Abbreviations

Abbreviation	Meaning
ADEME	French Environment and Energy Management Agency (Agence de l'Environnement et de la Maîtrise de l'Energie)
ADW	Advanced Dynamic Waiting
ATIS	Advanced Traffic Information System
AVL	Automatic Vehicle Location
CPU	Central Processing Unit
CSR	Complete Route Reconstruction
CVRP	Capacitated Vehicle Routing Problem
DARP	Dial-A-Ride Problem
DCVRP	Distance Constrained Capacitated Vehicle Routing Problem
DF	Drive-First
DRSM	Dynamic Routing and Scheduling Module
DSS	Decision Support System
DW	Dynamic Waiting
EDOD	Effective Degree of Dynamism
$EDOD_{TW}$	Effective Degree of Dynamism when addressing the problem containing Time Windows
FIFO	First-In-First-Out
FM	Frequency Modulation
GDP	Gross Domestic Product
GPRS	General Packet Radio Service
GPS	Global Positioning System
ICT	Information and Communication Technology
IRSM	Initial Routing and Scheduling Module
ITS	Intelligent Transport System
IVHS	Intelligent Vehicle Highway System
LNS	Large Neighbourhood Search
MMS	Multimedia Messaging Service
M2M	Many to Many
M2O	Many to One

NPDPEO	Normal Pickup and Delivery Pair Exchange Operator
NPDPRO	Normal Pickup and Delivery Pair Rearrange Operator
NPDPSO	Normal Pickup and Delivery Pair Shift Operator
PDP	Pickup and Delivery Problems
PDPTW	Pickup and Delivery Problem with Time Windows
PDVRP	Vehicle Routing Problem with Pickup and Delivery
PDVRPTW	Pickup and Delivery Vehicle Routing Problem with Time Windows
PTS	Parallel Tabu Search
RPDPSO	Reverse Pickup and Delivery Pair Shift Operator
SA	Simulated Annealing
SMS	Short Message Service
SP	Shortest Path
SPI	Single Pair Insertion
TD	Time-Dependent
TDSP	Time-Dependent Shortest Path
TS	Tabu Search
TSP	Travelling Salesman Problem
TW	Time Windows
UTS	Unified Tabu Search
VFP	Vehicle Fleet Performance
VRP	Vehicle Routing Problem
VRPB	Vehicle Routing Problem with Backhauls
VRPTW	Vehicle Routing Problem with Time Windows
WAP	Wireless Application Protocol
WF	Wait-First

Contents

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Introduction

"All you have to decide is what to do
with the time that is given to you"

- J. R. R. Tolkien (1892 - 1973)
"The Lord of the Rings"

Chapter 1

Finding support in the published records, this chapter provides the theoretical base indispensable to create a framework upon which all the work in the current thesis project was performed. It briefly introduces relevant research areas and highlights the underlying problems and key concepts employed throughout the thesis. However, its main objective is to define the work's motivation, to introduce the proposed innovations and specify the set of goals.

The main subject of the current research is transport and logistics operations in city areas. Hence, the introduction to this chapter provides basic terms and definitions regarding fleet operations in urban environments. The study is motivated by the opportunity to achieve economic savings and reduce negative impacts. The characteristics of City Logistics defined on the basis of the impacts resulting from urban freight operations are presented in Section 1.1. In order to optimise the City Logistics system as a whole it is necessary to define the implicated actors. The list of the involved stakeholders is provided in Section 1.2. In the same section there are described different levels of the decisions aiming at improving the performance of the City Logistics system. Section 1.3 explains the technological developments enabling fast acquisition of information supporting real-time freight management which results in creation of alternative operational patterns improving the strategies concerning optimization of delivery service's efficiency. The purpose of the thesis is to propose and develop a Decision Support System for real-time freight management. The details on both the purpose and the scope of the thesis are provided in Section 1.4. The objectives and the expected contributions are listed in Section 1.5. The contents of the current document are presented in the last section (1.6).

Distribution Logistics in Urban Areas

The Council of Logistics Management, 2001 (http_1) defines *logistics* as "*part of the supply chain process that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services, and related information between the point of origin and the point of consumption in order to meet customers' requirements*". The objective of logistics is to optimise the existing production and distribution processes through efficient management techniques. It involves such activities as: warehousing, inventory, transportation, administration of: information, energy, human resources, materials, packaging and oftentimes security. Figure 1.1 presents an overview of the logistics system.

The three main components of the logistics system are:

- *logistics services* - activities supporting the movement of raw materials and products from their source defined as input through production and distribution to the final customers (also includes the disposal of waste and reverse flows); they include not only physical activities such as transport and storage but also non-physical ones such as supply chain design, selection of contractors, freightage negotiations, etc.,
- *information systems* – their objective is to provide and manage the required data; they support the decision-making processes and are responsible for tracking and tracing the flow of goods,
- *infrastructure/resources* – include: human and financial resources, packaging materials, warehouses, transport and communication means.

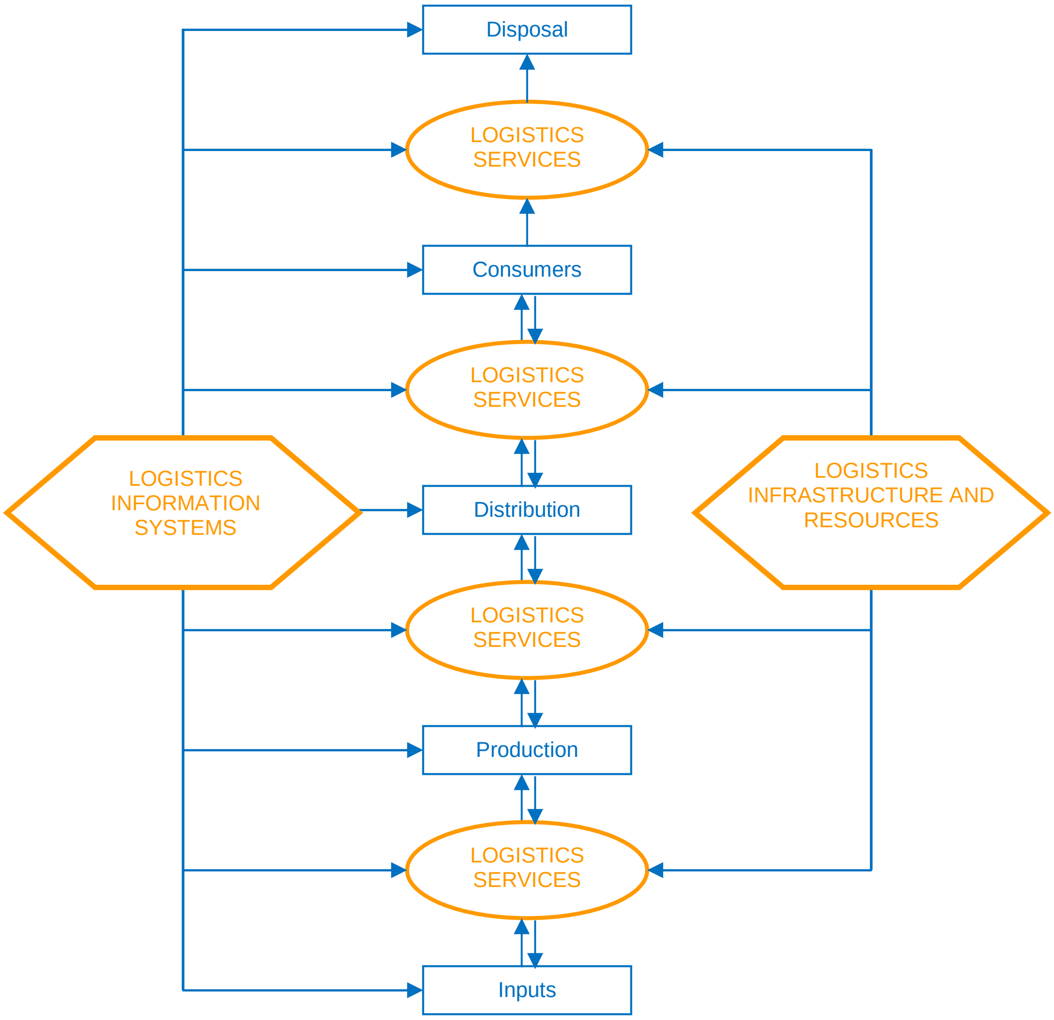


Figure 1.1 Logistics system (by Tseng et al., 2005, adapted from Bureau of Transport and Regional Economics 2001, http_2)

The transportation system connects all the segments of the goods delivery chain. Since it links all the activities it has a strong influence on the performance of the logistics system as a whole. An efficiently functioning transport system can provide better efficiency, reduce operation cost, and promote service quality of logistics activities.

According to Rodrigue (http_9) the world-wide logistics expenditures represent about 10-15% of the total world Gross Domestic Product (GDP). Figure 1.2 describes the percentage of the total logistics expenses on each of the activities. Out of all the logistics activities, transportation results in the biggest economic impact. It constitutes more than one third of total logistics cost (39%).

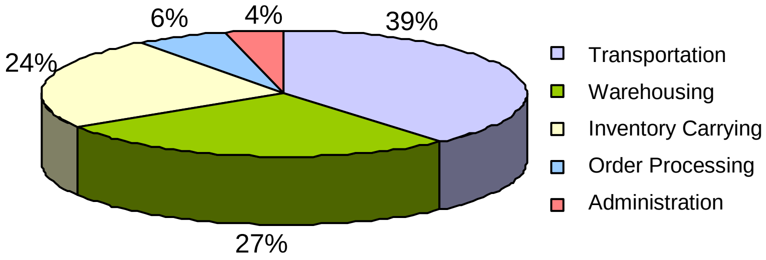


Figure 1.2 World-wide logistics costs 2002 (http_9 by Rodrigue, adapted from http_10 by Roberts)

An analysis of the distribution of costs within the freight transport chain performed by the Council of Logistics Management and Differentiation for Performance Excellence in Logistics (2004) indicates that the share of pickup and delivery operations, which take place in urban areas, in the total door-to-door cost reaches 28%, which constitutes 12% of the total logistics cost. These data acquire more importance when the physical distance of the trip performed in the urban area is compared to the total distance travelled. It indicates that almost one third of the total transportation cost of a thousands-kilometres-long journey is spent on the first and last couple of kilometres. The operations performed on these short distances, constitute a large part of the total logistic cost not only financially, but also regarding the level of customers' satisfaction and the success of the complete delivery undertaking.

The fact that transportation is the most resource intensive of all the logistics activities indicates that there is great potential to make savings. Since the cost of the transportation operations performed under the conditions and according to the dynamics of urban regions constitute a significant portion of total costs, their optimisation is particularly promising. Therefore, it became the main research subject in the current thesis project.

The term used to define freight operations which take place in urban areas is *last-kilometre* (or *last-mile*) *logistics*. As shown in Figure 1.3, it refers to this *final, time-sensitive step in the sequence of the supply chain, between the distribution point and the ultimate customer who receives an individual order*. It does not only take into consideration the physical travelled distance but also the imposed restrictions regarding time of operation and regulatory conditions determining the process, which are imposed by administration entities. In the vast majority of cases the complete operation needs to be completed in one work-day.

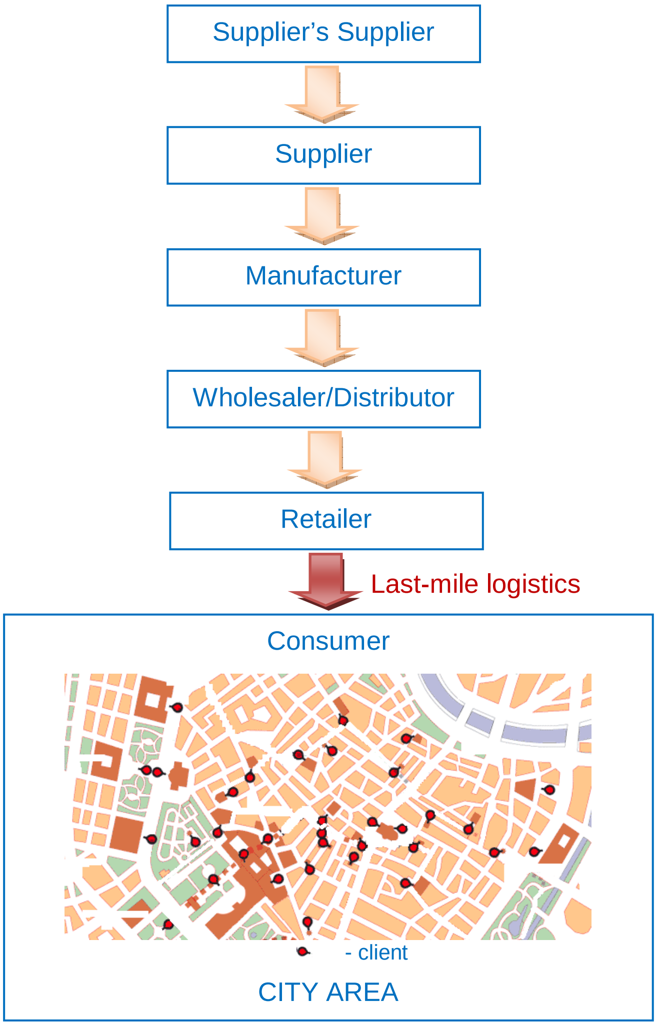


Figure 1.3 Supply chain

Taniguchi et al. (2001) provide a description of logistics activities, conducted in a metropolitan environment, which are subjected to specific impacts such as traffic congestion which results in environmental changes. They are denoted as *City Logistics* (CL) and defined as: *“the process of totally optimizing the logistics and transport activities by private companies in urban areas while considering the traffic environment, traffic congestion and energy consumption within the framework of a market economy”*.

Due to the characteristic dynamics of the metropolitan environment and the constantly changing demand for goods, urban freight transport and logistics deal with many requests regarding parcels which tend to be small-sized in frequently performed trips. Its direct consequence is the high number of vehicle-kilometres travelled and the conclusion that this can be improved by efficient vehicle fleet management within *Urban Freight Logistics* operations.

1.1 Characteristics of City Logistics

The logistics activities in urban areas aim at delivering consignments in the right composition both in terms of quality and quantity, at the precise time and at the lowest possible cost. However, since they take place in an environment with special features, their optimisation results not only with economical savings but also with the reduction of many caused negative impacts. The supplementary benefits enhance the importance of the optimization of urban freight operations and strengthen the motivation of the current thesis project.

CL as a phenomenon is characterised by a collection of peculiarities, which might be explained from the standpoint of caused impacts. These impacts are segmented following the guideline proposed by Anderson et al. (2005):

- economic and energy consumption impacts such as:
  - traffic congestion,
  - hindered accessibility,
  - inefficiency,
  - resource waste,
  - etc.
- environmental impacts such as:
  - emission of air pollutants, especially in terms of greenhouse gases and other contaminants emitted into the atmosphere as a result of incomplete fuel combustion and fuel impurities,
  - use of non-renewable fossil-fuels,
  - generation of waste products such as tires, oils, acids and other materials,
  - etc.
- social impacts such as:
  - physical consequences of pollutant emissions on public health like: death, illness, hazards, etc.,
  - injuries and death resulting from traffic incidents,
  - noise,
  - vibration,
  - smell,
  - visual intrusion,
  - problematic essential journeys realisation lacking a car or appropriate public transport,
  - other issues concerning quality of life, including the loss of green-field sites and open spaces in urban areas as a result of transport infrastructure developments,
  - etc.

The problems of increasing congestion and hindered accessibility within urban areas are a direct result of the growing numbers of both: passenger and consignment-transporting vehicles as well as the lack of adequately organized infrastructure to maintain general augmented traffic and delivery operations. Curiously, although these issues are common and well known, no estimations have been defined that permit easy economical representation and assessment of the impact made. Notwithstanding, in order to evaluate the magnitude of congestion the following measures may be used:

- *travel time index* – the ratio of travel time in the peak period to travel time in the free-flow conditions (a measure of congestion that focuses on each trip and each mile of travel) e.g.: a value of 1.30 indicates a 20-minute free-flow trip takes 26 minutes in the peak,
- *peak travellers* – number of travellers using any travel mode, who begin a trip during the morning or evening peak travel periods,
- *annual delay per traveller* – annual sum of all the delays per trip, to illustrate the effect of the per-mile (or kilometre) congestion as well as the length of each trip; the extra time required to travel in the peak period is divided by the number of travellers who begin a trip during the peak period,
- *total delay* – to represent the overall size of the congestion problem; it is measured by the total travel time above that needed to complete a trip at free-flow speeds,
- *excess fuel consumed* – value of the increased fuel consumption due to travel in congested conditions,
- *annual increase needed to maintain constant congestion level* – number of lane-miles (or kilometres) that must be added to the road system each year – or – the number of new transit riders or car-poolers that must be added to keep congestion levels the same as the previous year,
- *number of rush hours* – the time when the system might have congestion.

In this context, the congestion cost might be presented as the value of travel delay and excess fuel consumption. For example, according to the Urban Mobility Report 2009, published by the Texas Transportation Institute (http_6), providing the traffic patterns prepared for 439 U.S. urban areas from the year 1982 through 2007, the total amount of wasted fuel reached 2.8 billion gallons, which constitutes the equivalent of three weeks of gas for every traveller. Moreover, the amount of time wasted in traffic amounted to 4.2 billion hours - almost a full week of work or vacation for each travelling person. The final calculation based on the wasted fuel and lost productivity indicates that the overall cost of congestion reached 87.2 billion dollars in the year 2007, which is more than 750 dollars for every U.S. traveller.

According to the Organisation for Economic Co-operation and Development (OECD) (2001), in French urban areas freight vehicles constitute a substantial portion of urban traffic. In terms of private car equivalent units [road occupancy] it corresponds to 18%. Hence, goods transport is considered to be one of the most significant factors affecting urban mobility and a major cause of congestion.

According to the French Environment and Energy Management Agency (ADEME) (http_4) the transportation sector in general is the leading consumer of petroleum derivatives. In the year 2003, transit operations used 67% of the total quantity of the petroleum derivatives produced. Between the years 1973 and 2004 this value nearly doubled in volume and from the year 1990 it increased by 20%. Among all types of transportation, carriage by road is responsible for the consumption of 81% of the energy. The means used to transport goods within urban areas represent 30% of all the vehicles on the roads and highways. Although it consists of only one third, the commercial delivery vehicles account for nearly 50% of all the diesel fuel consumed in the cities. Furthermore, the consumption of fossil fuels is constantly growing. As reported by the OECD (2001), consumption increases at the rate of about 2% a year. Moreover, it is predicted that between the years 1997-2020 the total demand for energy will grow by around 40% with a significant portion of this increase due to greater demand for oil products used by trucks and cars. Hence, the effective management and utilization of this energy will provide a strong source of economical savings.

The importance of the subject of air contamination within metropolitan areas is expressed by a significant number of published studies. A substantial portion are based on specific real-life scenarios, such as for example the work on air toxic emissions in Inner Sydney (Marquez and Salim, 2007), Salt Lake City (Pataki et al., 2006) or in the city of Florence (Monaci et al., 2000). Freight transport substantially contributes to global contaminant emissions as well as to local pollution. Figure 1.4 presents the percentage of total emissions of the corresponding harmful gases, which are emitted by goods-transporting vehicles in the depicted cities.

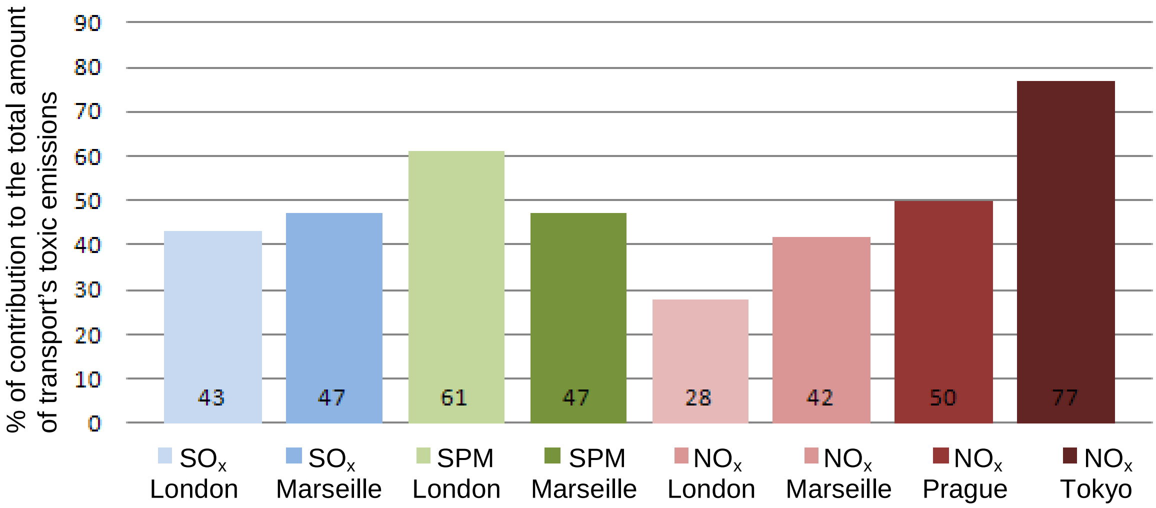


Figure 1.4 Percentage of contribution of freight vehicles to the total amount of transport toxic emissions (prepared on the basis of OECD, 2001) SO_x - sulphur oxides, SPM - Suspended Particulate Matter, NO_x nitrogen oxides

Freight transport also contributes to noise pollution. Prolonged exposure to excess noise strongly affects human health. The level from which a sustained exposure may result in partial or complete loss of hearing is 85 dB. According to the research conducted by ADEME (http_4), a person subjected to a continuous noise of between 85 to 90 dB for eight hours a day for several years might suffer irreparable damage in the inner ear. For comparison, the city traffic heard from inside a car reaches between 70-85 dB, a truck/tractor engine produces noise equal to 90-100 dB, while a running motorcycle reaches 100 dB. The noise that vehicles produce is not only, and exclusively, the result of continuously working engines. The noise is also a result of for example: opening and closing of vehicle doors, using the exhaust tires, vehicle body rattle and using additional freight equipment such as fork-lifts. Moreover, the fact that a fair portion of the delivery operations are conducted at night is burdensome for residents.

Another quantitative way of representing the social impact of the freight system is the accident rate, which corresponds to the number of fatal or injury collisions per one million vehicle-kilometres. This measure is around twice as high within urban areas as it is outside. For example, according to the OECD (2001), in Japan the accident rate for freight vehicles in metropolitan areas is 0.96 and 0.47 in non-urban regions. Nevertheless, it must be remembered that the benefit of eliminating an accident involving a delivery automobile is much higher than in the case when only passenger cars collide. This is because of the fact that an accident involving a delivery vehicle often results in the dispersion of the carried load. In some cases, it is dangerous not only for the traffic but also for the environment in general. The time needed to recollect the load, unblock the road and eliminate the congestion constitutes a serious social loss.

1.2 City Logistics Stakeholders and Decision Levels

The complexity of operations and conflicting objectives of involved parties make urban freight transport a complex area. The essence of CL initiatives is to optimize the functioning of logistics systems as a whole considering the diverse interests and handicaps of all the involved actors and within the urban area environment. However, as presented by Muñuzuri et al. (2005), the considered problem can be addressed in two distinct manners. The main difference between them relates to the scale of the expected results. There are:

- *specific* solutions referring to particular problems or requirements of:
  - one actor e.g.: a retail company,
  - set of actors from the same type group e.g.: the shippers.
- *combined* solutions generated by a combination of several compatible specific solutions, that do not exclude each other, that are not redundant and that comprise a uniform policy strategy for CL.

The influence of a combined solution on a chosen group of actors is different from the sum of the individual outcomes induced by the specific solutions. While a specific solution may generate a profit for only one group or one particular actor the combined solution may distribute the benefit in a sufficiently even manner among all the involved groups avoiding sharp violation of their conflicting interests. Thus, in order to optimize the functioning of the CL system as a whole it is essential to start the process of the analysis of the original problem by defining all the involved actors and studying their objectives, handicaps and criteria.

Thompson and Taniguchi (2001), specify four fundamental stakeholders involved in urban freight transport. This list of the key actors might be extended as follows:

- *Shippers*, e.g.: manufacturers, wholesalers, retailers, etc., actors operating from warehouses and/or CL centres, whose location requires appropriate determination when looking for operations optimization. They tend to maximize their service levels, which include: costs, service times, transport reliability and information management.
- *Freight Carriers*, e.g.: transporters, warehouse companies, etc., actors operating the fleets supplying the customers, whose optimal operation requires proper decisions-making on fleet planning and management such as: fleet size, types of used vehicles, vehicles routing and scheduling, dispatching and monitoring systems. Their main objectives focus on service cost minimization in order to increase profits. However, they are pressured by other actors to increase service quality as well, e.g.: just-in-time requirement (Taylor, 2001), which does not generally facilitate cost reduction.
- *Residents*, e.g.: consumers, customers, retailers etc., actors located inside an urban area in a dispersed manner, who submit defined demands and require the service to be executed in a timely way (e.g.: during a predetermined time interval) and according to a set of formally stated criteria (e.g.: to represent the ordered goods delivery assignment as one

task only). Nevertheless, at the same time, residents tend to search inside the urban area for an environment with limited noise, traffic congestion, pollution and accidentology. The fulfilment of those requirements might impede, suspend or hinder other actors' labour and considerably affect their affairs. This is a direct consequence of the lack of compatibility between the policies.

- *Administrators*, e.g.: local governments, city authorities, administration, etc., actors which define the traffic operation and supply policies on the urban level. Their main goal is to control and encourage the economic development of the city, as well as to provide quality of life to its population. Those conflicting objectives place the Administrators in the position of a coordinator and a mediator among the other actors in the collective CL initiatives, since the common good is their major interest.
- *External visitors*, e.g.: tourists, business guests, visiting residents of suburbia etc., actors whose domiciles remain located outside the considered city range, but which on a daily or occasional basis move into the urban area affecting the traffic flow and forming part of the increment of: service demand, noise, pollution, traffic congestion, accidentology, etc., influencing other actors' interests. The role of External Visitors is the most visible while studying problems in the heart of touristic cities in high season or when big events, such as several days long international conferences, take place (e.g.: United Nations Climate Change Conference in Poznan, Poland, 2008 (http_7)).

In the process of improving the CL system's performance it is necessary to take appropriate decisions aiming at solving specific problem as well as determining more general initiatives. Each of the feasible alternatives concern different spheres of application and affect the system in different ways, at the:

- *strategic level* - regarding long-term, complex operations affecting the generic system's performance,
- *tactical level* - involving short-term policies and management operations within a particular system scenario, to provide a prompt response to the changes in the real system's environment,
- *operational level* - affecting the functional procedures.

1.2.1 Strategic Decisions

Among many, the decisions made on the strategic level regard problems of localization of transportation infrastructure and its structural adjustment. These decisions may result in construction of a new facility (e.g.: a multi-company distribution centre, also known as *public logistics terminal,* Yamada et al., 2000) or in adaptation of existing base. Feasible initiatives concern not only the improvement of complex units like HUBs, gateways and outskirts logistic centres, which combine the transport means and establish a connection point with the interurban transport. Also, the construction and modification of small freight transport centres such as urban terminals and mini-warehouses located inside the metropolitan area enhances the general CL system performance.

Decisions regarding organizational regulations, next to infrastructural alternatives, need to be made on the strategic level. The employed approaches require centrally-imposed organizational regulations and also cooperation between other involved actors. For example, common agreements regarding the rules of sharing access time in loading zones for goods deliveries or receptions (e.g.: shared night deliveries, double-parking, individual time windows, etc.), improves the operational efficiency and proves the profitability of collaboration resulting from a compromise between the actors and governing entities.

1.2.2 Tactical Decisions

In the context of CL, tactical decisions are taken by the management of freight companies. They regard optimization of the service efficiency by making choices concerning the used freight fleet: its size, type of used vehicles, their capacities, incorporated technology and equipment, etc.

The approaches taken up at the strategic level often impose additional requirements on transportation enterprises affecting their tactics when it comes to vehicles. For example, it is common that due to regulations imposed by the municipal authorities, such as restricted access to specific city areas, freight companies need to augment the loading rates of held vehicles in order to comply with the limitations of urban freight transport load factors. Moreover, oftentimes a complementary precondition is demanded, which includes the fulfilment of established environmental standards.

Another example is the closure of special zones to regular traffic. This strategy mobilizes transportation companies to search for substitutes in term of transportation fleet. It is an opportunity for other, more efficient means of small-size package-conveyance such as motorbikes or bicycles. Also, as shown by Nesbitt and Sperling (1998), the contemporary idea of the use of *Alternative Fuel Vehicles* is a promising approach for the privately or publicly administrated, light-duty transport fleets.

1.2.3 Operational Decisions

Apart from the organization of strategic and tactical transport activities, the additional field of possibilities for CL system optimization is operations planning. In this context, one of the basic objectives regards the reduction of the number of used vehicles.

A novel and promising technique for the improvement of vehicle fleet utilization and performance in the metropolitan environment is an approach based on the integration of resources of small and middle-size transportation companies. *Cooperative freight systems* are founded on the idea of extensive collaboration, which brings benefits to all the participants. The unification of forces results in the amplification of service zones and a reduction in the overlap between common areas. The unnecessary, empty or semi-empty vehicle trips are eliminated and the vehicle load rates properly incremented. The number of delivery journeys is optimised, which has economic advantages both collective and individual.

Besides the reduction of the number of used vehicles, the optimization of travelled distances also depends on appropriate operational modifications made by an urban goods-delivering company. Practical experiences show that freight transport is essential for a city's sustainability and that a good choice of the route made by an experienced driver may not only significantly affect the final delivery costs and company's benefits, but also impact the urban network, and by consequence other actors. Thus, intelligent fleet management should take into consideration the advantages offered by vehicle routing and scheduling techniques. They allow the estimation of not only the optimal number of vehicles necessary to meet order demands but also to define the most favourable path to follow.

In the current thesis project all the efforts were concentrated on providing a *specific* solution for optimising CL operations performed by one group of actors: the *freight carriers*. The optimisation regards decisions taken on the *operational level* regarding freight routing and scheduling.

1.3 Technological Support for Real-Time Freight Management

The behaviour of an urban network is not static and the performance of the freight vehicles depends on evolving real-time traffic conditions. As a consequence, proficient fleet management in urban areas has to explicitly account for the dynamics of traffic conditions leading to congestion and the variability in travel times severely affecting the distribution of goods and the provision of services. It requires consistent updating of information and planned activities and leads to *real-time fleet management*, which requires a specific input.

Significant recent developments in the area of the *Information and Communication Technology* (ICT), has resulted in new possibilities to implement real-time fleet management and to explore potential improvements in cost and service efficiency. These solutions introduced in the transportation area are denoted *Intelligent Transport System* (ITS). This term concerns the efforts of incorporating ICT both in transport infrastructures and vehicles. Its objective is the management of factors, which in general are conflicted with each other. For example, in the case of the vehicle, to increase: loads, efficiency, safety and speed; to reduce: vehicle wear, transportation time, pollution, fuel consumption, etc.

Information distribution might be effected by systems which operate using radio frequency. A communications protocol standard based on conventional FM radio broadcasts can be used to distribute small amounts of digital information on: traffic congestion, availability of service and parking areas, road works, road accidents, etc. The requirement of extended-accessibility solutions directed the shippers' interest onto long-range electronic appliances such as pagers or mobile phones equipped with many other features appropriate for data exchange, e.g: SMS, MMS, WAP, Bluetooth, etc.

Those supplements facilitate not only communication objectives, but also participate in automatic data collection providing feedback for fleet management procedures. The information on: changing demands, travel times, service level, unusual or emergency situations, general network performance, etc. might also be provided by vehicle-tracking routines based either on usage of infrastructure-incorporated detection and measuring devices like: electro-magnetic loop sensors, video cameras, velocity radars, etc., or the vehicle incorporated mechanisms as *Automatic Vehicle Location* (AVL) appliances, which constitute a valuable source of information on the general traffic - *floating car data.*

The dominant approach is based on a combination of *Global Positioning System* (GPS) - a worldwide available, global navigation satellite system, which provides the users with detailed dynamic data on their current location, time and velocity - with a device such as the *General Packet Radio Service* (GPRS) which provides an extensive data collection required for real-time freight management. GPRS allows transmission and reception of information in a quick and efficient way across the mobile network. It can provide instant connections subject to radio coverage and thus ensure consistent communication between the driver and the dispatcher. On the other hand, GPS is able to track individual vehicles and thus support fleet monitoring functions. The simultaneous usage of the two devices enables the dispatcher to optimize the currently-performed operations on the basis of the recently provided data and to directly issue decisions, which will be executed immediately.

Technological advances have strongly affected the operations of data acquisition concerning not only the fleet and the traffic conditions, but also the customers. Novel concepts of service appeared recently which, using the classification provided by Nemoto et al. (2001), might be categorised as follows:

- electronic commerce (*e-commerce*),
- electronic logistics (*e-logistics*),
- electronic fleet management (*e-fleet management*).

In the CL field, e-commerce notably facilitated contact between the actors and increased their interaction volume, which translates to a higher number and quality of performed operations. The Internet has improved communication allowing distributors to react in real-time for new requests and consequently to improve the quality of service and reduce the warehouse storage. The collected real-time information provides the input for dynamic optimization.

E-logistics involves controlling operations processes and monitoring goods and information flow through a supply chain in order to enhance: quality, speed and efficiency of logistics manoeuvres. Improved real-time data visibility enhances the decision-making process and in the long-run provides better customer-service while reducing manipulation expenses.

The evolution of e-fleet management was also strongly reinforced by the development of ITS. In order to meet the elevated shipper's requirements, it was necessary for logistics service providers, such as for example the freight dispatchers, to adapt various solutions from a wide range of advanced information technology. This supported the automation of data collection and the communication processes.

The potential provided by advanced technologies to trace vehicles, monitor the urban network's performance and incoming customer requests makes it possible to dynamically search for solutions. The gained interactivity and flexibility open the door to new possibilities in fleet management and system optimization, creating new opportunities to use traffic flow patterns and vehicle routing and scheduling models. The current thesis aims at researching these opportunities.

1.4 Thesis Scope and Purpose

The efficiency of dynamic fleet management is due to the possibility of taking the advantage of advanced technological solutions, which provide the dispatchers with real-time information permitting an immediate reaction. The collected data regards changes of:

- traffic conditions (travel times, waiting times, congestions, accidents, etc.),
- customers (location, time window, service time, amount of goods, priority, etc.),
- freight vehicles (location, load, status, etc.).

In order to take a full advantage of the great amount of continuously-incoming information, it is necessary to utilize tools facilitating the real-time decision-making processes. These tools need to be based on specialized methodologies considering both fixed and sequentially-updated values and incorporating fast-response mechanisms. Hence, instead of relying exclusively on the experience of a dispatcher, an efficient freight management system should rely on a professional *Decision Support System* (DSS) which facilitates the consideration of all relevant factors.

Foresight of the probable consequences of contemplated manoeuvres requires a proper quantification that would be practical and beneficial for the decision-making processes as well as for the planning and final results estimation. From this standpoint, basing the conceptual approach of the DSS for the CL operations on models is justified, since they are adept at creating a competent and efficient, synthesized replica of a real urban freight system which allows for incorporation of: freight carrier's activities, stakeholder's characteristics, traffic flow description and the general system's transformation quantification.

A proposal for such a DSS was provided by Regan et al. (1996, 1998). The approach includes the generation of a set of initial vehicle assignments that takes known and predicted future demands into account and incorporates strategies for reacting to changes as they occur. Hence, the process starts with the preparation of an initial routing plan that considers the already known information regarding customer demands and freight vehicle availability. This plan is executed and, as new real-time data become available, the dynamic assignment generator unit uses it to modify the current course of operations. In this case, the novel alternatives also obey the pre-established load acceptance and pooling policies.

The current thesis was inspired by the work of Regan et al. (1996, 1998). Its main purpose is to propose, implement and computationally test, on the basis of a simulation, the architecture of a Decision Support System which enhances the efficiency of dynamic fleet management by using advanced technological solutions and the real-time information they provide (Barceló et al. 2005, 2006 and 2008, Barceló and Orozco 2010b).

The proposed DSS is based on the assumption that real-time information on city traffic, fleet performance and customer requests is available due to network monitoring, vehicle-tracking and direct communication with customers facilitated by modern ICT tools. As a consequence, the modifications of the vehicle routes and schedules may be conducted online. The scheme of the DSS is presented in Figure 1.5. The green rectangle on the scheme embraces all the elements required in order to provide an efficient support to the dispatcher's decision-making process employing real-time information.

Preparation of an initial routing plan is preceded by the processes of gathering, selection and analysis of information. In this context, the data taken into account can be determined as: *known* and *forecasted*. The known information concerns: customer requests that could not be served the previous day and are to be performed now, past and current traffic conditions, vehicle positions and states. It is assumed that, in order to make a forecast, the decision-maker has access to a database containing historical data.

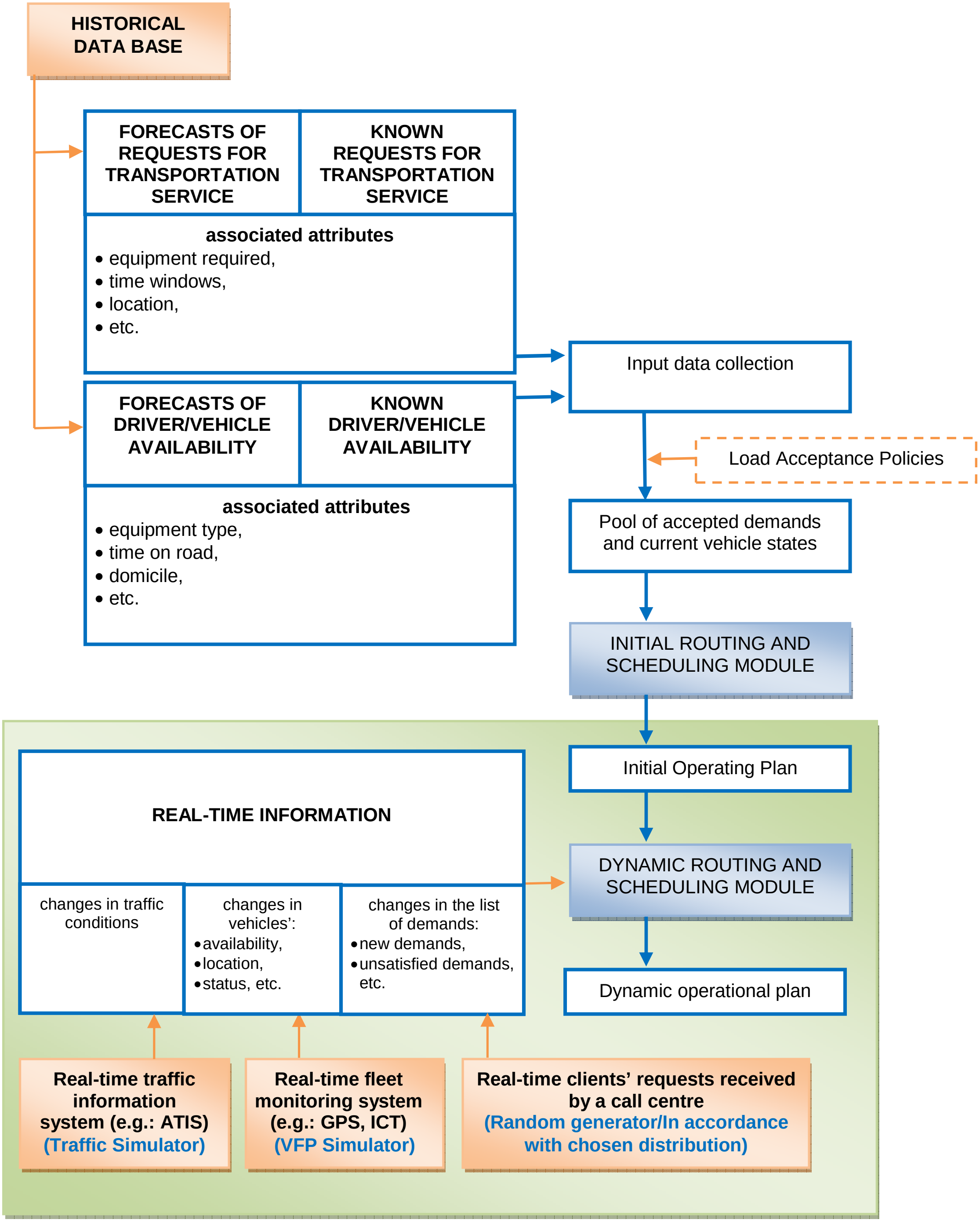


Figure 1.5 DSS for real-time freight management using information provided by modern ITS tools

The considered travel times are *time-dependent*. In real life this information could be provided by a professional *Advanced Traffic Information System* (ATIS). In the current thesis, the functioning of an ATIS was emulated and the information it provides was substituted by a time-dependent travel times matrix obtained from a simulation. The time-dependent travel times were recorded for each link of the underlying urban network and stored in two data bases: one representing the past and the other representing the current network conditions.

In order to include the forecast of the future network's performance in the real-time decision-making process, there was developed a *Time-Dependent Travel Times Data Forecasting Module*. It merges both current and past information and provides travel times until the end of the studied scheduling horizon, which corresponds to one day for work of an urban freight company.

For the initial routes planning there was used the data base representing the past network conditions. It was assumed that all the vehicles of the fleet were housed at the depot and were not assigned to any customer. Also, there was defined a number of known customer requests. The data regarding both known and new customer calls were generated artificially in accordance with the contemplated testing scenarios.

The map of the underlying urban network can be translated into a directed graph where the nodes correspond to a set of considered customers and depots, while the arcs represent all the feasible paths between them. In order to define the shortest paths between the customers there was introduced into the DSS structure a *Time-Dependent Shortest Path Calculator* (TDSP Calculator).

Once the input data collection and the shortest paths calculations are complete, they are used by the *Initial Routing and Scheduling Module* (IRSM). Its core constitutes a heuristic whose objective is to solve a corresponding routing problem and rapidly provide a near-optimal solution. There have been tested different approaches. All of them consist of three steps: initial solution creation, optimization and post-optimization. In the first stage, three distinct candidate methods were implemented. In the post-optimisation step, two methods were implemented. The optimization part constitutes a common element for all of the tested composite scenarios and includes a Parallel Tabu Search Heuristic using two different operators for the neighbourhood's definitions. In sum, each tried approach is a combination of different single methods. The objective of this study was to define an appropriate strategy to rapidly and efficiently solve the addressed routing problem and to employ this strategy in the DSS structure. The choice was made on the basis of the collected results comparison.

The initial routing plan created by the IRSM constitutes the basic input to the *Dynamic Routing and Scheduling Module* (DRSM). The DRSM is a key element of the proposed DSS. Its design and development constitutes a major challenge and one of the main objectives of the present thesis.

The design of the DRSM includes a bank of algorithmic tools whose principal task is to optimally modify the current routing plan taking into consideration the most recent real-time information. Each method from the bank may solve a different routing problem. The collection was started by adding a heuristic, which is a modified version of the same approach which was used in the IRSM. This heuristic was chosen because throughout the whole project there was considered only one specific routing problem: the *Pickup and Delivery Vehicle Routing Problem with Time Windows* (PDVRPTW).

The DRSM is triggered by an *event*. It corresponds to a particular incident or circumstances specified by the data provided by: the real-time traffic information system, real-time fleet monitoring system or a call centre receiving the customers' requests in real-time. The events are classified as follows (Barceló et al. 2008):

- *internal* – depending on the traffic flow dynamics (e.g.: changes in travel times and their results: moment of vehicle arrival to or departure from a customer, delays affecting the start service times, etc.),

- *external* – not depending on traffic conditions (e.g.: new request arrival, cancelation of service, changes in the order characteristics, vehicle breakdown etc.).

To simulate the behaviour of a real-time fleet monitoring system there was designed a *Vehicle Fleet Performance Simulator* (VFP Simulator). It uses the current data provided by ATIS and updates the present values of attributes specifying each vehicle, such as: location, status, amount of carried cargo, visited customers, next customer to visit, etc. This process is run each time the DRSM needs to be provided with fresh data and can be triggered by either an external or internal event.

1.5 Thesis Objectives and Contributions

Since an urban network is subject to numerous random events it can be defined as a highly dynamic system. The traffic conditions change rapidly and oftentimes in a manner difficult to predict, e.g.: as a consequence of an accident. The changes take place unevenly in the network and may relate to both different sections (e.g.: main arteries) and time intervals (e.g.: peak hours).

However, the literature review of projects whose objective was to optimize freight operations within city areas reveals that the most common approach is to employ average travel time estimates as input data. Consequently, the created models may significantly deviate from reality and the proposed approaches may be inappropriate when implemented in the real-life situations. It is clear that broad approximations of rapidly-changing network conditions may result in a loss of optimization opportunities.

These conclusions were also drawn by Barceló and Orozco (2010a). The study was based on utilization of a calibrated dynamic traffic simulation model of the downtown area of Barcelona. The same model was used in the present thesis. The authors calculated the variances and the average values of the travel time on all the links of the considered urban network. The collection of obtained results is shown in Figure 1.6.

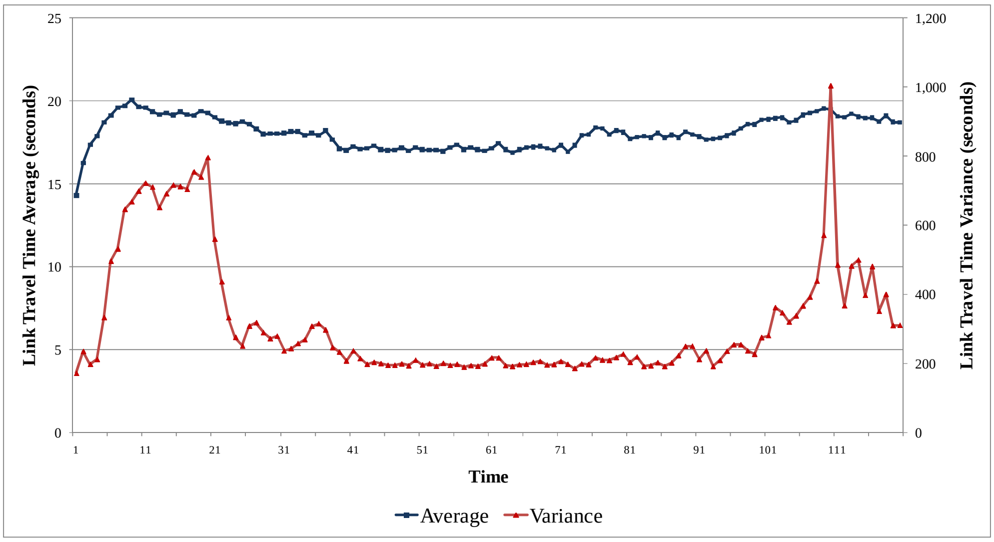


Figure 1.6 Average travel times and travel time variances calculated for the downtown area of Barcelona (Barceló and Orozco, 2010a)

The graph displays two clearly-distinguishable time intervals during which the variability of the vehicles' travel times reaches high values with respect to the rest. It is a direct result of growing traffic congestion corresponding to the two, morning and afternoon, peak-hour periods during the day. The time interval between the peaks characterizes with lower values of the travel time variance and corresponds to the "normal" traffic conditions.

As CL activities are impacted by traffic congestion, the development of traffic is affected by urban freight logistics operations. This mutual dependence must be taken into account when proposing solutions to CL problems. The simulation models of urban traffic need to include the effect of CL deliveries and commercial activities, while routing and logistics optimization models must consider time-varying traffic congestion and operational constraints.

Consequently, the argument defended in the current thesis is:

> *Since the urban network is a highly dynamic system, modern and efficient freight fleet management in urban areas should be based on decisions accounting for all factors conditioning the problem. These factors include: customers' demands and service conditions (e.g.: time windows, service times, etc.), operational conditions of employed fleet (e.g.: vehicles' availability, status, positions, current occupancy of the load carriage space, etc.) and dynamics of traffic conditions and variability in travel times.*

The technological developments that enable fast acquisition of information to support freight management also result in the creation of alternative operational patterns which improve the strategies concerning the optimization of delivery service's efficiency. The goal of the present thesis is to seize the opportunity of employing the recent technological developments achieved in the field of ICT and use the data which might be provided in a real-time fashion.

For the proficient dynamic fleet management decisions it is proper instead of relying exclusively on the experience of a dispatcher, to base the freight management decisions on information provided by a professional DSS, which facilitates the consideration of all the factors conditioning the addressed problem.

Thus, the list of the objectives set in the present thesis includes:

- design of a DSS able to use the data provided in a real-time fashion by advanced ICT devices,
- design and implementation of a composed heuristic which is able to solve the addressed routing and scheduling problem and rapidly find a near optimal solution; this method forms the core of both IRSM and DRSM,
- design and development of the IRSM based on a selected composite heuristic approach,
- design and development of the DRSM as a key segment of the designed DSS,
- implementation of the TDSP Calculator,
- design and development of the Time-Dependent Travel Times Data Forecasting Module,
- design and development of the VFP Simulator,
- design of the testing scenarios and generation/compilation of necessary data.

The research work described in this thesis extends the current state of the art through taking advantage of more detailed and dynamic information than was previously available. The DSS described provides improved travel time which is known to correlate with economic, social and environmental impact. The DSS provides a freight operations optimization strategy for the specific network and circumstances in which it is deployed.

1.6 Thesis Outline

Considering the above-mentioned objectives, the work performed in the current thesis project was organised in accordance with the scheme shown in Figure 1.7.

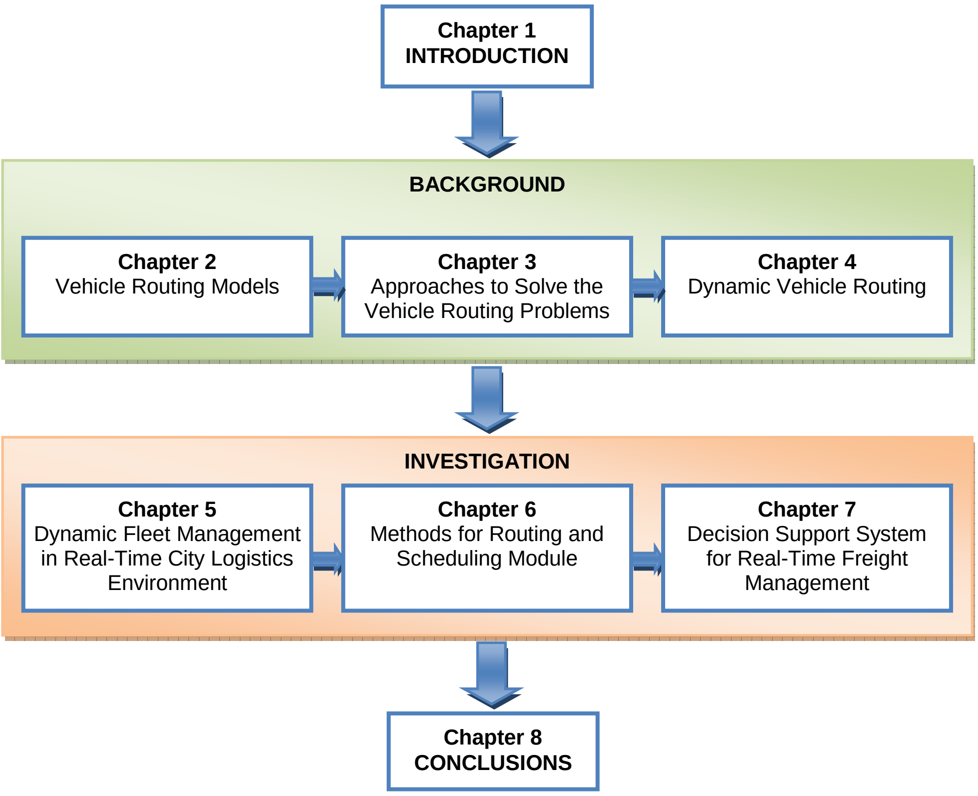


Figure 1.7 Scheme of documented work

First, there was carried out a study of the literature regarding the issues of modelling and solving both static and dynamic routing problems. The findings were organised and placed in three chapters of the current document. They are identified as: *Background*.

The second main part of the current thesis project is called *Investigation*. It provides a description of the undertaken research strategy. The explanation of the performed work was also segregated in three chapters. Each one of them corresponds to a separate stage of the project.

The last segment constitutes a summary of the complete undertaking. It contains the final conclusions and identification of possible directions in the future research.

The main objective of Chapter 2 is to introduce key definitions and concepts used throughout the thesis. It aims to present the most important aspects related to the modelling of static routing problems. Moreover, it indicates that in the context of CL it is necessary to take into consideration the special characteristics of the underlying street network regarding both its geography and circulation rules.

The objective of Chapter 3 is to present both the panorama of approaches and the progress in development of strategies to solve PDVRPTW. The discussion of the publications concentrates on the articles issued after the year 2000, since the main goal was to present the latest advances in the field. Due to the fact that the current thesis is based on the usage of heuristics this chapter provides additional information on the procedures that were taken into account before choosing one to implement.

Chapter 4 aims at defining the dynamic character of the vehicle routing problem. For this purpose, it shows how other authors define dynamic problems, models and applications. It presents the dynamic routing problem in contrast to its static version, thereby making the essential differences more visible. A review of articles defining and solving the dynamic PDVRPTW is also provided.

The objective of Chapter 5 is to outline: challenges, contributions and differences between the proposed approach and other published studies. It defines the motivation of the project and highlights both the necessity of considering the dynamic features affecting the addressed problem and the utilisation of real-time information for optimal freight management. The fundamental assumptions, necessary inputs and basic requirements are also provided.

Chapter 6 presents the design, construction and evaluation of the candidate approaches apt to solve the addressed PDVRPTW. Each approach includes three stages: initial solution construction, optimization and post-optimization, which are presented sequentially. The different compositions of all the mentioned methods results in the creation of 16 distinct approaches. On the basis of the analysis of the outcomes provided by computational tests, one of them was chosen and implemented as a key element of the IRSM. After performing the necessary modifications, the same procedure was also used as a part of the DRSM.

Chapter 7 provides details on both the design and functioning of all the modules composing the proposed DSS. The architecture of the TDSP Calculator, IRSM, DRSM, Time-Dependent Travel Times Data Forecasting Module and VFP Simulator is explained. Moreover, the selected case study is presented, the testing scenarios are defined and the obtained results are outlined.

Finally, Chapter 8 recapitulates all the work performed in the current thesis. The main goals are summarised and there are reviewed all the major steps undertaken in order to achieve these goals. A short resume of main findings and contributions is provided. The obtained results are briefly described as are the conclusions which were drawn on their basis. The possibilities of deploying the proposed strategies in real-world environments are highlighted. Finally, there are presented suggestions of paths to follow in future research undertakings.

The final sections of the current document are the annexes.

The objective of Appendix A is to provide complementary information on the composition and generation of the numerical data sets used to test and evaluate the performance of both the employed algorithms and the proposed strategies. The benchmarks used to examine the reviewed methods solving the PDVRPTW are presented in attachment A1. Annex A2 contains information on the instances used in the experiments evaluating the performance of the proposed DSS.

Appendix B contains numerical results of the conducted experiments, which were gathered in order to clarify the current document. Similarly as in the previous case, it consists of two sections: B1 and B2. The first one shows the collection of results obtained due to examination of the composite methods proposed for solving the PDVRPTW. The second one includes the ordered outcomes demonstrating the performance of the proposed DSS.

Background

"The secret of success is to start from scratch and keep on scratching"

-Anonymous

Chapter 2

The present chapter addresses the issue of modelling routing problems. Since it is intended to serve as reference it introduces key determinations used throughout the thesis.

Following the introduction, the first section 2.1 provides description of the Travelling Salesman Problem. Next, the details and the nature of its generalization - the Capacitated Vehicle Routing Problem, are provided in section 2.2. In order to meet the real-life requirements various side constraints have been added to the problem's general formulation, which gave rise to creation of an extended family. Two of its members: the Vehicle Routing Problem with Time Windows and the Pickup and Delivery Problem with Time Windows are presented in the consecutive sections: 2.3 and 2.4 respectively. They have been chosen due to the fact, that they are commonly addressed in the context of City Logistics.

Vehicle Routing Models

Vehicle Routing Problem (VRP) techniques constitute a core fundament for the transportation, distribution and CL systems modelling.

VRP appears for the first time in a paper by Dantzig and Ramser (1959) as *The Truck Dispatching Problem*, where the new algorithm is presented on a real-life example. The article describes a practical problem regarding delivering gasoline to gas stations by the Atlantic Refining Company such that their demands are satisfied while the total route distance travelled by the vehicle fleet is minimal. Since that time, the intense investigation of the subject resulted with many scientific papers, commercial publications and technical reports providing each time model formulations suitable to capture specific conditions of each variant of the problem.

VRP is a common application of mathematical programming and a challenging combinatorial optimization exercise. In the broadest sense, it can be described as the problem of designing optimal delivery routes from one or more depots to a set of geographically scattered points (cities, customers) respecting constraints, which depend on the type of the problem, such as:

- each route starts and ends at the depot,
- each customer is visited exactly once by exactly one vehicle,
- total demand of each route does not exceed the vehicle's capacity,

- total routing cost is minimized.

Depending on the characteristics of the problem there can be specified different variants in terms of the pursued objective. The collection of restrictions common with the objective function defines the problem and displays it as a particular member of the VRP family. Among many, a wide survey on the VRP variants was provided by Fisher (1995) and by Toth and Vigo (2002). Some of the main classes are: *Capacitated Vehicle Routing Problem* (CVRP) and its extensions: *Distance Constrained Capacitated Vehicle Routing Problem* (DCVRP), *Vehicle Routing Problem with Time Windows* (VRPTW), *Vehicle Routing Problem with Pickup and Delivery* (PDVRP) and *Vehicle Routing Problem with Backhauls* (VRPB).

2.1 Modelling Vehicle Routing Problems in the Context of City Logistics

Depending on the objective of the study the cost of a trip between customers corresponds to the: physical distance between their locations, time necessary to travel, economical cost of the journey e.g.: costs of gasoline, vehicle exploitation, toll fees, etc. In the ideal case, the graph defining the VRP is undirected, complete and its arcs' costs are Euclidean distances satisfying the triangle inequality:

$$c_{ij} + c_{jk} \geq c_{ik} \qquad \forall i, j, k \in N, \; i \neq j \neq k \qquad (2.1)$$

where:

N : set of nodes $N = \{0, 1, \ldots, n\}$, where 0 denotes depot and (1,…, n) denote customers,
c_{ij} : nonnegative cost of a direct travel between nodes i and j.

However, when modelling the VRP in the context of CL it is necessary to take into consideration the special characteristics of the underlying street network regarding both its geography and circulation rules. The constructed graph should contain nodes representing the locations of depots and customers, as well as the street junctions, which constitute connection points between the arcs. The arcs correspond to the road sections. The lanes of the same direction are represented as one directed arc. The arcs are associated with a nonnegative cost. In the case of the undirected graphs this cost is symmetric. It means that the cost of a journey between two points is exactly the same independently on its direction:

$$c_{ij} = c_{ji} \qquad \forall i, j \in N, \; i \neq j \qquad (2.2)$$

This equation does not hold while modelling an urban network both at the level of a single street and on the level of the path between two customers and/or depots. The link between two customers/depots is represented by the shortest path between them. Respecting the geometry and the circulation rules of the urban road network, the shortest path between customers i and j rarely corresponds to the shortest path between customers j and i (Figure 2.1 provides an example of such situation). As a consequence, the arcs of the graph interpreting the VRP for the CL modelling purposes need to be not only directed but also asymmetric.

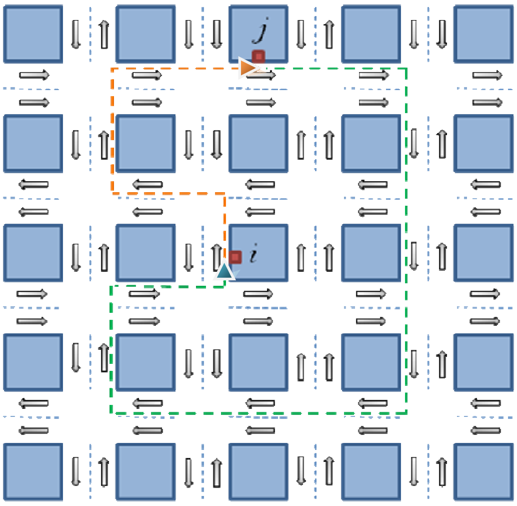


Figure 2.1 Example of shortest paths between customers *i* and *j* and *j* and *i* - the results of street routing problem:
■ - customer
⇢ - shortest path between customers *i* and *j*
⇢ - shortest path between customers *j* and *i*

The task of translating the actual streets and junctions into a graph is not a simple process based on substitution. In most of the cases, a junction cannot be represented as a single node just as a street cannot be interpreted as one arc. It is demonstrated using examples shown in Figures 2.2 and 2.3.

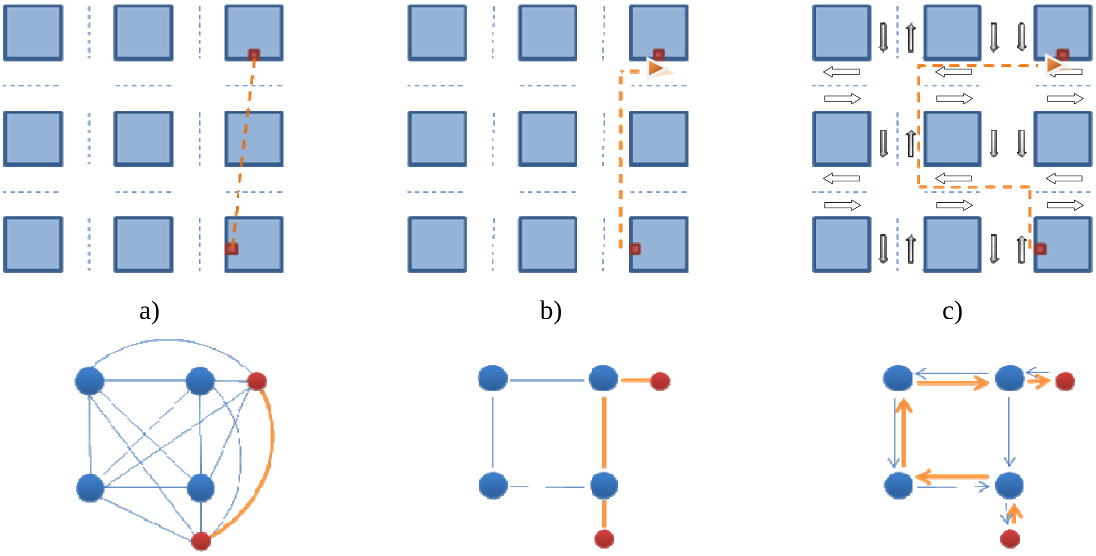


Figure 2.2 Representation of different approaches while searching for the shortest path (marked as orange line) between two customers (marked in red). The underlying street network can be represented in terms of a graph:
a – undirected, complete graph; the shortest path is a physical, Euclidean distance between the customers
b – undirected, incomplete graph with symmetric costs; the shortest path between the customers is a solution of a routing problem
c – directed, incomplete graph with asymmetric costs; the shortest path between the customers as a solution of a street routing problem

Figure 2.2 presents three feasible approaches of graphical illustration of the city structure and the shortest path search result. All depicted cases consider the same network fragment. In the situation (a) the underlying street grid is interpreted in terms of an undirected, complete graph, where the arcs' costs are Euclidean distances. This method provides a large generalization and does not represent the city network's performance and architecture with sufficient accuracy. The second example (b) takes into consideration the geometry of the underlying street grid but not the traffic organization and circulation rules. So, the corresponding graph is uncompleted and undirected. The last case (c) presents the street network as a directed graph, regarding both the geometry and the traffic management. The VRP solution is optimal in urban conditions although it does not correspond to the minimal physical distance between the considered nodes. In certain sense, starting from the most generic method, Figure 2.2 illustrates the direction of the evolution of the approach implemented in the current thesis.

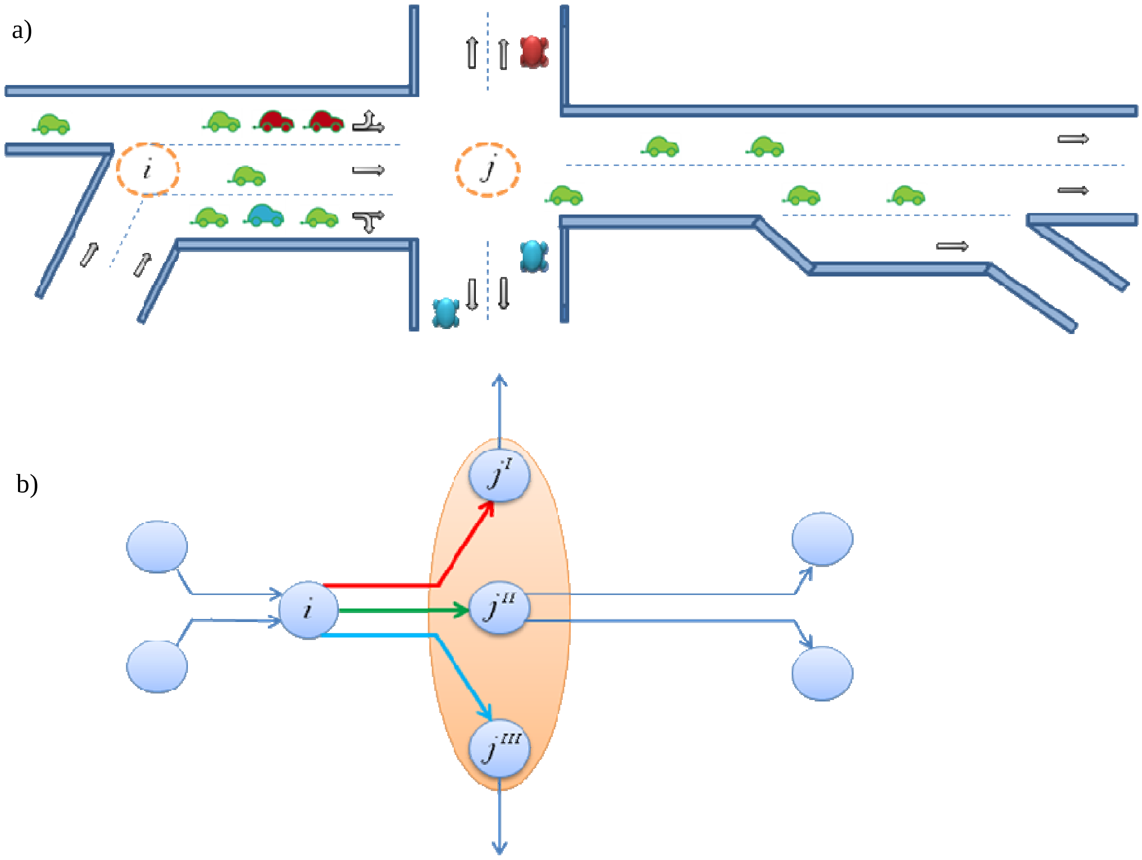


Figure 2.3 Example of situation when an urban street cannot be represented in a graph by a single undirected edge:
a – fragment of an urban network with not signalized junction,
b – graph representing the selected network fragment; the average travel time on the *i-j* street is different on each lane and needs to be represented by three arcs with distinct costs; accordingly, the junction is outlined with three, duplicate nodes

Figure 2.3 presents the method of translation of the street network into a graph used in the present thesis. In the shown example, the organization of junction *j* allows the vehicles coming from the direction of junction *i* to turn right, left and to go forward. Hence, the vehicles on the *i-j* network section might be classified by the turning movement they plan to perform (they are marked in different colours). The turnings require the reduction of velocity causing the increment of the travel time. Also, the changing course vehicles delay the others, which need to go straight on. Consequently, the average travel time for each group of vehicles is different. It consists of the sum of the time needed to traverse the street section and to perform the corresponding turning manoeuvre at the junction. Considering, that the arc cost is the average travel time between nodes, in order to accurately represent the *i-j* urban network section it is necessary to use three arcs: $i\text{-}j^{I}$, $i\text{-}j^{II}$ and $i\text{-}j^{III}$ associated with different values. The nodes j^{I}, j^{II} and j^{III} define the entrance to each subsequent section.

Summarizing, in the context of the CL the VRP refers to the task of providing by a fleet of vehicles, a service (delivering/picking up goods) requested by customers located inside the city area, originating and/or terminating at a depot and with the intention of minimizing the total cost of performed routes in order to comply with customers' requirements. So as to fulfill the stated objectives, it is desired that the route performed by a vehicle is a shortest path between the customers, which does not correspond to the Euclidean distance between them. The solution is obtained by applying a street VRP solving algorithm, which needs to consider the geometry and the traffic organization rules of the studied city area, since their character strongly affects the final result. The urban network might be presented in a form of a graph, where the junctions, as well as the customers/depots locations are represented by the nodes, and the arcs correspond to the roadways joining them.

2.2 Travelling Salesman Problem

Travelling Salesman Problem (TSP) is a specialization of VRP. It is oftentimes explained on an example of a salesperson, who wants to visit each of a set of towns starting from and returning to his hometown, following the cheapest, feasible round trip and avoiding visiting the same city twice. The sequence of ordered locations is nominated as a *tour*. The problem might also be illustrated using as a demonstration the shoe-lacing activity, where an optimal solution is obtained when a lace passes through each of the shoe eyelets once and only once, using a minimum length of cord, before being tied up in a knot (Gutin and Punnen, 2002). Anyhow, its objective consists in finding a *Hamiltonian cycle* (Jünge et al., 1995).

The problem has been studied ahead of its title was created. The origin of TSP term as well as its author and the clear moment of its coming into use are not clear. Nonetheless, it can be noted that the name came into light in the thirties last century, supposedly at Princeton University, by initiative of mathematician Haasley Whitney (Applegate et al., 2006).

TSP arises in many different contexts and has numerous applications, which explains why it is considered to be fundamental and has been very intensively studied. However, the most common TSP applications include people and goods displacement. They are of use for planning the routes for e.g.: postal services, school buses, salesmen or inspectors' journeys, tourists' trips, commercial deliveries, etc.

Mathematically the problem can be formulated as follows:

$$\min \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} x_{ij} \tag{2.3}$$

Subject to:

$$\sum_{i=1}^{n} x_{ij} = 1 \qquad \forall j \in N \tag{2.4}$$

$$\sum_{j=1}^{n} x_{ij} = 1 \qquad \forall i \in N \tag{2.5}$$

$$\sum_{i \in S} \sum_{j \in N \setminus S} x_{ij} \geq 1 \qquad \forall S \subset N(S \neq \emptyset, S \neq N) \tag{2.6}$$

$$x_{ij} \in \{0, 1\} \qquad \forall i, j \in N \tag{2.7}$$

where:

x_{ij} : is equal to 1 if the travel was made between nodes *i* and *j*, otherwise it is equal to 0,
S : nonempty proper subset of *N*; $S \neq N$.

This model is very basic and can be extended due to addition of complementary constraints. The objective function (2.3) aims for minimization of the total circuit's cost. Equations 2.4 and 2.5 are respectively in and out-degree constraints. They indicate that every customer must be visited only once on the salesman route. These restrictions are necessary but not sufficient, since the created solution might consist of separated sub-tours. That is why, on the path to sufficiency, it is requisite to add the constraint (2.6), which states that the circuit is Hamiltonian. In other words, it implies the sub-tours elimination. The presented variant is one of the possible alternatives of defining this constraint.

Solving TSP is a complex task. A problem with a property of the non-polynomial time of algorithm execution is called *NP-hard* or *NP-complete* and TSP was one of the first one to be proven to have this attribute. Since VRP constitutes a generalization of TSP al its variants are also NP-hard. Due to this fact, there arose a need for computationally efficient methods able to provide a solution comparable in quality with the one offered by the exact methods but in much shorter time.

2.3 Capacitated Vehicle Routing Problem

Capacitated Vehicle Routing Problem (CVRP) is a basic version of VRP and a widely studied member of the family. Its definition provides foundation for the formulations of the problem's derivative specifications. It aims at designing a collection of optimal routes for a fleet of vehicles in order to provide a group of customers with a transportation service, knowing the values of their demands' requests and subject to vehicle capacity constraints. Its objective is to supply all customers minimizing the total cost of all the routes, which start and finish at the depot.

The problem can be defined on a graph *G*=(*N*, *A*), where *N*={0, 1,…, *n*} is a set of nodes and *A*={(*i*, *j*): *i*, *j*∈*N*} is a set of arcs with an associated nonnegative cost c_{ij}, assuming that: $c_{ij} = c_{ji} \forall i, j \in N$.

Mathematically CVRP can be formulated as follows:

$$\min \sum_{i \in N} \sum_{j \in N} c_{ij} x_{ij} \tag{2.8}$$

Subject to:

$$\sum_{i \in N} x_{ij} = 1 \qquad \forall j \in N \setminus \{0\} \tag{2.9}$$

$$\sum_{j \in N} x_{ij} = 1 \qquad \forall i \in N \setminus \{0\} \tag{2.10}$$

$$\sum_{i \in N} x_{i0} = K \tag{2.11}$$

$$\sum_{j \in N} x_{0j} = K \tag{2.12}$$

$$\sum_{i \notin S} \sum_{j \in S} x_{ij} \geq r(S) \qquad \forall S \subseteq N \setminus \{0\}, S \neq \emptyset \tag{2.13}$$

$$x_{ij} \in \{0, 1\} \qquad \forall i, j \in N \tag{2.14}$$

where:

$r(S)$: minimum number of vehicles needed to serve subset S,
K : number of vehicles in a fleet.

In this state, CVRP shares the definition of the objective function with TSP formulation. The cost of a route is calculated as the sum of the costs of the arcs forming it, under the assumption that the matrix of the least-cost paths between each pair of customers is symmetric and known. The sum of all the routes' costs is minimized. Similarly, as in the case of TSP the first two equations: 2.9 and 2.10 state the customers' in and out-degree constraints, respectively. The objective is to design vehicle routes, where all customers would be visited once and only once. Another two equations: 2.11 and 2.12 impose the depot degree requirements. In other words, K is the number of vehicles and at the same time it is the number of the circuits which source and sink is located in the depot. Consequently, there is only one route for each vehicle. The following expression 2.13 is known as *the capacity cut constrain*, which assures the sub-tour elimination and fulfilment of the vehicle capacity restriction.

Real fleet transportation operations are carried out with respect to certain rules. When considering the real-world circumstances, the cost of a journey between two locations should also include the service time, which a vehicle spends at the customer's. The delivery loading and unloading processes affect the total travel time of the tour. In order to obtain a definition of VRP, which reflects the character of the real-world transportation services, in addition to the constraints reflecting the relationship between the vehicles' capacity and customers' demands, it is necessary to concern additional aspects describing the customers' requirements, such as for example their time windows. Thus, the formulation of the basic model needs to be extended in order to fit the addressed real-life problem.

2.4 Vehicle Routing Problem with Time Windows

Vehicle Routing Problem with Time Windows (VRPTW) is an extension of the basic VRP, supplemented with a *time window* (TW) constraint providing a convenient approach for emulating various, real-life supply chain procedures e.g.: goods distribution in the urban area such as deliveries to supermarkets, newspapers distribution, individual customers' deliveries, postal services, school buses, special residue collection routing, etc. It offers a more detailed problem description and is associated with a number of developed procedures for its optimal solving.

The *time window* term refers to a time interval when a vehicle can give a service to a customer. It may be defined as *hard*, which cannot be violated in any case. In consequence, any solution, which does not respect the restriction, is rejected. It might also be determined as *soft*, which implies that a service may be provided after exceeding the permitted period but at the same time a quantitative "penalty" will be appended to the final solution's cost. Additionally, in the cases when a vehicle arrives at the customer's before its TW is opened, certain VRPTW formulations permit them to wait there without penalizing the pause, but adding the waiting time to the total solution result. By analogy, it is possible to permit vehicles to wait at the depot. It is of special importance when implementing certain *waiting strategies*.

Mitrovic-Minic and Laporte (2004) and Mitrovic-Minic et al. (2004), define four waiting strategies. *Drive-First* (DF) and *Wait-First* (WF) are the basic ones which combination gives more complex approaches known as: *Dynamic Waiting* (DW) and *Advanced Dynamic Waiting* (ADW).

The TW [e_i, l_i] is an attribute associated with each customer *i*. Its limit e_i defines the earliest and l_i the latest time instant when the customer's servicing process may start. Thus, the earliest and the latest moment, when a vehicle may leave a customer is equal to a sum of a corresponding window limit and the service time duration:

$$a_i^e = e_i \tag{2.15}$$

$$a_i^l = l_i \tag{2.16}$$

$$b_i^e = e_i + s_i \tag{2.17}$$

$$b_i^l = l_i + s_i \tag{2.18}$$

where:

a_i^e : the earliest allowed arrival time at customer *i*,

a_i^l : the latest allowed arrival time at customer *i*,

b_i^e : the earliest allowed departure time from customer *i*,

b_i^l : the latest allowed departure time from customer *i*,

e_i : instant of TW opening (lower-bound) at customer *i*; it is the earliest moment when vehicle may start giving service to customer *i*,

l_i : instant of TW closing (upper-bound) at customer *i*; it is the latest moment when vehicle may start giving service to customer *i*,

s_i : service time at customer *i*.

The above definition is employed in the present thesis. However, there is another way of interpreting the TW's limits, where the upper bound is regarded as a moment when all the activities at the customer's are abandoned (e.g.: the end of the working day, the customer leaves his residence and is not available for the courier, etc.). In this case the service time has to be included in the TW duration.

The depot may also be assigned with a TW, which simultaneously defines the problem's *scheduling horizon*. In order to make the formulation clearer, it is common to create a copy of the depot and add it to the set of nodes $|N|=n$, where n is the number of all customers. Therefore, the depot's node is defined as 0, while it's duplicate is marked as $n+1$. When considering problems, assuming that the vehicles are permitted to stay at the depository or to be assigned to more than one routing tasks, to execute in a consecutive manner, it is recommended to construct an arc joining the two warehouse-defining nodes and add it to the set of arcs A complying the equality:

$$c_{0,n+1} = c_{n+1,0} = 0 \tag{2.19}$$

Both depository nodes are associated with TW: $[e_0, l_0]$ and $[e_{n+1}, l_{n+1}]$ respectively and since they denote the same point the following relation is valid:

$$[e_0, l_0] = [e_{n+1}, l_{n+1}] = [E, L] \tag{2.20}$$

where:

E : start of the problem's scheduling horizon; it is an instant of the earliest allowed vehicle departure from depot,

L : end of the problem's scheduling horizon; it is an instant of the latest allowed vehicle arrival to depot.

In other words, the vehicles shall not leave the depot before e_0 and return later than at time l_{n+1}. Consequently, a feasible solution exists only if:

$$e_0 = E \leq \min_{i\in N\setminus\{0\}} l_i - c_{0i} \tag{2.21}$$

and

$$l_{n+1} = L \geq \min_{i\in N\setminus\{0\}} e_i + s_i + c_{i,n+1} \tag{2.22}$$

With respect to the depot's duplicity it is also necessary to define its demands d and service times s, which values are defined as follows:

$$d_0 = d_{n+1} = 0 \tag{2.23}$$

and

$$s_0 = s_{n+1} = 0 \tag{2.24}$$

Depending on their span, the TW might be defined as *wide, medium* or *narrow*. The boundaries of this classification depend on the studied problem, but the difference between the types is the most visible in a comparison of the final solutions and required computation time. It is more difficult and time consuming to find a good solution for a problem, which TW' span, is narrow.

Considering VRP's underpinning mathematical formulations, VRPTW with added capacity constraint can be written as follows:

$$\min \sum_{k \in K} \sum_{(i,j) \in A} c_{ij} x_{ijk} \tag{2.25}$$

Subject to:

$$\sum_{k \in K} \sum_{j \in \Delta^+(i)} x_{ijk} = 1 \qquad \forall i \in N \setminus \{0, \mathrm{n}+1\} \tag{2.26}$$

$$\sum_{j \in \Delta^+(0)} x_{0jk} = 1 \qquad \forall k \in K \tag{2.27}$$

$$\sum_{i \in \Delta^-(j)} x_{ijk} - \sum_{i \in \Delta^+(j)} x_{jik} = 0 \qquad \forall k \in K, j \in N \setminus \{0, \mathrm{n}+1\} \tag{2.28}$$

$$\sum_{i \in \Delta^-(n+1)} x_{i,n+1,k} = 1 \qquad \forall k \in K \tag{2.29}$$

$$x_{ijk}(z_{ik} + s_i + c_{ij} - z_{jk}) \le 0 \qquad \forall k \in K, (i,j) \in A \tag{2.30}$$

$$e_i \sum_{j \in \Delta^+(i)} x_{ijk} \le z_{ik} \le l_i \sum_{j \in \Delta^+(i)} x_{ijk} \qquad \forall k \in K, i \in N \setminus \{0, \mathrm{n}+1\} \tag{2.31}$$

$$E \le z_{ik} \le L \qquad \forall k \in K, i \in \{0, \mathrm{n}+1\} \tag{2.32}$$

$$\sum_{i \in N \setminus \{0, \mathrm{n}+1\}} d_i \sum_{j \in \Delta^+(i)} x_{ijk} \le Q \qquad \forall k \in K \tag{2.33}$$

$$x_{ijk} \in \{0, 1\} \qquad \forall k \in K, (i,j) \in A \tag{2.34}$$

where:

N : set of nodes such that $N=\{0, 1, \ldots, n, n+1\}$,
x_{ijk} : equal to 1 if the travel was made between node i and j by vehicle k, otherwise it is equal to 0,
Q : vehicle capacity,
$\Delta^+(i)$: set of all the arcs leaving from node i,
$\Delta^-(i)$: set of all the arcs entering node i,
z_{ik} : start of service at customer i by vehicle k,
d_i : demand of customer i.

Similarly, as in the case of CVRP, the objective function 2.25 aims for minimisation of the total routing cost. The equation 2.26 assures the assignment of every customer to one and only one route, while the next three formulations specify the manner in which they are served by designated vehicles. Notations 2.27 and 2.29 specify that there is permitted only one entrance and one exit to a depot, respectively. Analogically, the line 2.28 states that every customer shall be visited only once. The schedule feasibility is regulated by equation 2.30, along with 2.31 and 2.32, which impose the time intervals compliance with respect to TW. Every vehicle may start the service only during customer's TW interval. The same rule is applied in case of the depot. The last constrain defined by 2.33 ensures, that the capacity of each vehicle shall never be exceeded.

VRPTW admits many alternative formulations (Toth and Vigo, 2002). The one presented above is basic and commonly used.

2.5 Pickup and Delivery Problem with Time Windows

Pickup and Delivery Vehicle Routing Problem with Time Windows (PDVRPTW) is a specification of the previously mentioned VRPTW. In this problem, each individual request includes a pickup and a corresponding delivery, between which a specific demand is to be transported. The relationships between customers are expressed by both *pairing* (also known as *coupling*) and *precedence constraints.* The first one defines customers' membership in a couple while the second specifies that each pickup customer must be visited before its corresponding delivery.

Therefore, the main objective of the PDVRPTW is to determine, for the smallest, possible number of vehicles from a fleet, a route with a corresponding schedule, in order to service a collection of customers with determined transportation pickup and delivery requests, satisfying their TW and the vehicles' capacity constraint in such a away, that the total cost of all the trips is minimal. In other words, it consists of determining a set of vehicle routes with assigned schedules so that:

- each route starts and ends at depot (a vehicle leaves and returns empty to the depot),
- each customer is visited exactly once by exactly one vehicle,
- cargo accumulated in the vehicle, never exceed its capacity,
- a pair of associated customers is serviced by the same vehicle (pairing constraint),
- cargo's sender is always visited before its recipient (precedence constraint),
- service takes place within customers' TW intervals (TWs constraint),
- entire routing cost is minimized.

PDVRPTW is a suitable approach for modelling routes and service schedules for optimizing the performance of freight companies such as for example the couriers'.

In order to describe mathematically the demonstrated PDVRPTW let us define for each vehicle *k* a complete graph $G_k \subseteq G$, where $G_k = (N_k, A_k)$. The set N_k contains the nodes representing the depot and the customers, which will be visited by the vehicle *k.* The set $A_k = \{(i, j) : i, j \in N_k, i \neq j\}$ comprises all the feasible arcs between them. Thus, the problem formulation takes the form:

$$\min \sum_{k \in K} \sum_{(i,j) \in A_k} c_{ijk} x_{ijk} \tag{2.35}$$

Subject to:

$$\sum_{k \in K} \sum_{j \in N_k \cup \{n+1\}} x_{ijk} = 1 \qquad \forall i \in N^+, \tag{2.36}$$

$$\sum_{i\in N_k^+}\sum_{j\in N_k} x_{ijk} - \sum_{j\in N_k}\sum_{i\in N_k^-} x_{jik} = 0 \qquad \forall k\in K, \tag{2.37}$$

$$\sum_{j\in N_k^+\cup\{n+1\}} x_{0jk} = 1 \qquad \forall k\in K, \tag{2.38}$$

$$\sum_{i\in N_k\cup\{0\}} x_{ijk} - \sum_{i\in N_k\cup\{n+1\}} x_{jik} = 0 \qquad \forall k\in K,\ j\in N_k, \tag{2.39}$$

$$\sum_{i\in N_k^-\cup\{0\}} x_{i,n+1,k} = 1 \qquad \forall k\in K, \tag{2.40}$$

$$x_{ijk}(z_{ik} + s_i + c_{ijk} - z_{jk}) \le 0 \qquad \forall k\in K,\ (i,j)\in A_k, \tag{2.41}$$

$$e_i \le z_{ik} \le l_i \qquad \forall k\in K,\ i\in N_k\cup\{0\}, \tag{2.42}$$

$$z_{i,k} + c_{i,p(i),k} - z_{p(i),k} \le 0 \qquad \forall k\in K, i\in N_k^+ \tag{2.43}$$

$$x_{ijk}(q_{ik} + d_j - q_{jk}) = 0 \qquad \forall k\in K,\ (i,j)\in A_k, \tag{2.44}$$

$$d_i \le q_{i,k} \le Q \qquad \forall k\in K, i\in N_k^+ \tag{2.45}$$

$$0 \le q_{p(i),k} \le Q - d_i \qquad \forall k\in K, i\in N_k^+ \tag{2.56}$$

$$q_{0k} = 0 \qquad \forall k\in K, \tag{2.47}$$

$$x_{ijk}\in\{0, 1\} \qquad \forall k\in K,\ (i,j)\in A_k, \tag{2.48}$$

where:

N : set of customers, where $N = N^+ \cup N^-, \left|N^+\right| = \left|N^-\right|$,

N^+ : set of all customers that notify pickup request,

N^- : set of all customers that notify delivery request,

c_{ijk} : nonnegative cost of a direct travel between nodes *i* and *j* performed by vehicle *k*, assuming that: $c_{ijk} = c_{jik} \forall i, j \in V$,

i : customer, where $i\in N_k^+$,

$p(i)$: pair partner of customer *i*, where $p(i)\in N_k^-$,

d_i : customer's demand that will be picked up/delivered at *i*/*p*(*i*) respectively, and where $d_i = d_{p(i)}$,

q_{ik} : vehicle's *k* capacity occupancy after visiting customer *i*,

a_i : arrival time at customer *i*,

w_i : waiting time at the customer *i*, where $w_i = max\{0, e_i - a_i\}$,

z_{ik} : start of service at customer *i* by vehicle *k*, where $z_i = a_i + w_i$.

The nonlinear formulation of the objective function 2.35 minimizes the total travel cost of the solution that assures its feasibility with respect to the specified constraints. Equation 2.36 assigns each customer to exactly one route, while formulation 2.37 is a pairing constraint, which ensures that the visit of each pickup-delivery pair of customers (i^+, $p(i^+)$) is performed by the same vehicle k. The three following constraints secure the commodity flow. Equality 2.38 defines the depot as every route's source and states that the first visited customer is the one with a pickup request. Likewise, formulation 2.40 determines the depot as every route's sink and the last visited customer is the one that demands a delivery service. The degree constraint 2.39 specifies that the vehicle may visit each customer only once and as a consequence eliminates the possibility of sub-tours' construction. The schedule concordance is maintained by equations 2.41 and 2.42 according to which, in case that a vehicle arrives to a customer early it is permitted to wait and start the service within the TW interval only. The precedence constraint 2.43 assures that for each pair of customers the pickup i is always visited before its delivery partner $p(i)$. The next three restrictions express the dependencies between the customers' demands and the vehicles' restrained current and total capacities. Equation 2.44 indicates that after visiting the customer j the current occupancy of the carriage loading space of the vehicle k is equal to the sum of the load carried after visiting the preceding customer i and the demand collected at customer j. According to inequality 2.45 the dimension of current occupancy of the total capacity of the vehicle k after visiting a pickup customer i shall be neither smaller than its demand d_i nor bigger than the entire vehicle's capacity. Similarly, following formulation 2.46, the current capacity of the vehicle k after visiting a delivery customer $p(i)$ shall never be smaller than zero and bigger than the difference between the total vehicle capacity and the size of its delivery request $d_{p(i)}$. The capacity constraint that considers the depot 2.47 states that the vehicle does not provide it with any service. The last formulation expresses the binary and nonnegative nature of the problem involved variable.

In the present thesis, the PDVRPTW is understood as in the above demonstrated formulation. The selected model constitutes one of many possible alternatives to describe PDVRPTW (Toth and Vigo, 2002). This one was chosen due to its clarity.

Chapter 3

The twofold objective of the current chapter is to present an overview of the methods used for solving the routing problem addressed in the present thesis project as well as to highlight and explain the functioning of these ones, which have been ultimately selected to complete the undertaken tasks.

After introduction, in section 3.1, there is presented a survey on the latest achievements regarding PDVRPTW. In order to provide the most actual state of the art, the reviews are based on the publications issued in the last decade. The papers were arranged chronologically, by the date of their edition. Since the current thesis project is based on the usage of heuristics, there is also provided additional information on the procedures, which were taken into account if it comes to their possible employment. Thus, section 3.2 presents number of construction algorithms providing initial solutions, which later might be subjected to optimization operations, such as these conducted by the local search heuristics presented in section 3.3. The selected operators constitute an important segment of the Tabu Search (TS) strategy, which has been chosen to solve the analysed PDP. Its functioning is explained in detail in section 3.4. The same section contains also explanation of how the parallel computing process operates. It has been used to improve and accelerate the functioning of the complete method.

Approaches to Solve Vehicle Routing Problems

Since the first formulation of the VRP an intense search of efficient solving methods takes place. Many efforts have been directed to research concerning exact methods. An extensive review on the subject was provided by Laporte and Nobert (1987). However, among others, Cordeau et al. (2002) state that, the exact algorithms are in general inadequate for working out VRP since they are able to solve to optimality only the problems with small number of customers. That is why, although the heuristics do not guarantee optimality but since they are capable of providing a feasible solution in a relatively short amount of time, they strongly dominate in the quest for good methods. What is more, they are proven to be quite flexible in adaptation to different problem variations, which is of special importance when considering the real-world applications.

One of the most known heuristics, which is oftentimes described as classical, is the two-phase, mathematical programming based, Fisher and Jaikumar's (1984) method. In the first step the customers are grouped in clusters. Every cluster is assigned to one and only one vehicle. The clustering process is performed on the basis of the *General Assignment Problem* and can be solved by Lagrangean Relaxation. When the feasible clusters of the customers are defined, the second phase of the heuristic starts. By solving a TSP there are specified the sequences of the customers in the routes. This method is an example demonstrating that it is possible to clearly distinguish separated parts in the complete approach. It appears that the whole is made up of individual algorithms. In fact, when solving large problems most frequently used practice is to use complex methods – *Meta-Heuristics* (Glover, 1986).

In a meta-heuristic, it is possible to distinguish an initiation part, which provides first solution. It does not necessarily have to be feasible. The decision depends on the adopted main strategy. The algorithms employed in this segment are called the *Construction Heuristics*. The objective of the next segment is to improve the solution constructed earlier. The duration of this process is limited and may be specified either by the quantity of permitted computation time or by the number of allowed repetitions. The *Local Search* heuristics are the iterative improvement methods, which stand up to the challenge and compose a promising group of efficient methods apt to fulfil the defined objectives. Finally, there can be included at the end a part, which consists of a heuristic responsible for the post-optimization of the improved solution. In sum, the appropriate combination of these three segments permits to obtain a complete and efficient approach. It is why such three-step approach was implemented in the present thesis.

Every meta-heuristic is characterized by a different strategy concept. The most known ones, following the order of their appearance are: Genetic Algorithms (Holland, 1975), Simulated Annealing (Kirpatrick et al., 1983), Neural Networks (Hopfield and Tank, 1985), Tabu Search and Ant Colony Optimization (Colorni et al., 1991, Dorigo, 1992, Dorigo et al., 1991).

Tabu Search has been applied by very many researchers to solve VRPs. It is known to be a very effective method providing good, near-optimal solutions to the difficult combinatorial problems. This is why it was chosen in the current thesis to be implemented as main optimization method.

3.1 Algorithms for Pickup and Delivery Vehicle Routing Problem with Time Windows – State of the Art

An efficient method for solving PDVRPTW determines the cornerstone of the present thesis project. There are many examples demonstrating that this is a problem often found in the CL environment. Among many: the specialized transportation of people, bus routing, taxi services and courier services, which are often invoked in the implementation of this work, define a significant collection of tasks, the fulfilment of which can be optimized by means of application of an appropriate algorithm. Finding the optimal solution is not an easy task and many different strategies were tested in order to provide the best feasible outcome in a matter of a moment.

Nanry and Barnes (2000) address the formulation of PDVRPTW as it is presented in Chapter 2. The final routes must comply with pairing, precedence and vehicles' capacity constraints, which are strictly enforced at all times during the computation process. The customers' TW are considered to be *semi-hard*, which means that the vehicles are permitted to wait if they reach the customer's location before its TW is opened. However, in the case, when the instant of the vehicle's arrival is bigger than the TW's upper-bound a penalty is added to the total route cost. Moreover, unlike in the present thesis project, the authors consider unlimited number of available vehicles to perform the transportation tasks. The initial solution is constructed on the basis of a *Simple Insertion Heuristic* (Solomon, 1987a). The solution obtained in this way is subjected to the improvement process by applying the *Reactive TS* method. The approach was tested on original instances initiated for the purposes of the current project. The authors developed their own test instances for PDVRPTW on the basis of the set of benchmark problems proposed for VRPTW by Solomon (1987b).

Similarly as in the previous case, the approach proposed by Li and Lim (2001) is TS-embedded and the initial solution is obtained by applying the specially modified Simple Insertion Heuristic (Solomon, 1987a). Instead of individuals, the customers are introduced into the routes as pickup-delivery pairs with respect to three measures: the largest aggregated distance from the depot, the smallest aggregated TWs' upper-bound and the smallest aggregated TWs' interval. The ultimately obtained initial feasible solution is optimized by TS method, which allows keeping the track of the recently visited solutions and protects the process from cycles. It applies two different operators in order to define the local search neighbourhoods: *Shift* and *Exchange*. The *Rearrange* moves are employed in the post-optimization phase. The novel aspect of the method concerns the incorporation of the SA algorithm in TS performance. It is employed each time, when after a certain number of iterations TS is not able to find an improved solution.

Similarly to Nanry and Barnes's (2000) approach, Li and Lim analyse the problem concerning the search of an optimal schedule duration respecting semi-hard TWs, capacity, precedence and pairing constraints. However, in contrast to the previous example the number of available vehicles is not unlimited and is of special importance. These two publications are also linked with the practice of the evaluation of the algorithms, since Li and Lim first check the operation of their algorithm on the set of test cases introduced by Nanry and Barnes (2000). They also develop their own benchmark cases by modifying Solomon's (1987b) VRPTW instances.

Another TS based approach was proposed by Lau and Liang (2001). In order to construct the initial solution the authors examined two methods: Simple Insertion Heuristic and *Sweep Algorithm*. They have also designed a novel procedure adapted to the original nature of PDP - *The Partitioned Insertion Heuristic.* It is a combination of the two previously mentioned methods. It provides the best result of all three procedures in most of the studied cases. The second phase of the proposed approach includes TS, where the neighbourhood definitions are adapted from Nanry and Barnes's (2000) proposal. The variation refers to the fact that it is not single customers but clusters of customers, which are moved in the operators. Similarly as Li and Lim (2001), Lau and Liang test their approach on the benchmark instances proposed by Nanry and Barnes (2000). The final obtained solution must comply with: precedence, pairing, homogeneous vehicles' capacity and TWs constraints, minimizing the number of used vehicles and the total travel cost represented by distance.

The proposal of Pankratz (2005) is founded on the *Grouping Genetic Algorithm*. In brief, the whole strategy reduces to solving two problems. The first regards the appropriate division of customers into clusters. The second one concerns their arrangement in a route. The grouping modifications performed sequentially by the genetic operators preserve the best solutions during the search. They also eliminate the possibility of keeping duplicates of one individual in the solution. The approach was tested on the sets of instances proposed by Nanry and Barnes (2000), Li and Lim (2001) and Lau and Lang (2001), respectively.

A new insight into the insertion-based construction heuristic to solve the multi-vehicle PDP with TW was proposed by Lu and Dessouky (2006). The originality of the approach lies in the fact that the insertion evaluation function takes into account not only the increment of the travel cost, but also the decrement of TWs' *slack*. This novel, customer-determining variable is calculated as the difference between the customer's TW and the time required to perform the service. Furthermore, the authors introduce a non-standard measure: the *Crossing Length Percentage*, which permits to create solutions characterized by higher visual attractiveness. The idea follows the practice, since the real-life operators tend to pick solutions, when a route does not have cycles or when two routes do not cut across. One of the main objectives of the presented approach is to minimize the total cost of the solution, which takes into consideration both the fixed vehicle cost and the travel cost proportional to the travelled distance. It was tested on the benchmark instances originally provided by Li and Lim (2001).

A PDVRPTW was also addressed by Bent and Van Hentenryck (2006). The innovation is found in the way in which the authors approach the problem. Namely, they first specify two main objectives to fulfil: to lower the total cost of the routes and the number of used vehicles. Then, each of these objectives is analysed separately as a sub-problem and is applied with a distinct method. The SA algorithm is used to reduce the number of routes. The second part of the proposed heuristic applies the *Large Neighbourhood Search* (LNS) algorithm based on the branch and bound method. Its objective is to minimize the total travel cost. These two algorithms executed consecutively form the whole heuristic for the multi-vehicles PDVRPTW. Its performance was examined using the Li and Lim's (2001) benchmark instances. However, the final result was also compared with the collection of the best known outcomes obtained by other approaches. It is available at VRP and TSP dedicated website (http_12).

Similarly as in the previous case, Ropke and Pisinger (2006) base their approach on the LNS algorithm. Nevertheless, the original addressed problem shows some differences in the underlying formulation. Firstly, it is a multi-depot problem since the sources and sinks of the routes might be placed at different locations defined for the purposes of the studied case as *terminals*. Secondly, similarly as in the case of a singular depot problem, where the general depot was assigned with a TW defining the permitted schedule duration time, all the vehicles terminals are assigned with a time interval, which serves the same purpose. In addition, during the process of construction of the routes a supplementary condition must be taken into consideration. It states that all the vehicles must start their performance exactly at the same time and when there is reached the lower-bound of the TW of the route's source terminal. Lastly, the authors assume the opening number of available vehicles to be unlimited. The collection of undertaken objectives contains three targets: minimization of the travelled distance, decrement of the summarized vehicles' performance time and downsizing the engaged size of the bank of the requests. In order to calculate the performance time of each vehicle the authors deduct from the moment of its arrival at the final terminal the moment in which it left the source location of the route. The whole heuristic was tested on the instances proposed by Li and Lim (2001). However, the authors also came up with randomly generated testing cases inspired by Solomon's (1987b) benchmark problems (http_11).

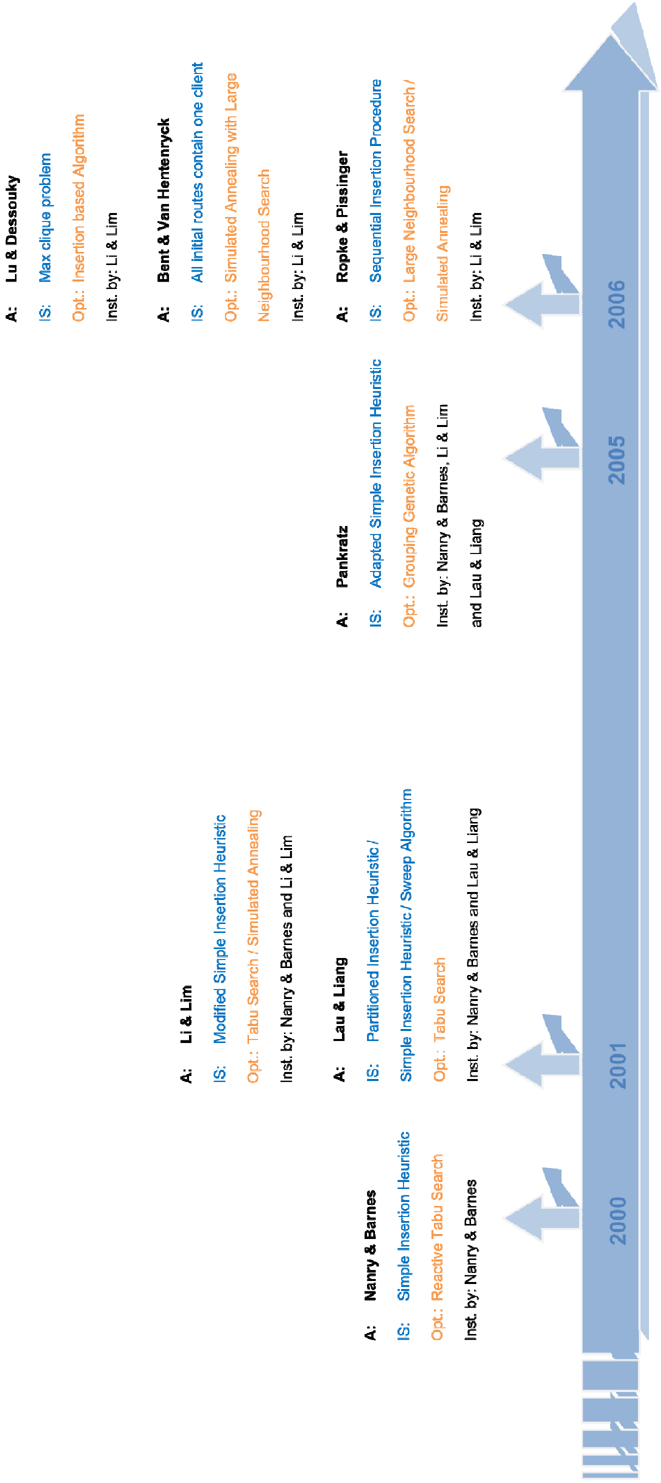


Figure 3.1 Chronologically ordered publications regarding solving PDVRPTW; A: - authors, IS: - method used to construct the initial solution, Opt: - method used to improve the initial solution, Inst. by: - authors of used benchmark instances

In order to summarize the contents there was prepared a diagram shown in Figure 3.1 presenting chronologically all the discussed publications. This scheme helps to draw the three basic conclusions. Firstly, the initial solution is mainly obtained by applying an adapted version of the Simple Insertion Heuristic. Secondly, the most frequently used meta-heuristics are both TS and SA. In one case, these two methods got even merged providing one approach. The last conclusion concerns the testing instances. The most often used benchmarks were these proposed by Nanry and Barnes (2000) and by Li and Lim (2001).

Consequently, taking into consideration the earlier experiences of other authors it was decided that TS heuristic shall be applied to solve the addressed PDVRPTW in the present thesis project. Moreover, an adapted version of the insertion-based construction heuristic was chosen to create the initial solution. The performance of the complete approach was tested using the benchmarks introduced by Li and Lim (2001).

Although, the insertion based construction heuristics are the most commonly used, it is not the only efficient method which can be used. The situation is similar for the procedures used to improve the initial result. The next sections provide an overview of the methods, which have been analysed in terms of suitability for the present thesis project.

3.2 Construction heuristics

The quality of the initial solution is essential for the whole search process. It provides a base for further operations of relocating or incorporating customers. That is why, instead of applying the easy methods offering little-promising results, the specialised algorithms are used. A construction heuristic determines tours according to certain, previously established rules, but does not try to improve them. Its characteristic feature is that a route is built successively and the parts already constructed remain unchanged throughout the algorithm. In the current thesis project, initially there were taken into consideration several construction heuristics.

3.2.1 Construction Heuristic based on Simple Pairing Approach

The easiest approach which might be applied in order to construct an initial feasible solution is to join all the considered customers with the depot with two arcs. As a result, there are created as many routes as customers. In the case of PDP, since there are considered pairs of customers, it is necessary to incorporate both of them in a single route, respecting the permitted order of visits. Thus, the result consists of as many routes as pairs of customers. This approach does not consider any restriction regarding the number of the initially available vehicles. However, it provides the first feasibility check of the considered data. The solution obtained by this method always has to be feasible.

3.2.2 Sweep Algorithm

The name of this method was introduced by Gillett and Miller (1974), however its beginnings might be noticed in earlier published work of other authors, e.g.: Wren (1971) and Wren and Holliday (1972). Sweep heuristic is generally used to prepare an initial solution of the VRP in the more complex approaches. The name of the algorithm fits the idea of constructing the feasible routes very well, since the process of gradually including the customers in a vehicle route resembles the process of sweeping by a virtual ray that takes its beginning in the depot. When the route length, capacity or the other previously set constrain is met the route is closed and the construction of the new one is started. The whole procedure repeats until all the customers are swept in the routes. Its functioning is graphically presented in Figure 3.2.

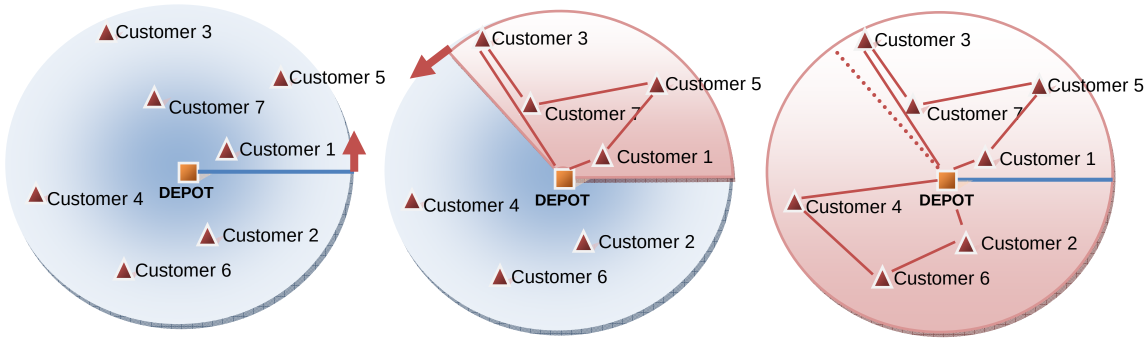


Figure 3.2 Sweep Algorithm

3.2.3 The Nearest Neighbour Heuristic

The concept on which this method is based on is very intuitive and probably the most often applied in the real life. The route starts at the depot and first customer to visit is the one which is located the closest. From this point, the next destination point is defined by another, the closest located, not visited customer. The route construction process lasts until all the customers are visited or until the vehicle's capacity constraint is met. In this case, another route starting at the depot is created according to the same construction rules. All the tours are closed and end up at the depot. Although this heuristic is probably the closest to accurately represent the real salesman's behaviour it provides poor quality results. However, at the same time, since the routes consist of sequences of customers connected by very short arcs, they constitute a good base to start with for the improvement algorithms. The functioning of the Nearest Neighbour Heuristic is presented on an example in Figure 3.3. This method inspired the design of the algorithm creating the initial solution on the basis of the definitions of Customer Aggregation Areas. Its complete description is provided in Chapter 6.

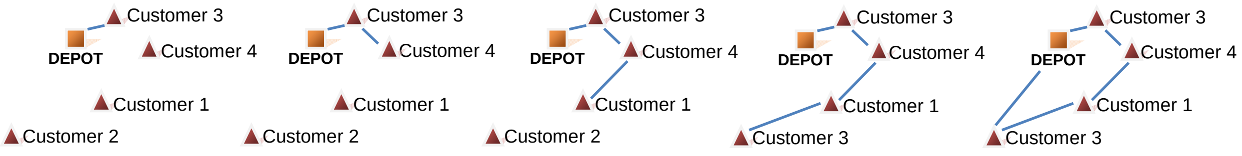


Figure 3.3 The Nearest Neighbour Algorithm

3.2.4 Insertion-Based Heuristics

Another possible way to construct the tours of the initial solution is to start with a sub-tour and consecutively incorporate all the remaining customers into it searching for an optimal position. In this process, the first decision to make concerns the choice of the customers to start with. Secondly, one must decide on the method to apply to create the initial sub-route. There are multiple possibilities. Usually, when dealing with problems based on Euclidean distances, a good initial route consist of a convex hull of the considered customers. In other cases, one might link with arcs three different customers in such a way that the obtained route forms a triangle covering the largest possible surface. Also, a feasible strategy consists of choosing few customers, which are located the furthest from the depot and construct single sub-touts, each containing only one customer. This approach seems reasonable, since the customers, which are the farthest from the depot are usually the most difficult to incorporate in the existing routes.

The following step regards the incorporation of the remaining customers. Usually, a customer is inserted in a route in such position that the length of the newly obtained, enlarged route is increased by the smallest possible value. Therefore, the order in which the customers are introduced is not without significance. In fact it is the main feature, which distinguishes the different insertion schemes.

One of them is known as the *Cheapest Insertion* or *Greedy*. It consists of choosing from all the candidate customers the one which, once inserted in the route, causes the lowest increment of the length of the tour. Consequently, the customers whose insertion is the most "expensive" are inserted into the routes as last. It constitutes a serious problem, since at this stage most of the routes are already full and the number of the feasible insertion possibilities is reduced. On the other hand, the whole computation time is short, because of the fact that in each iteration only one route is modified and it is not necessary to recalculate the insertion costs for all the rest of the tours. The functioning of the insertion-based heuristic, where the initial sub-tour is a convex hull of the considered customers, is presented on an example in Figure 3.4.

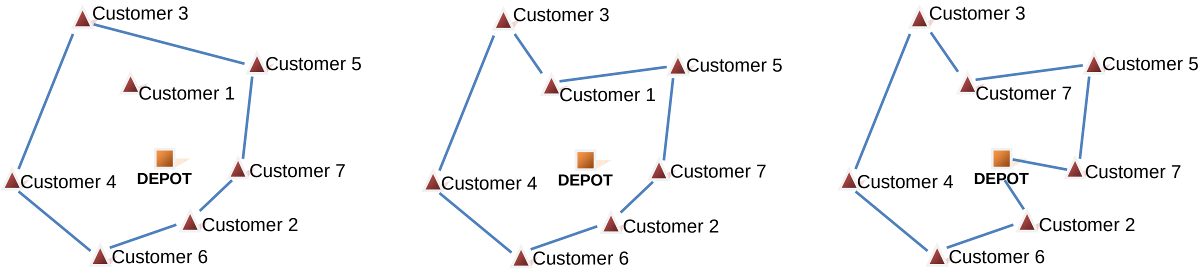


Figure 3.4 Insertion-based heuristic using a convex hull of the considered customers as initial sub-tour

Another popular strategy is the *Farthest Insertion* procedure. It first chooses the non-visited customer, which is located in such position that the minimal distance from the customers already belonging to the route is maximal. The main objective is to arrange the order of visits at the early stages of the heuristic.

The insertion-based construction algorithms create fast and good quality initial solutions to start the improvement procedures from. Moreover, they are pretty adaptable to the addressed problems. Thus, it was decided to employ a modified version of the insertion-based construction heuristic, as the first stage of the approach solving the PDP addressed in the present thesis project. The main concepts agree with the Greedy insertion scheme. However, in order to exploit the advantages, which provide both the Sweep Algorithm and the Farthest Insertion process the final composite heuristic consists a combination of selected elements belonging to these methods as well. The description of the complete algorithm is presented in Chapter 6.

The insertion-based heuristics are not only efficient when used for creation of the initial solution. They are also able to effectively improve the existing routes executing modifications consisting of removal of a selected individual customer (or a set of customers) and its reinsertion in a different position according to pre-established strategy. The whole process is iterative and at each step a locally optimal choices are made, which might not lead to a global optimum. In this context, the greedy, insertion-based algorithms correspond to the *Local Search* procedures. Basically, these heuristics search the space of candidate solutions evolving from one to another until either no better result can be found or the permitted time limit is reached. These improvement methods are often used because of their advantages of being very fast and at the same time producing reasonably efficient solutions. For these reasons they were also employed in the present thesis project for the optimization purposes.

3.3 Local Search Heuristics

Local Search Heuristics provide a tool for solving NP-hard optimization problems, which can be formulated in terms of searching of the best outcome among a number of candidate solutions maximizing or minimizing a chosen criterion.

As a rule, the procedure starts with establishment of the initial solution as best. In each iteration a neighbourhood $N(s^*)$ of the current best solution s^* is defined by performing a collection of a priori designed movements modifying the primal structure. Next, a new solution s is searched. It characterises with the best result of the objective function and consists an upgrading of the original solution. When found, s it is set as the best. This repetitive routine lasts until no further improvement can be found, which is interpreted as reaching the optimum. The consequent choice of the next best solution is determined by the current neighbourhood and defines the general direction of the search. The lack of broader perspective in most of the cases leads to finding a final solution, which represents a local optimum instead of a global. It is also due to the decision on when to finish the whole procedure. It might be determined either by a designated time limit for the complete performance or by a previously established number of repetitions, which do not bring any further improvement. Hence, in the case, when the upgrading solution is located far from the currently defined neighbourhood it may never be found due to the limited duration of the search process. Consequently, the Local Search methods can be seen as incomplete. In order to overcome this handicap a possible approach to apply is the one, which modifies the general scheme of the method and engages various exploration procedures instead of just one. Simultaneous performance of varied moves results in determination of multiple, different search areas. Hence, on the basis of a single original solution it is possible to define several, dissimilar neighbourhoods. As a consequence, the exploration territory gets expanded allowing to diverse the search towards spaces, which would not be accessible otherwise. This strategy has also been implemented in the present thesis project within TS procedure.

Local Search algorithms are commonly used in the composition of larger and more complex heuristics. They might be employed for the post-optimization steps as well as intermediate routines performed during the main search process. Notwithstanding, they constitute individual algorithms. Some of them appear under the name of an *operator* with specified features and others possess their own denomination. For instance, the local optimization methods involving neighbourhoods, which apply to the original solution a number of modifications equal to *k*, are known as the *k-opt* heuristics.

3.3.1 k-opt Heuristics

k-opt heuristics is a family of simple Local Search algorithms apt to solve network optimization problems. Its most common representative is the 2-opt procedure, which has been introduced by Croes (1958) for solving a TSP. The main idea of the 2-opt method is valid for the other k-opt heuristics.

In the main, it consists of removing two non-consecutive arcs connecting the route in a whole and substituting them by another two arcs re-connecting the circuit in such a way that there is obtained a new solution which fulfils the pre-established objectives. This move is commonly called a *swap* since it consists of swapping two customers in the original sequence. The swap can be performed in accordance with one of the following strategies:

- search until the first possible improvement is found, and perform the swap,
- search through the entire tour, find all possible improvements and perform only the swap resulting in the best improvement.

The second strategy is employed in the present thesis. By consequence, it is referred to when explaining the functioning of both the 2-opt heuristic and the Local Search Operators in continuation of this document.

The functioning of the 2-opt heuristic was presented in Figure 3.5. The complementary description of the method is provided in a form of a pseudo-code by Algorithm 3.1.

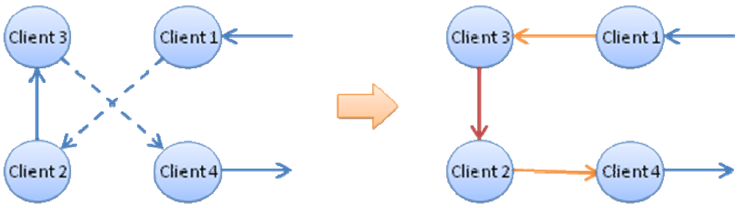


Figure 3.5 2-opt heuristic

In Figure 3.5 the dashed lines indicate the eliminated connections substituted by new orange links. The arc with reversed direction is marked in red. The same designation was used in figures presenting the functioning of the operators.

```
1.  For route each r of solution s do
2.      Calculate c(r) – the cost of route r
3.      Set the best route r*=r and the best route cost c(r*)=c(r)
4.      Let i and j be customers in route r such that j≠i and j≠i+1
5.      For all i and j in r do
6.          Take two pairs of consecutive customers: i, i+1 and j, j+1 from route r
7.          If distance (i, i+1) + distance (j, j+1) > distance (i, j) + distance (i+1, j+1) then
8.              Swap i+1 and j creating new route r′
9.              If c(r′)<c(r*) then
10.                 r*=r′ and c(r*)=c(r′)
11.     If r≠r* then Set r=r* and go to Step 2
12.     Else STOP
```

Algorithm 3.1 2-opt algorithm

3.3.2 Shift Operator

The main task of this operator is to remove a selected customer from its route and incorporate it in a different route in such position that the cost of the newly obtained solution is smaller than the original one. It is a repetitive process, where the best found solution, serves as a basis for further optimization in the subsequent iteration. Within each replication all the customers from all the routes are successively moved and all the possible reinsertion positions in the existing routes are checked. The finally performed modification is not only the most profitable of all but also implicitly feasible. It is a common practice to calculate the penalties related to violations of the constraints and use them in the evaluation of the objective function. Usually, they correspond to the cumulative value of which the permitted limit was exceeded. This is also how they were evaluated in the present thesis project. The functioning of this operator is presented in Figure 3.6. To complete the description of the method there is provided its pseudo-code by Algorithm 3.2.

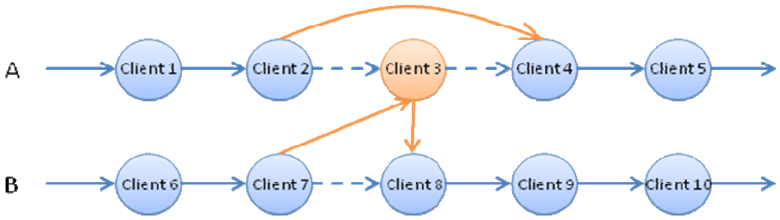


Figure 3.6 Shift Operator

```
1.  Let $s$ be solution such that $s \in \{r_1, r_2\}$, where $r_1$ and $r_2$ are routes to be modified by Shift Operator
2.  Let $c(s)$ be the cost of $s$ such that $c(s)=c(r_1)+c(r_2)$
3.  Set the best solution $s^*=s$ and the best route cost $c(s^*)=c(s)$
4.  Let $D$ and its copy $D+1$ be the depot for $r_1$ and $r_2$, where $D$ is the first and $D+1$ is the last location
    to be visited
5.  For each customer $i \in r_1$ such that $i \neq D$ and $i \neq D+1$ do
6.      Remove $i$ from $r_1$ creating new route $r_1'$
7.      For each customer $j \in r_2$ such that $j \neq D$ do
8.          Insert $i$ before $j$ creating new route $r_2'$
9.          Let $s'$ be new solution such that $s' \in \{r_1', r_2'\}$ and $c(s') = c(r_1')+c(r_2')$
10.         If $c(s')<c(r^*)$ then
11.             Set $s^*=s'$ and $c(r^*)=c(r')$
12. Set $s=s^*$ and go to Step 1
13. Repeat the process until no more improving shift movements are found
```

Algorithm 3.2 Shift Operator

3.3.3 Exchange Operator

Exchange Operator might be seen as a developed version of the Shift Operator, since it consists of a couple of shift movements. Similarly, it modifies two routes, but by relocating two customers. The exchange is to result in modified routes, which are feasible, cost-optimizing and containing the same number of customers as originally. The way in which this operator functions is presented in Figure 3.7. The functioning of the Exchange Operator is also presented in a form of a pseudo-code by Algorithm 3.3

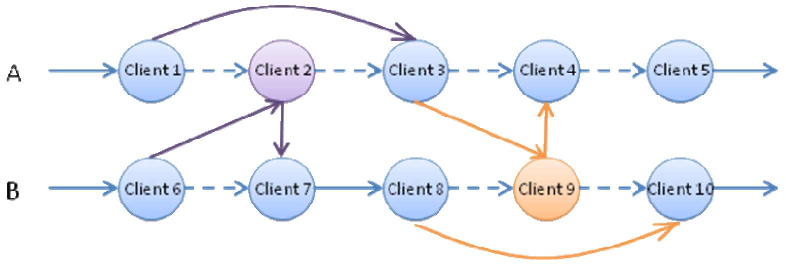


Figure 3.7 Exchange Operator

```
1.  Let $s$ be solution such that $s \in \{r_1, r_2\}$, where $r_1$ and $r_2$ are routes to be modified by Exchange Operator
2.  Let $c(s)$ be the cost of $s$ such that $c(s)=c(r_1)+c(r_2)$
3.  Set the best solution $s^*=s$ and the best route cost $c(s^*)=c(s)$
4.  Let $D$ and its copy $D+1$ be the depot for $r_1$ and $r_2$, where $D$ is the first and $D+1$ is the last location to be visited
5.  For each customer $i \in r_1$ such that $i \neq D$ and $i \neq D+1$ do
6.      For each customer $j \in r_2$ such that $j \neq D$ and $j \neq D+1$ do
7.          Remove $i$ from $r_1$ creating new route $r_1$'
8.          Remove $j$ from $r_2$ creating new route $r_2$'
9.          For each customer $h \in r_2$' such that $h \neq D$ do
10.             Insert $i$ before $h$
11.             For each customer $g \in r_1$' such that $i \neq D$ do
12.                 Insert $j$ before $g$
13.                 Let $s'$ be new solution such that $s' \in \{r_1', r_2'\}$ and $c(s') = c(r_1')+c(r_2')$
14.                 If $c(s')<c(r^*)$ then
15.                     Set $s^*=s'$ and $c(r^*)=c(r')$
16. Set $s=s^*$ and go to Step 1
17. Repeat the process until no more improving exchange movements are found
```

Algorithm 3.3 Exchange Operator

3.3.4 Rearrange Operator

Rearrange Operator reorganizes the sequence of customers placed within one route searching for a new order that would maximally decrease the value of the objective function without violating any of the constrains. More precisely, the selected customer is moved forward or backwards in the route. This method might be used as a correction step, after applying a procedure which does not comply with the imposed restrictions. It provides a certain polishing feature of the result which might bring lost feasibility back. Due to its repairing characteristics it also fulfils well its tasks in the post-optimization phase of complex algorithms. Its functioning is presented in Figure 3.8. Similarly as before, the graphical description is complemented with a pseudo-code provided by Algorithm 3.4.

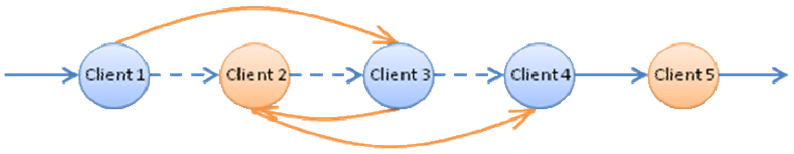


Figure 3.8 Rearrange Operator

```
1.  Let $r$ be route to be modified by Rearrange Operator and $c(r)$ be the cost of $r$
2.  Set the best route $r^*=r$ and the best route cost $c(r^*)=c(r)$
3.  Let $D$ and its copy $D+1$ be the depot for $r$, where $D$ is the first and $D+1$ is the last location to be visited
4.  For each customer $i\in r$ such that $i\neq D$ and $i\neq D+1$ do
5.      Remove $i$ from $r$ creating new route $r'$
6.      For each customer $j\in r'$ such that $j\neq D$ do
7.          Insert $i$ before $j$
8.          If $c(r')<c(r^*)$ then
9.              Set $r^*=r'$ and $c(r^*)=c(r')$
10. Set $r=r^*$ and go to Step 1
11. Repeat the process until no more improving rearrange movements are found
```

Algorithm 3.4 Rearrange Operator

The general comparison of the performance of the three above-mentioned operators shows that the Shift Operator is the most time consuming. On the other hand, it is characterized by the greatest potential of improvement of the objective function, since it is the only one, which results in reduction of the number of the routes. In order to facilitate the maintenance of the feasibility of the solution, it is recommended that in the case, when a customer-shift move results in destruction of the route the new solution is implicitly feasible. The Exchange Operator allows redirecting the search process into the new, unexplored areas, which would not be possible in the case when only one, for example the Shift Operator is applied. It also permits to overcome the detention of the search, when for example no improvement shift move can be found due to the narrow TWs. The Rearrange Operator is the most efficient, when applied in the post-optimizing step and when the customers are characterised by wide TWs. When used as a core heuristic searching for the optimal solution, although it is not very time consuming, it does not bring significant improvements.

The above mentioned methods: 2-opt, Shift, Exchange and Rearrange Operator were employed in the present thesis project. Notwithstanding, beforehand they needed to be adapted to the addressed PDVRPTW. It is due to the fact, that in order to solve a PDP any of these routines must take into consideration the extended set of restrictions and perform the changes with precaution, since the new links between the customers do not always preserve the mandatory precedence constraint. As a consequence, the number of feasible, improved, alternative routes is reduced. The final combination of individual procedures common with the way, in which each selected method has been adapted to solve the addressed PDVRPTW are presented in details in Chapter 6.

3.4 Tabu Search

The *Tabu Search* term was firstly introduced by Glover (1986). The concepts on which TS is based had been previously analysed by the same author (Glover, 1977). It belongs to the family of meta-heuristics aiming at solving difficult combinatorial optimization problems. Depending on the chosen criteria there are different ways of classifying the methods belonging to the collection. Relying on the review of most important categorizations provided by Blum and Roli (2003) TS can be specified as:

- *an approximate* algorithm, which in contrast to the *complete* ones, does not guarantee finding the optimal solution in bounded time,
- *a local-search* method, which objective is to optimize the existing solution, unlike the *constructive* methods, which generate solution from the scratch,
- *a non-nature inspired* meta-heuristic, contrary to the *nature-inspired* such as the Ant Colony or Genetic Algorithms,
- *a trajectory* or *a single point search* method, since number of the solutions used at the same time is equal to one, opposite to the *population based search* methods, which perform search processes describing the evolution of a set of points in the search space,
- considering *dynamic* or *static objective function*; the first one aims at taking the advantage of the already known information and escape from being trapped in local minima by modifying the limits of the search territory (e.g.: Guided Local Search); however, in the present thesis project there is used TS with static objective function,
- considering *one* or *various neighbourhood structures*; the latter allows to diversify the search and explore different territories; it has been applied in the current work,
- *using the memory* in contrast to the *memory-less* algorithms such as these performing Markov process; the used memory might be:
  - *short-term*, registering the recent changes regarding for example the performed moves, visited solutions, etc.,
  - *long-term*, registering synthetic parameters specifying the search process accumulated during the complete routine.

The main intention for TS creation was the necessity to overcome the barriers, stopping the Local Search heuristics from reaching better solutions than the local optima and explore intelligently a wider space of the possible outcomes. In this context, TS might be seen as extension of the Local Search methods or as a combination of them and the specific memory structures. The adaptive memory is the main component of this approach. It permits to flexibly and efficiently search the neighbourhood of the solution.

The term *neighbourhood* corresponds to all the possible solutions, constructed in the process of controlled modification of the original sub-optimal result by selected collection of operations. Thus, the neighbours can be reached directly from the initial result by executing a procedure called: *move*. This local improvement method is usually executed by the insertion-based heuristics such as the Local Search algorithms or another process which performs the reinsertion routines according to a rule defining the position for the customer's insertion or randomly.

The short-time memory eliminates the possibility of cycling. It is avoided by prohibiting the moves leading back to the already known results, during established number of iterations. They are labelled as *tabu* and placed at the last position in the *tabu list* - a short-term memory structure of length defined by a parameter called *tabu tenure*. In accordance with the First-In-First-Out (FIFO) policy, at the same time the solution which was the first in a row is removed from the tabu list and shifted to the set of allowed solutions within the neighbourhood. The fact that this set changes dynamically permits to classify TS as *dynamic neighbourhood search technique*. The value of the tabu tenure might be fixed, as in the present thesis project, or regularly updated according to the pre-established rules, e.g. recurrently reinitialised at random from the interval limited by specific minimal and maximal value (Taillard, 1991).The higher the value of the tabu tenure is the larger is the search space to explore.

Because of the fact, that it is highly inefficient to manage the tabu list containing the complete solutions it is advised to store their *attributes* instead. The attribute corresponds to a part of the solution or the move or the specified difference between two solutions. There might be considered more than one attribute. A tabu list is specified for each one of them. The collection of attributes and their lists is called the *tabu conditions*.

Apart from the short-term memory TS procedure also includes the long-term type of the memory based on the historical data accumulated during the complete search process.

The monitored features and record of changes they are subjected to might regard:

- "recency" – resulting in the record of the most recent iteration regarding each solution or attribute,
- frequency – resulting in the record of number of times a specific solution or attribute has been visited during the complete search,
- quality – resulting in the record of information accumulated and extracted from the complete search history in order to identify good solution components,
- influence – resulting in the record documenting the choices made during the search; it indicates which one of them appeared to be the most critical.

The short and long-term types of memory are used by two different procedures. Generally, in the whole TS process there might be distinguished two characteristic phases: *intensification* and *diversification*. Both terms were introduced by Glover and Laguna (1997). The success of the complete method depends on the balance established between these two stages, which complement each other instead of competing.

The intensification regards more thorough check of the promising neighbourhood areas. It includes methods aiming at modifying the rules of the selection of the moves in order to guide the search towards the solutions, which in the past were defined as the best. It uses the information stored in the short-term memory (also called the *"recency" memory)* recording a number of consecutive iterations in which certain components of the best solution have been present.

The diversification procedures intend to drive the exploration process towards never visited territories. It seeks the attributes, which are different from the already known. Thus, it requires access to the information accumulated during the whole search process and stored in the long-term memory structure (also known as the *frequency memory*). In order to escape from local optima TS permits operations, which result in deterioration of the currently best solution.

Possible diversification techniques include:

- the restart diversification - based on the concept of the re-initiation of the computational process by imposing a few used components in the selected solution and starting the procedure of new search from that point,
- diversification based on the assumption that it is a continuous process and needs to be integrated with the general search procedure; it might be obtained by introducing a certain distortion into the operation of evaluation of the potential moves (usually, it is achieved by adding to the objective function a property related to components frequencies),

- the strategic oscillation - employs the systematically modified penalty weights and leads the search process until it crosses the boundaries of the feasibility of the solutions and reaches the so far unexplored area.

The functioning of the algorithm based on tabu bans is very efficient. However, oftentimes it may result in losing improvement opportunities by not accepting highly attractive moves, if they are prohibited. In such cases, the *aspiration criteria* should be activated. It is an algorithmic mechanism, which basically consists in cancelling the tabu restrictions and permitting the move, if it results in construction of the new solution with the best yet value of the objective function.

In order to abort TS procedure it is required to activate a *stopping criteria*. This mechanism based on a predetermined rule regulates the complete duration of the process. It may start up when the complete permitted number of iterations or the *Central Processing Unit* (CPU) time gets exceeded or when the value of the objective function takes the pre-established value. However, the most popular method regards stopping the complete TS process when there was reached a fixed number of iterations not resulting in an improvement.

3.4.1 Parallel Tabu Search

Despite of the fact that TS is an efficient method on its own, its performance might be enhanced for example by introducing the parallelization into its operations. Depending on the addressed problem a different strategy may be applied.

One of the ways is to divide the complete problem in a number of separate sub-problems and perform them simultaneously, according to the principle: divide and conquer. Consequently, the final solution consists of a collection of routes, each being constructed on the basis of selected set of data. This approach might be especially efficient for solving very big optimization problems (Taillard, 1993).

Another known *Parallel Tabu Search* method includes synchronized and simultaneous search of the next move to execute. The routine starts with dividing the collection of the possible moves into as many sub-sets as the number of available processors. Then in each sub-division the individual processor seeks the best move. In the end, there is created a group of optimal proceedings, among which the best one is selected and carried out.

The above method, adjusted by engaging different search processes, was employed in the present thesis project. Both the PDP adapted Shift and Exchange Operators were selected to be executed simultaneously in all iterations of TS. As a consequence, two different neighbourhoods of the same, solution are created and searched. A synchronization of these two local search methods is required, since once the best solution in each neighbourhood is found the one which brings bigger benefits is selected for the final realisation.

In the present thesis project, the changes employed in the general functioning scheme of TS regard not only the introduction of the parallelization. The main modifications are due to the fact that instead of moving individual customers it is the couples of customers that get relocated. That implicates consideration of additional pairing and precedence constraints, changes in the structure of the memory, adjustment of general execution of the potential moves and neighbourhood creating operators. All the changes concerning both the overall performance of TS and its individual segments are presented in detail in Chapter 6.

Chapter 4

The way in which the real-time features can be introduced into the definition of the vehicle routing and scheduling problem, changing its static character, is addressed in the current chapter. Moreover, there is provided an extensive description of a number of appropriate approaches feasible for solving dynamic VRP.

After a short introduction, section 4.1 presents the dynamic nature of the problem in comparison with its static version. Next, there are demonstrated the real-time features of dynamic VRP regarding: customers' requests (section 4.2.1), travel times (section 4.2.2) and vehicle incidents (section 4.2.3). The following part 4.3 constitutes a supplement to the description of the time-dependent character of the dynamic problems and defines a manner of their classification based on their degrees of dynamism. The ending of the whole constitutes section 4.4 which provides the state of the art regarding dynamic PDVRPTW.

Dynamic Vehicle Routing

The two previous chapters focus on presenting vehicle routing models, with special consideration of problems regarding pickup/delivery operations and TWs, and reviewing both methods and algorithms proposed for solving them. These approaches reckon with all the required information to be known a priori and constant throughout the time. However, in the context of CL, in most of the real-life cases, a large part of the data is revealed to the decision-maker when the operations are already in progress.

On that account, according to both character and availability in time of required information it is possible to classify VRP as follows (Ghiani et al., 2003):

- *static* – when the input data do not depend explicitly on time,
    - *deterministic* – when all the information is known a priori and time is not taken into account explicitly,
    - *stochastic* – when the vehicle routes are designed at the beginning of the planning horizon, before the uncertain data become known,
- *dynamic* - when the input data depend explicitly on time,
    - *deterministic* – when all the information is known a priori and some of its elements depend on time, e.g.: time-dependent travel times,

- *stochastic* (also referred to as *real-time*) – when the information is uncertain and represented by stochastic processes.

Stochasticity in information appearance in time in dynamic VRP concerns different variables regarding: vehicles (e.g.: break-downs), customers (e.g.: size of the demand), travel times, etc. As a consequence, the decisions must be made inevitably before all the required data are available.

Once the designed actions are in progress, their determinations need to be modified accordingly in an ongoing fashion as the new information is received. The decision-makers can observe both: impacts and results of some of the operations conducted due to their decisions, and events, which appearance was uncertain, and react in response to them. Hence, the dynamism constitutes a characteristic feature not only of the addressed problem but also its model representation and subsequent application.

According to Powell et al. (1995):

- *a problem is dynamic if one or more of its parameters is a function of time*
  this definition includes the problems with both: dynamic data which are constantly changing and with the time-dependent information known in advance,
- *a model is dynamic if it incorporates explicitly the interaction of activities over time*
  here, it is necessary to have in mind the difference between the dynamic deterministic and stochastic models since the staging of decisions and the realization of random variables is significant for the latter,
- *an application of a model is dynamic if the model is solved repeatedly as new information is received*
  in this context, both the vast access to the real-time information and utilization of potent tools to perform the calculations in the matter of seconds play fundamental role.

At present, due to the recent advances in the ICT, the easy and fast acquisition and processing of the real-time information is feasible and affordable. It permits integration of various technological components providing an opportunity for development and application of solving methods and management tools proper for dealing with the problems of dynamic nature. Notwithstanding, such problems require modern methodology. It might be based on adaptation of the known static strategies but also needs to incorporate new ideas. There are required algorithms able to provide fast and in ongoing fashion such solutions, which take into consideration uncertainty with respect to the input data. This issue is addressed in the present thesis. The work should start with understanding what does it mean that a routing problem is dynamic. In order to facilitate this task, it is presented in contrast with its known static version.

4.1 Dynamic versus Static Vehicle Routing Problem

The main feature distinguishing dynamic vehicle routing problem from its static variant is the incorporation of the time’s dimension as a descriptive factor of the resolving case. The difference regards the way in which the information concerning the addressed routing problem comes to light and evolves through time. That is why it is often referred to as *real-time* or *on-line*. With respect to the characteristics of the required input data Ghiani et al. (2003) distinguish between the two types of routing problem specifying that:

A VRP is said to be static if its input data do not depend explicitly on time, otherwise it is dynamic. Moreover, a VRP is deterministic if all input data are known when designing vehicle routes, otherwise it is stochastic.

Extending this assumption also on the expected solving result, each of the addressed versions of the problem might be formulated as follows (Psaraftis, 1995):

A vehicle routing is static:

- *if all inputs are received before the determination of the routes and do not change,*
- *if the output of a certain formulation is a set of pre-planned routes that are not re-optimized and are computed from inputs that do not evolve in real-time.*

A vehicle routing is dynamic:

- *if information (input) on the problem is made known to the decision-maker or is updated concurrently with the determination of the set of routes,*
- *if, the output is not a set of routes but rather a policy that prescribes how the routes should evolve as a function of those inputs that evolve in real-time.*

Notwithstanding, these are not the only features permitting differentiation between the two types. Psaraftis (1988) provides a listing of twelve elements which clearly distinguish the dynamic routing problem from its static version:

1. *Time dimension is essential.*
   Regarding the static routing problems the time dimension may or may not be considered as a defining factor. To underline the difference, in the cases, when the time is taken into account the static problem is referred to as *routing and scheduling* problem.
   On the contrary, in the formulation of the dynamic version of the vehicle routing problem the consideration of the time measure is crucial. It is indispensable to have information on the location of all the vehicles from the fleet at any moment, and particularly in situations, when important incidents appear such as e.g.: a new service request.

2. *Problem may be open-ended.*
   The duration of the routing process in the static version of the problem is finite and known beforehand. Each course starts and finishes at the depot and is referred to as tour (closed route).
   The termination of dynamic routing process might be neither known nor defined. Hence, the considered solution consists of open paths.

3. *Future information may be imprecise or unknown.*
   According to the previously defined features regarding the input data, in the static vehicle routing, it is all to be known a priori and to be of the same quality.

In the dynamic version of the problem, the only information regarding events that is certain considers the incidents which already happened. The reliability of the data on future actions (e.g.: forecasts, probabilistic information, etc.) is unsure and oftentimes not available.

4. *Near-term events are more important.*
   Since all the information is uniform in quality, known in advance and does not get modified, every event is equally important for the static routing problem.
   On the contrary, in the dynamic case where the information about the future is uncertain, it is crucial to assign greater priority to the events that occur in the nearest term.

5. *Information update mechanisms are essential.*
   In the case of the static vehicle routing, since all the required information is known a priori and remains unchanged, the information update mechanisms are not required.
   The situation is exactly reversed in the dynamic case where all the inputs are continually evolving in time. Hence, the mechanisms bringing the information up to date necessarily need to be integrated with the problem solving method.

6. *Re-sequencing and re-assignment decisions may be warranted.*
   Sudden modifications are not necessary in the case of the static routing, due to the fact that the considered input data does not change unexpectedly.
   However, in the dynamic routing problem the real-time evolution or appearance of new developments make the initially designed paths suboptimal. It motivates the dispatcher to re-examine and re-define them taking into account new information e.g.: introducing new customers, modifying the current scheme of visits, changing the assignment of the vehicles to the customers' serving operations, etc.

7. *Faster computation times are necessary.*
   In order to prepare a plan of action for the static routing problem one may use a lot of time (i.e. hours). As a consequence, oftentimes the obtained solution is optimal.
   In the case of the dynamic routing, the dispatcher must react as quickly as the changes occur. Therefore, the decisions must be made as soon as possible (in the matter of minutes or seconds) and the re-calculation procedures may not last long. This is why for this purpose there are often used simple and little-time consuming heuristics.

8. *Indefinite deferment mechanisms are essential.*
   These mechanisms mean delay or undefined postponement in service of a specific customer due to its unfavourable geographical location with respect to the others, as a consequence of which this customer is always visited last. This problem might be mitigated by employing: priority constraints, time constraints or introducing waiting time penalizations into the nonlinear objective function.

9. *Objective function may be different.*
   Since the dynamic routing problem might be open-ended, the traditional static objectives such as the schedule time minimization might be inadequate. For that reason, it is reasonable to use a collection of alternate objectives applied to specific parts of the complete problem. The optimization over known inputs is a way to go if the information

about the future is not known. In the contrary case, it is advised to include such information in the objective function. Moreover, in order to avoid unsuitable phenomena the objective function might be defined as non-linear.

10. *Time constraints may be different.*
    In the case of the dynamic routing problem, the time constraints (i.e. customers' TWs) are considered to be softer than in its static version. It is due to the fact, that in the eyes of a dispatcher it is usually more beneficial to permit violation of the time constraint and pay the price of the penalty regarding the delay than to completely deny a service to a specific customer.

11. *Flexibility to vary vehicle fleet size is lower.*
    Regarding static routing, the time between their design and implementation is usually long enough to permit making modifications with respect to the assignment of the considered vehicle fleet.
    In the main it is not the case in the dynamic routing. Due to the limited availability of the vehicles it is possible that some of the customers will be provided with the service of lower quality.

12. Q*ueuing considerations may become important.*
    When the number of orders significantly exceeds the specified threshold, beyond which the dynamic vehicle routing system is not able to fulfil all the servicing tasks without producing extreme delays, it gets saturated. In this situation any assignment making or routing algorithm using static criteria brings worthless solutions. In this context, the integration of the queuing theory approaches with vehicle routing might be beneficial. However, there are few records on the subject.

In order to characterize the addressed routing problem as dynamic or static one can also analyze the way in which the input data evolves over time and is adopted by the person making a definitive decision. Hence, regarding the feeding information of a particular VRP there might be specified the following taxonomy characterizing its attributes (Psaraftis, 1995):

- *Evolution of information.*
  For the entire duration of the routing process, in the static case, all the data is known in advance and never updated. By contrast, the dynamic vehicle routing characterises with successive reveal of information as the time goes by.

- *Quality of information.*
  The input data provided to the decision-maker characterises with specific grade of certainty. Hence, it might be:
    - *deterministic* – trustworthy and certain throughout the complete duration of the routing process, e.g.: number of vehicles in the fleet, their capacities, number of depots, etc.,
    - *forecasted* – known with uncertainty but possible, requiring verification, e.g.: customer's demand, service duration, travel time between customers, etc.,
    - *probabilistic* – it may follow certain probability distribution or stochastic process, e.g.: quantity of customer's demand, travel time between locations, etc.,

  - *unknown* – impossible to predict, e.g.: location, time of appearance and quantity of demand of a new customer.

  The quality of the information is better for the near-term events than for the more distant ones.

- *Availability of information.*
  The required data might be available:
  - *locally*, e.g.: the required service time that is known to the driver when the vehicle reaches the customer,
  - *globally*, e.g.: the record of customers, which is stored, updated and continuously diffused among the vehicle's drivers by a centralised device.

  The recent advances in the development of the ICT allow increasing the accessibility of information. As a result, dispatcher has to decide when and which data should be revealed to the drivers.

- *Processing of information.*
  The information management schemes might be:
  - *centralised* – all information is gathered, analyzed and diffused by a central unit e.g.: dispatcher or automated system,
  - *decentralised* – when part of the information is processed on an individual basis, e.g.: when a driver makes decisions regarding the path to follow.

To summarize, the standard practice of introducing the dynamism into the definition of a routing problem is to determine specific features to be time-dependent.

4.2 Real-Time Features of Dynamic Vehicle Routing Problems

Reviewing the literature, it might be noted that the way in which the dynamic VRP are approached can be classified according to the manner in which the real-time features are engaged within the underlying problem definition. The majority of the publications focus on the information revealed in the ongoing fashion regarding the appearance of the new customers' requests and fluctuating travel times. Oftentimes these two issues are addressed in the context of the same problem.

4.2.1 Dynamic Customer Requests

In the face of the intense e-commerce development customers' behaviour constitutes a substantial source of dynamism in a routing problem. The data regarding customer's location, size of the order, restrictions such as specific TW, etc., become known after the initial routing plan is already determined and in process of being executed.

With respect to the requests arriving in real-time, there might be distinguished two groups of methods regarding (Chen and Xu, 2006):

- *local approaches* (also might be referred to as *myopic*), which only create initial routing plan and modify it using known information without looking into the uncertain future,
- *look-ahead approaches*, which intend to incorporate probabilistic features of future events or forecasted information into the static problem at each decision stage.

In the first case, in every decision step, a static problem is solved with respect to the data, which got revealed before the moment of verdict and regards the customers' orders, which have not yet been provided with the service.

The look-ahead approaches assume that part of the probabilistic information regarding the future events is known a priori. The dynamically reported requests might be forecasted on the basis of probability distributions using the recorded historical data. There are two ways of exploiting such data regarding:

- analytical studies, which objective is to examine both efficiency and profitability of varied deterministic dispatching strategies; they specify only one source of uncertainty and it regards the arrival of a new customer's request and/or the duration of the service time a vehicle must spend at specific customer,
- explicit stochastic and dynamic algorithmic approaches, which apart from using the estimated probabilities of the coming occurrence of specific events, also use current information.

Literature review indicates that the arrivals of dynamic customers' orders are modelled either as random events (e.g.: Chen and Xu, 2006) or as events which appear in accordance with a known distribution (e.g.: Ichoua et al., 2006).

In the present thesis, the dynamic arrivals of customers' requests are modelled using exponential random variables (Appendix A2). The dispatcher is not provided with any deterministic or probabilistic data regarding the future customers' calls and takes decisions only according to the known information.

4.2.2 Dynamic Travel Times

Vast majority of VRP models found in the literature assume the values of travel times to be constant. Notwithstanding, the fluctuating travel times constitute a substantial source of dynamism and are of special importance in urban areas, where the time duration of a trip between two loactions does not depend only on the travelled distance, but also on the conditions in the road network. The variation in travel times can be caused by traffic density due to temporal variations e.g.: rush hours, weekly cycles, etc., as well as random factors as e.g.: the accidents or weather conditions.

This type of information can be provided by an ITS and divided in three categories:

- *historical* - designate records of changes in travel times which took place in the past and which can be used to create forecasts,

- *real-time* - regards changes in travel times at present e.g.: due to unforeseen events as road incidents and represent the current state; this information can be used alone or to be employed to update travel times provided by a forecast,
- *predicted* – it can consider variations of travel times during a reviewed period of time e.g.: one work day, showing the regular rush hour congestions in certain areas; these data are not dynamic in the strong sense because they are available to the decision-maker in advance; they can be presented as time-dependent and used in deterministic routing; they require forecasting tools and are valuable for making plans.

The predicted travel times can be defined according to (Potvin et al. 2006):

- *long-term forecasts* – they stand for competently reported long-term trends, which are known to the dispatcher in advance and are not subject to stochastic variations,
- *short-term forecasts* – they represent the influence of a new, at the last moment appeared information on the routing plan design,
- *dynamic perturbation* – it is a truly dynamic component of the travel time, which interprets any unpredicted events that might occur.

Most commonly used way of incorporating dynamic information on travel times into vehicle routing models regards division of the considered time horizon in short intervals (e.g.: Potvin et al. 2006 and Taniguchi and Shimamoto, 2004). Within each interval the value of the travel time on each link between two nodes of the graph defining the underlying road network, is different and can be obtained for example by multiplying the basic estimate by a pre-established coefficient or provided by simulation. Notwithstanding, in this case the travel time value is considered to be static throughout the duration of entire interval. Hence, both travel times and cost functions for each considered link are assumed to be step functions of the starting time at the corresponding origin node, which constitutes a firm approximation of the real-world condition.

An original approach, based on time-dependent speeds of vehicles was proposed by Ichoua et al. (2003), where the travel times are calculated using time dependant travel speed matrix. As a result, the speed is represented by a step function of the time of the day and the travel time is a piecewise continuous function evolving over time.

In reality urban traffic is dynamic, which means that the travel times in urban networks are time-dependent. The expected role of an ATIS is to provide information on such time-dependency. It is the current trend to employ the dynamic data. However, the operational systems using it are not yet available. Thus, in order to deal with this characteristic we need to emulate the time dependencies in the network. This is achieved by simulating urban traffic.

In addition, a cost of a trip between two customers is represented in terms of a time-dependent shortest path between them. There is taken into consideration: historical, current and forecasted traffic information. Some testing scenarios include the dynamic perturbation provoked by an incident.

4.2.3 Dynamic Vehicle Incidents

Both, previously presented features are the most commonly modelled when defining a dynamic VRP. However, there can be implemented a different approach based on careful observation of the behaviour of thefreight and other vehicles in traffic in general. A solution, for goods transportation service disruptions due to unexpected vehicle breakdowns or road accidents, constitute optimal reassignment of customers (*rerouting*) which in other case due to the incident would not be provided with ordered service as scheduled. In this case, the objective is to minimize: operational, service cancellation and route disruption costs (e.g.: Li et al., 2009).

When modelling dynamic PDP, it is of special importance to know, at the time of preparing the new rerouting plan, if a broken vehicle was to deliver or to pickup goods. In the first case (delivery), the reassigned vehicles have to go first to the place where the defective truck is localized, recuperate the cargo that needs to be repartitioned and then follow the new scheme of visits. In the latter case (pickup) other vehicles can change their routes in such a way that they shall go directly to collect the packages from the remaining customers.

This dynamic feature is not considered in the current thesis.

4.3 Degree of Dynamism

The previous sections present the ways of solving and defining the dynamic vehicle routing models with respect to varied real-time features. However, they do not specify the existing measure methods, which allow not only to examine and compare the performance of the same algorithm employed under different conditions but also to classify the vehicle routing system under study by describing its level of dynamism.

The above presented review of examples shows that in significant proportion of cases, a number of customers are known to the dispatcher before designing the routing plan. This information permits to define the level of dynamism of the problems which do not include determination of the customers' TWs in their models. This most basic measure is a ratio of the requests arriving in the real-time to their total number. The essential frailty of this formula regards the fact that it does not take into consideration the moment of arrival of the dynamic requests.

The way in which the incoming calls asking for the service are distributed over the complete time horizon might be classified as approximately *uniform* or *clustered*. The first situation is less troublesome for a dispatcher in comparison to the second one. The planner has more time and smaller number of new requests to deal with at a time, giving him a higher comfort of work. In the contrary case, if the dynamic requests appear in elevated number at the end of the considered time horizon there might not be enough time left to react. However, the solutions obtained in the scenario with accumulated requests are more prone to be improved with respect to the objective function minimizing the total travelled distance. It is due to the fact, that a dispatcher has information on higher number of customers at a time which permits him to implement an algorithm optimising the outcome. Larsen (2000) discusses which one of these two alternatives characterizes with higher level of dynamism. The author opts for following the intuitional reasoning and classifies the scenario with uniformly distributed arrivals of requests as more dynamic, although the scenario with grouped calls is more difficult to manage by a dispatcher.

The same author introduces a more extended measure of dynamism for the vehicle routing system, where the customers are not assigned with a specified TW. The *effective degree of dynamism* (EDOD) takes specifically into consideration the moments when the new requests calls arrive and represents an average of how late the requests arrive with respect to the latest possible time they could be received:

$$EDOD = \frac{\sum_{i=1}^{n_d} (\frac{t_i}{T})}{n_{tot}} \tag{4.1}$$

where:

T : complete planning horizon,
t_i : arrival time of a dynamic request *i*,
n_d : number of all dynamic requests,
n_{tot} : number of all the requests, static and dynamic.

When addressing the problems where the TWs are designated the approach used to define the degree of dynamism should take them into account (EDOD$_{TW}$). In this context, it is important to calculate the *reaction time* which specifies the difference between the latest possible time at which the service of the request *i* should begin (TW's upper-bound l_i) and the time it arrives t_i.

$$EDOD_{TW} = \frac{1}{n_{tot}} \sum_{i=i}^{n_{tot}} (\frac{T - (l_i - t_i)}{T}) \tag{4.2}$$

In practice a dispatcher would prefer to deal with wide TWs and long reaction times since they facilitate insertion of the new requests within planned routes.

In order to label the real-life routing systems Larsen (2000) proposes a three-level scale describing them either as: *weakly*, *moderately* or *strongly dynamic*. This classification provides support for categorising the addressed problems and is not to be considered as strict.

The weakly dynamic systems characterise with a higher number of a priori known requests with respect to their total number. The proportion of static requests to the dynamically received ones is at least 4:1. In general the reaction times are considerably long and the main objective is to minimise the routing cost in terms of the travelled distance or time. Such description fits the problems found in the real life such as Dial-A-Ride Problem (DARP) regarding transportation of the elderly or handicapped people or the home devices installation/repair services run in residential areas.

A long-distance courier service or a home appliances repair service constitutes an example of a moderately dynamic system. In this case, at the end of a work day the executed routes contain more or less alternately placed static and dynamic requests. Hence, their number is comparable. The primary objective in solving such problem constitutes a compromise between the minimisation of the routing cost and the response times.

The strongly dynamic systems deal with very rapidly changing data regarding customers' requests, which are also characterised by high degree of urgency and require quick decisions on the response (e.g.: taxi cab services, emergency services such as police or ambulance, etc.). The information on the a priori known requests is usually of poor quality. Moreover, the dispatcher needs to consider the intensity of the traffic, which habitually results in vehicles queuing affecting the travel times. Hence, the minimisation of the response times is essential in optimizing the problems of the strongly dynamic systems.

In this context, the problems addressed in the present thesis project might be classified as weakly and moderately dynamic. Within considered scenarios, the regarded proportion of the static to dynamically arriving requests is: 1:4, 1:1 and 4:1 respectively. Moreover, the time-dependent travel times on each section of the underlying street network are taken into consideration.

4.4 Dynamic Pickup and Delivery Vehicle Routing Problem with Time Windows – State of the Art

The dynamic routing and dispatching problems are under intensive investigation. However, the dynamic version of PDVRPTW was rarely used as a base.

In many papers, where in the definition of the studied PDP there were considered requests arriving in real-time, the underlying problem regards transportation of people, which turns it into a DARP. Moreover, the uncertainty is related only with the occurrence of new request and a cancellation or a possibility of having erroneous information is not considered.

The majority of articles reckoning with dynamic travel times address VRP or VRPTW. Besides, it is oftentimes presented using strong simplification and no unexpected perturbations are assumed to come from the external world, like e.g.: sudden congestion due to an accident.

Above all that, in a vast majority of papers there is only one dynamic feature considered and it regards either the arriving requests or the travel times.

Nevertheless, this chapter provides a review of studies published in the last decade, which address the dynamic variant of PDVRPTW. The articles do not determine the problem exactly as it is formulated in the present thesis. In fact, in each one of them there are taken into account different set of constraints and initial assumptions.

The only dynamic feature, addressed by Yang et al. (2004), regards continuously arriving customers' requests. The authors analyse the real-time multi-vehicle truckload pickup and delivery problem on the example of a trucking company which possesses a finite number of freight vehicles with capacity equal to one unit. Its main function is to serve the customers known to the dispatcher and located within the limits of the considered area. It is assumed that the vehicles move at constant speed and the distances between the customers are consistent with Euclidean metric. The locations of the pickup-delivery request pairs are: independent, identically distributed, uniform, random variables in a unit square of the limited plane. Moreover, the considered distribution of the requests' arrival times corresponds to the Poisson process.

The pair of pickup-delivery requests is referred to as a *job* and a vehicle can perform only one job at a time. As a consequence, since each request calls for one unit of goods to transport, the capacity constraint is not taken into consideration in the formulation of the problem. The way in which customers' TWs are defined also differs from the well-known schemes. When an order call is received by a dispatcher he/she is informed about the location of both pickup and delivery customers, the earliest pickup time and the latest delivery time of the job. In this context, one can say that the customers' windows are defined unilaterally. In the case, when a vehicle arrives to the delivery customer when his TW is closed, it is still allowed to perform the service. However, the process will get penalised by a value proportional to both *job's length* (the distance between the pickup and delivery location of the same job) and amount of occurred delay.

Apart from customers locations the dispatcher is given a feedback on:

- time between the arrival of the job and its earliest pickup time,
- *slack time* – time available between the earliest possible and the latest allowed delivery; it captures the tightness of the job's completion deadline,
- time which the company needs to respond to a job request with a final acceptance/rejection decision.

The decision-maker may either accept or reject the request. The revenue generated from a given accepted job is proportional to its length. In the contrary case, the cost of rejection is equal to the gross revenue the company would have created if it had accepted the job. The problem also considers the additional cost regarding the empty truck trips performed in order to serve the accepted jobs. In effect, the complete problem definition includes various fleet operational costs measures associated with: job acceptance/rejection, penalties regarding the delays in completion of the orders and trucks empty travel distances.

Except for making a decision on orders' acceptance, the company must also pick a vehicle and assign it to the job. The collection of all these choices is referred to as *policy* or *strategy*. Hence, the major objective is to define such strategy which maximizes the overall net revenue despite of the fact that the information on: possibility of appearance, timing and characteristics of the future requests is not known.

The moment of arrival of a request determines the moment of the decision. The strategy executed so far gets interrupted and new routes are created on the basis of the available information recorded up until the current moment. At this stage, the decision-maker has no knowledge on the future. Hence, the new plan is myopic and performed till the new order call is made. The acceptance/rejection decision becomes indisputable at the moment when the time interval that the company has to decide comes to end.

At any moment, each vehicle is assigned with a queue (it can be empty if a vehicle is idle) of jobs to do. They might be accepted either permanently or tentatively. In any case, the queues are never pre-emptive, which means that once a job is picked up, it is delivered without disruption.

The authors tested five different rolling horizon policies for solving the real-time version of the addressed problem

All the presented policies were compared under typical probabilistic setting and under various parameters. For this purpose there was employed computer simulation to identify through experiments the good strategies under varying situations which consider different: traffic intensities, degrees of advance information and degrees of flexibility for job acceptance/rejection until. The final conclusions demonstrate that the best policy is the one which takes some information on the future requests distribution into account.

A different approach dealing with dynamically arriving requests which are not stochastically modelled or predicted was presented by Mitrovic-Minic et al. (2004). The authors address PDPTW emulating operations of a real-life courier company transporting letters and small parcels within city area. This company every day contracts a significant number of private drivers, thus a fixed fleet size is not specified. Moreover, the number of used trucks is not minimised and each route starts at different point representing the home base. As a consequence, the problem does not take into consideration the existence of a central depot and the created paths constitute opened routes because of the fact that they terminate at the last served customer. The freight vehicles move at constant speed and the arcs of the graph defining the underlying road network are associated with values specifying both distance and travel time. Since the volume of transported consignments is very small in comparison to the truck's dimensions the capacity constraint is not taken into account. Furthermore, each customer has a specified, wide, hard TW, which permits waiting in the situation when a vehicle arrives to the customer before its lower-bound was reached. In the contrary case, if a vehicle arrives when customer's TW is closed it is not allowed to provide the service. The considered final schedule time corresponds to one work day of a courier company. The information about the customers' requests is not known to the dispatcher in advance. Their arrivals were modelled on the basis of a continuous uniform distribution. They can all be feasibly served by the freight within the specified schedule horizon and they cannot be rejected at any moment. The location of the pickup and delivery customers' pair is defined due to random generation and the pickup's TW opening time is always equal to the request arrival.

The previously explained approach of Yang et al. (2004) handles the standard rolling horizon, first introduced by Psaraftis (1988), which operates with dynamically redefined short-term time horizon. However, when making an assignment of a request to a vehicle it is of interest to consider the impact which this decision has not only in the short-term but also in the long-term perspective. The on-line solved *double-horizon* based heuristic for routing and scheduling the real-time requests in the dynamic PDPTW proposed by Mitrovic-Minic (2004) is derived from this assumption.

On that account, there were specified two optimization goals regarding first: the decrement of the travelled distance in the short-term horizon and second: the minimization of the linear combination of distance and time over the long-term time horizon. The latter objective is to maintain the routes in such state that will provide opportunities for fast reaction to future requests.

The final conclusions indicate that the double-horizon based heuristic for dynamic PDPTW both routing and scheduling provides better results of total route length than the one using the rolling horizon. The ADW performs better in comparison to the DF strategy and the method including the TS procedure provides finest results than its simple version not counting in the optimization step. There was also noted the following relationship: in case of the instances containing big number of customers the routing cost is smaller, which implies that less distance would be gained by knowing all requests in advance. Quite the opposite dependence was observed with respect to the number of vehicles.

A different strategy was chosen by Fabri and Recht (2006) which undertook the task of modification of the model proposed by Caramia et al. (2001) taking into account the *many-to-many* (M2M) dynamic request dial-a-ride problem regarding transport of passengers by taxis and adapt it to goods transportation by freight vehicles. Caramia et al. (2001) addresses a local multi-cab metropolitan transport system, in which a single vehicle is permitted to carry six customers at a time. An interesting feature of problem definition regards the fact that a customer needs to define his/her *stretch factor* which denotes the maximal excess of the shortest possible travel time that he/she is willing to accept. Moreover, the vehicles are not permitted to wait if they reach the pickup customers before their TW is opened. These two features are modified in the problem formulation presented by Fabri and Recht (2006). Hence, not only the vehicles are allowed to wait, but also there has been assigned a hard TW for the delivery customers instead of the stretch factors. This approach is closer in concepts to the real-life situations. The amount of transported goods is specified for each customer, which implies consideration of the capacity constraint. The size of used vehicles fleet is defined as well as the complete planning horizon limit. The underlying road network is represented as a graph of Euclidean distances in which some of the nodes correspond to the customers' locations. Consequently, the elementary problem consists in finding the shortest path between the nodes representing customers. In order to solve it there was employed the A* algorithm originally introduced by Hart et al. (1968). Notwithstanding, the main objective is to minimise the distance travelled by all the vehicles during the pre-established planning horizon.

Equally as in the previous cases the dispatcher has no access to the information on the future requests calls. When the new service request arrives he/she needs to: decide whether to accept or to reject it, and if the job is accepted, to assign it to a specific vehicle and plan the routing operations. In this context, the proposed approach consists of two steps: a fast single-vehicle routing algorithm and a heuristic which solves the multi-vehicle routing problem using as a base the outcome provided by the single-vehicle routing procedure.

Apart from mentioned modifications, the authors test their approach using the same assumptions and instances which were proposed by Caramia et al. (2001). Local search based on one customers' pair shifting proves to be the most efficient of all studied combinations. Moreover, the fewer vehicles are available and the more requests calls arrive, the better local search performs. The TWs defined for delivery customers work better than the stretch-factor, the rate of accepted requests is increased and the cost per request is reduced with respect to the results obtained by Caramia et al. (2001).

Beside the articles, which in the definition of the problem take into account the in the real-time arriving customers' requests as the only dynamic feature, there have also been reviewed these which additionally incorporate the time-dependent traffic times.

Fleischmann et al. (2004) consider realistic planning situation for dynamic routing in urban area. It was inspired by a real-life problem regarding a goods transportation company, which commits to providing an express service of picking up a load within one hour of receiving a call from a customer and delivering it right after. On that account, the addressed problem corresponds to the static version of a PDVRPTW. Thus, each customer requires either pickup or delivery service. The vehicles of considered uniform fleet are able to transport only one unit of cargo at once. Hence, their capacities are not taken into account. Moreover, the designed paths are made up of alternating pickup and delivery customers' locations. Both the pairing and precedence constraints are respected. Due to the nature of the underlying real-life problem there are only considered the TWs of the customers notifying pickup service.

The dynamic aspect of the addressed problem regards first the fact, that only a part of the request is considered to be static and used to prepare initial routing plan, while the rest of the calls occur at any time while the vehicles already perform the assigned paths. Another dynamic aspect regards the travel times, which vary with the time of the day and according to a forecast, which is updated when random incidents occur. The forecasts are provided cyclically in regular intervals, while the new messages on the incidents arrive according to no rule. The travel times stand for the shortest paths. However, the novel aspect includes the time-dependent values and focusing on arcs instead of network's graph nodes.

The modelled approach assumes that the operations of the vehicles are monitored by a central dispatching unit, which has access to the on-line information on their status and location. Moreover, it is able to directly give instructions concerning next movements. Hence, the dynamic routing process regards updating of the current plan over a rolling horizon starting from the current moment. The actions are triggered by: new call, arrival of a vehicle at a pickup location, finalization of the delivery task and significant change in the travel time forecast. The additional modelling assumptions determine that the vehicles cannot be diverted while they are on their way. The only possibility concerns the moment when a truck is waiting without assigned task or just before ending the delivery. Moreover, any order cannot be rejected. As a consequence the planning horizon extends up to the fulfilment of all the reported requests.

The dynamic PDVRPTW addressed by Gendreau et al. (2006) also takes into consideration two dynamic factors: customer's requests arrivals and travel times. It corresponds to the problem faced by real-life companies providing in local area courier services of small sized parcels. Hence, the capacity constraint is not specified in the problem definition. The customers are associated a soft time window, which upper-bound may be violated and the waiting before reaching the lower-bound is permitted. The fleet is limited in size and the vehicles must start and finish their routes at the central depot. The communication between the dispatcher and truck driver is performed through a customer each time the service is being provided. It is the moment when the information on the next destination customer is revealed. A special assumption is made for the waiting time performance: in the case when a vehicle is expected to wait at next location it is asked to stay for the corresponding amount of time at the current customer after providing the service. This *last commitment strategy* allows extending the time before the made decisions become permanent, since once a vehicle is on its way to the next customer it cannot be diverted. All the incoming requests must arrive before the pre-established deadline is crossed. In the contrary case it cannot be guaranteed that they will be served the same day. If it is not feasible they will be kept and used as input when making a routing plan for the next day. On that account, the objective function focuses on minimization of: total travel time, sum of lateness over all customers and sum of overtime over all vehicles. The considered information regards only certain data at the current moment. The dispatcher has no access to forecasts of the future.

In order to solve the described problem the authors propose a neighbourhood search heuristic. The TS was implemented to optimize the planned routes in the intervals between new requests arrivals. However, the core of the designed methodology constitutes the approach of ejection chains. In this context, a pair of customers is taken out from one route and introduced into another one, which in turn forces a pair from the current path to be shifted to a different one in the same manner. The created chain of movements might be executed as a cycle or not and its length is not pre-defined. The problem of designating the best chain over the current set of routes is modelled as a constrained shortest path problem and it is solved by a greedy heuristic. It keeps on ejecting/inserting the requests in the best available position in the current path as long as the improvement is obtained. Beside the shifting moves the rearrangement of the customers within a route is also considered. It is implemented in the situations, when a pickup customer has already been served and the transfer of the corresponding delivery partner would result in violation of pairing constraint.

The moment of arrival to the next customer from the preceding location, as well as the end of the provided service are calculated for each planned route. The evaluation is based on the simplifying assumption that the trucks move at constant speed. Hence, the moment defining the end of the service is not random. There is not considered any stochastic event that could perturb the travel times between two locations.

The regarded time horizon is divided into five intervals, each corresponding to the time of the day characterised by different traffic intensity. In order to emulate the new requests arrivals there were used two sets of Poisson intensity parameters (in requests per minute) containing values for each time interval.

There were simulated scenarios regarding two different in length complete planning horizons. The performance of handling new requests by TS heuristic was compared with other approaches. The main finding of the study is that the methods using the local descent procedure perform better than the others. Moreover, the adaptive descent and TS prove to be the best.

Following the scheme introduced in Chapter 3, in order to summarize the contents of the present section there was prepared a diagram shown in Figure 4.1 which provides all the discussed publications ordered chronologically. Its objective is to facilitate the identification of differences between all the described problems and resume the methods employed by specific authors.

In short, in the reviewed publications there are taken into account no more than two dynamic factors defining the problem: dynamically arriving new customers' requests and time-dependent travel times. In the cases, when there are considered only dynamic requests, it is assumed that the vehicles move with constant speed. Thus, the travel time between customers is defined in terms of distance between them.

Most of the publications do not consider forecasts of either new requests or travel times (except Fleischmann et al., 2004). Similarly, the majority of documents does not reckon with capacity constraint (except Fabri and Recht, 2006). In each article TWs were defined differently. Also, in every case there were employed different solving methods.

In order to complement the state of the art, in the current thesis there are considered various intensities of dynamism regarding the novel requests factor. It means that, there are taken into account distinct proportions of static and dynamically appearing customers' requests. The higher the percentage of novel requests the more dynamic is the solved problem.

In addition, unlike in other papers, the designed testing scenarios deal with situations when there is reported more than one individual pair of customers at once. Still, the dispatcher has no knowledge about the future requests. He/she verifies whether the new request is rational and is allowed to reject it if it is incoherent with current network state represented by simulation parameters, e.g.: if the closing time window of one of the customers from the new pair is before the current time.

There are also considered time-dependent travel times in the underlying city road network. They define not only the evolving character of the urban traffic but also represent the effects of unexpected incidents. In order to both challenge and evaluate the performance of employed freight fleet there were designed testing scenarios in which the traffic flow is blocked in a vast network area.

Also with respect to travel times, unlike the majority of other authors, we consider traffic forecasts. They are provided in real-time by the specially designed and implemented module.

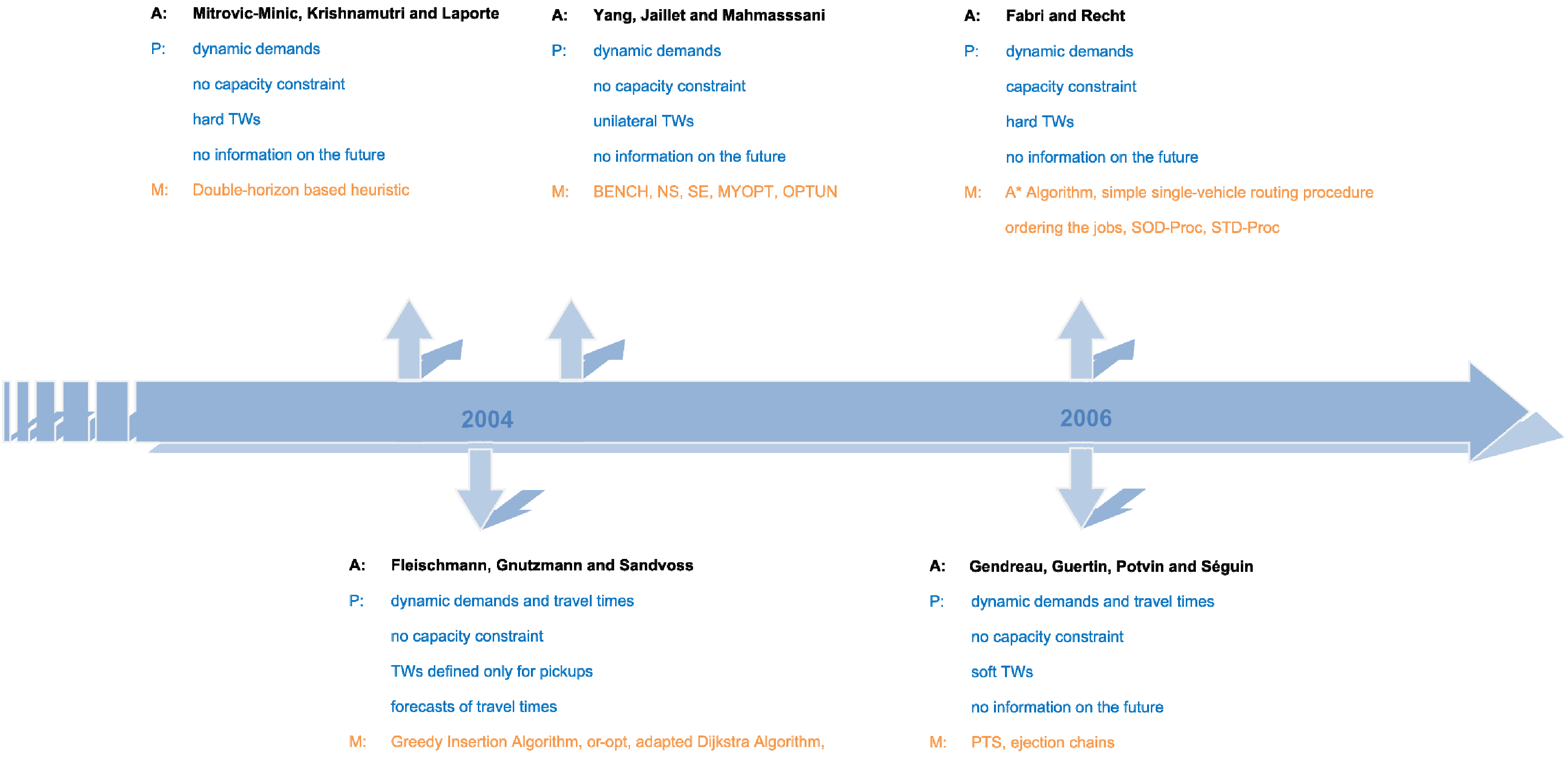


Figure 4.1 Chronologically ordered publications regarding solving Dynamic PDVRPTW (A: authors, P: problem, M: used methods)

In order to maintain high dynamism of the addressed problem it is assumed that the dispatcher can communicate his/her decisions to the drivers of freight vehicles at any time instant. It is related with the fact that the fright vehicles' diverting, while they are on their way to fulfil the next assignment, is permitted. This approach was not considered by other authors.

The modifications of the current routing plan are very frequent. They are triggered not only by the new requests arrivals but also by the fact that the service has just been provided or missed.

In the current thesis, the underlying problem's definition reckons with the capacity constraint. Since it was omitted by the majority of other authors, it constitutes one of the contributions of the current thesis. This constraint is not without significance as it affects the number of used vehicles and made tours. In order to represent the urban freight logistics operations as close to reality as possible the capacity restriction cannot be omitted.

Lastly, there are also considered two types of TWs: narrow and wide. The shorter the TW's span the more difficult it is to solve the addressed routing and scheduling problem. The objective of introduction of different TWs specifications is to investigate how the freight fleet will perform at various degrees of restrictions.

Investigation

"In another moment down went Alice after it,
never once considering how in the world she was to get out again."

- L. Carroll (1832 - 1898)
"Alice in Wonderland"

Chapter 5

The present chapter constitutes introduction to the investigation part of the current thesis project. Its objective is to provide an overview of the proposed approach, to highlight the main contributions, to identify the major challenges found during the implementation process and to appoint the contemplated ideas.

Hence, section 5.1 presents the main contributions. It discusses the principal differences between the manners of how other authors determine the addressed city logistics optimization problem and how this task has been carried out in the current project. Also, it provides justification of some of the initially taken decisions regarding problem's specification and solving. Section 5.2 defines essential assumptions on which the complete approach is based on. They mostly regard delineation of necessary input constituting the primal requirements. Thus, the objective of this part is to illustrate project's foundations. Section 5.3 presents the general scheme of the undertaken thesis project's framework. It demonstrates mutual dependencies between individual modules, required inputs and created outputs. In addition, it briefly explains the objectives and modus operandi of each of the implemented working units.

Dynamic Freight Management in Real-Time City Logistics Environment

There are no universal solutions to the CL problems. Various urban typologies require adoption of different measures. The type of provided service, the kind of transported products, customers' specifications and requirements, and other influencing factors, need to be studied in detail since they strongly affect not only the definition of the problem itself, but also the finally implemented improvement proceedings. On that account, there might be specified a wide range of problem defining variants and corresponding solving alternatives. Up until now, many of them were commonly addressed. As a result, there is available a high number of publications reflecting the carried out extensive studies. However, there can be still identified some, which although respond to relevant situations, have been investigated in an insufficient degree leaving many questions unanswered. In this way, there appears an opportunity to undertake research which would newly define the actual problematic issues, examine them in order to solve them and complement the existing records. This is not only the motivation but also the objective of the work carried out in the current thesis project.

The strategies, which aim at achieving more operative urban distribution and reduce the transportation costs related to commercial transactions through improved use of available resources and of the road network, have a key role within the range of the alternatives for solving CL. However, the so far contemplated approaches have paid little attention to the problem affecting dynamic features, which result from the nature of the phenomenon at the base.

The newly proposed, modern and efficient fleet management in urban areas should account for dynamics of traffic conditions and variability in travel times, since they significantly affect the distribution of goods and the provision of services. In addition, it is proper to consider other dynamic problem conditioning factors such as the customers' unpredicted requests arrivals and variable requirements regarding: quantity of demanded goods, TWs, etc. Similarly, the operational conditions of employed fleet (e.g.: vehicles' availability, status, positions, current occupancy of the load carriage space, etc.), which change in time, need to be also reckoned with.

Naturally, the dynamic fleet management in urban areas is associated with the necessity of prompt and direct response to the occurred changes. Consequently, it implies the necessity of recalculation of the current routing plan with respect to the registered variations in the real-time fashion. Moreover, the determined improving modifications have to be transferred immediately to the affected agents.

For the above mentioned aspects to be taken into account by the newly proposed approach aiming at improving the operations' optimization, it is indispensable to reckon with the recent technological developments permitting the access and intelligent transmission and processing of information. However, the improved data management capabilities are not the only important factor affecting the performance of the complete optimization strategy. On the basis of the freshly granted opportunities of specifying the distinctive components of individual procedures in real-time it is possible to intervene at any moment during the execution of the optimization process and to modify it in accordance with the newly arrived information. In this way gained flexibility and velocity of response strongly affect both definitive efficiency and quality of the complete approach.

From the point of view of the current thesis project, observing the progressing technological development resulting in faster access to the constantly growing number of data, the possibility of admission to detailed traffic information on selected city network sections in real-time is assumed to be valid. What is more, due to the every time more efficient tools and mechanisms for data storage and analysis, it is considered that it is feasible not only to observe the current states but also to examine the historical records and to prepare the effective forecasts of future changes. The knowledge, acquired both on the basis of granted access to good quality real-time information and thanks to the usage of data management instruments, is essential in order to formulate proper hypotheses regarding the addressed problem and constituting foundation of model to build.

The above assumptions are consistent with the trends visible in the real life. For instance, already now, there exist easily accessible public portals which provide in an on-going fashion the present traffic information as well as the short-term forecasts. A good example of the provision of such information is made available by the governing authorities of the city of Barcelona at its webpage (http_5). Figure 5.1 shows a sample of provided information which is being continually updated along with the elapse of time. What is more, if there was made a comparison of the subsequent editions of this web site over the years, it could show a substantial progress, that has been made both in terms of quantity (the size of the road network) as well as the detail of presented information. This trend is growing. Hence, although in this context, at present, the city of Barcelona belongs to the minority, more and more municipal authorities and private enterprises realize how big potential lies in the good quality real-time information and its importance for the CL optimization alternatives. In consequence, it is proper to expect in the close future the development of another trend which expresses itself in a growing demand for professional real-time data management tools and methodologies.

Figure 5.1 Example of real-time traffic information provided on-line by the city authorities of Barcelona

The resent technological developments achieved in the field of ITS facilitate the tasks of detection, recording and transition of information specifying the changes in customers' and vehicles' defining features, and travel times due to the variable traffic conditions. Notwithstanding, in order to take full advantage of such large variety and amount of accessible data, it is worthwhile to consider the possibility of utilization of tools facilitating the real-time decision-making processes. From the point of view of the dynamic freight management system efficiency, instead of relying exclusively on the experience of a dispatcher, it is advantageous to employ a professional DSS facilitating consideration of higher number of factors conditioning the addressed problem. Wanting to explore this alternative, the design of such system became the main objective of the current thesis project. The novelty of the proposal constitutes in basing it on specialized methodologies considering both fixed and sequentially updated values and incorporating fast response mechanisms.

5.1 Contributions

The review of literature indicates that most of the currently reported research employs either approximate or average values of accounted variables. For example, in the case of travel times, there is not taken into consideration the changeable nature of urban network nor the fact that its condition evolves in time due to traffic's random aspects such as congestion or incidents. The travel time variable is considered to be static instead of time-dependent, which adversely affects the feasibility and the general quality of created solution. Thus, unlike other alternatives, the current proposal employs the continuously updated time-dependent information on the dynamic factors determining the addressed problem.

The carried out literature review also indicates that the possibility of freight vehicle's diversion is another problem, which so far has not been paid much attention, leaving the room for further research. Notwithstanding, in the cases when it is contemplated, it is performed in accordance with certain approximations. For example, a vehicle is obligated to visit the next assigned customer as specified in the current routing plan, before it is allowed to implement its modified version. Another alternative regards the possibility of present paths' adjustment solely when a vehicle is waiting at customer's location in order to provide him with the service. Hence, only during these time intervals the performance of diversion is permitted. As a consequence, the response time is not prompt. In order to more thoroughly investigate this problem, in the present thesis project a strong emphasis was put on the quick reaction for the registered changes as they occur. Thus, the possibility of vehicles' diversion is considered independently from their status. This approach includes one exception: when a vehicle is providing a customer with service it is not allowed to interrupt the process and leave with intention to fulfil another assignment. This policy is employed since it is in line with situations occurring in the real life. Moreover, in order to better emulate the reality, it was decided that the injunction of visiting the subsequent customer should be limited to the obligation of reaching another network node on the shortest path between the customers. It is due to the fact that in real-life situations vehicle's driver needs time to manoeuvre. Also, it is not always possible to perform the operation scheduled in the last moment, e.g.: to change currently occupied street lane. Such revised diversion strategy, in comparison with other known alternatives, provides more accurate representation of real-life cases. Moreover, it grants the possibility of quicker reaction to the detected changes in this way assuring more flexibility of the process of current routes modification. Finally, it enables better optimization ultimately resulting in higher savings.

Next difference between the specification of the addressed problem in the current research and in other published records regards the number of accounted dynamic features. Most of the studies focus on one, changing in time, problem determining aspect and it is either: travel times, customers' requests or freight vehicles' conditions. Wishing to investigate new facets of the problem, in the current work, it was decided to simultaneously deal with multiple time-dependent factors. As a consequence, the group of dynamic components includes the traffic, which can be specified as highly dynamic. Also, there are taken into account the customers' orders, which depending on the tested scenario interpret different degrees of dynamism: from high to low. In addition, the changing in time characteristics of vehicles are registered and respected. Also, the modifications of both fleet's size and characteristics defining the vehicles are not permitted. The initial specifications of the employed freight stay valid throughout the complete performance of the routing process.

The subject for further investigation can also be identified analysing the research studies taking into account the problem with specified both pickup/delivery requests and TWs. The literature review indicates that the publications addressing a problem with both of these designations considered either omit or mitigate the definition of complementary restrictions. For example: TWs are specified only for the customers requiring pickup service, the capacity constraint is not determined or not strictly adhered to.

In this context, with intention to investigate new aspects, the problem addressed in the current thesis project has been defined in a way that in comparison with other studies is more restrictive. Both the precedence and pairing constraints are specified as hard and in no case can be violated. In fact, the employed algorithms were implemented in such a way that the fulfilment of these assumptions was straightforward. Similarly, the capacity constraint is defined as strict and under no circumstances can be violated. Next, as indicated before, the final solution has to be non-pre-emptive. The service, once it is started, has to be completed. Furthermore, the TWs are determined for all the considered customers. A vehicle may wait for the TW to be opened but cannot provide the service, once it is closed.

The selection of the PDVRPTW formula to define the problem researched in the present thesis project was not only inspired by the conclusion drawn on the basis of the effectuated literature review, indicating that so far it has been insufficiently studied leaving some questions unanswered. In main, it was chosen because it finely reflects the nature of the logistics operations carried out in an urban environment.

The PDVRPTW is NP-hard task. The degree of difficulty was additionally increased by designating the values of a number of problem determining features as time-dependent. Thus, the specification of one method efficiently solving the addressed problem constitutes a big challenge. It is necessary not only to properly capture the attributes' variability but also to manage the significant number of constraints and large amount of numerical data. On that account, the following chapter of the current document was designated in its entirety, to present the carried out research on the reviewed problem solving algorithms. In order to facilitate the analysis and evaluation of performance the considered strategies were examined using the static version of PDVRPTW. In the subsequent stages of the project, this formula has been adjusted by including the dynamic features, and the selected solving approach got suitably modified. The ultimately selected algorithm constitutes the key component of the complete study.

Furthermore, one of the basic intentions of the undertaken thesis project was to examine the performance of the proposed approach on a real-life street network instead of an artificial background, which is a strategy most frequently encountered in other publications. Hence, initially the area of the city of Barcelona was chosen as the testing site. Nowadays, such big optimization problem requires the usage of very potent computational tools. Due to the fact, that the whole of the work was carried out on a personal computer with limited properties it was necessary to reduce the size of the considered background to one quarter. Notwithstanding, it should be noted, that although within the current project there was utilised as background a segregated fraction of the complete city network, the proposed approach supported with larger outlays on employed computation tools can be also implemented for a much larger network of an entire town.

5.2 Basic Assumptions and Requirements

The primary objective of the current thesis project is to design such DSS, which beside static features takes into account the dynamic factors conditioning the addressed problem and provides optimal routing and scheduling plan to be performed by a specified freight fleet in depicted urban environment. Consequently, the main novelty of this approach regards the fact that all the paths are recalculated with respect to the dynamic information provided in real-time. In this context, in the preliminary step, there must be defined a collection of inaugural assumptions lying at the base of the contemplated design.

One of the fundamental requisites regards the description of the underlying urban roads network. It needs to comprise information on every street and all possible turning movement at every intersection. This level of detail is necessary since the complete sight is to be translated into a graph. The user of the proposed DSS may employ any tool providing as an output the network representing graph. In the present thesis project, the task of design and implementation of such data translating module was not contemplated. Instead, there was utilised a ready record arranged and facilitated by (http_3). For its creation there was used the same microscopic model which was employed to generate the required historical and present travel times data bases. Ergo, the first executed task, using the chosen microscopic simulator, was to construct a descriptive virtual graphic model of the urban road network of the selected district. It was subsequently translated into a graph. Thus, the complete data translation process consists of two steps: from real network to the micro-model and from the micro-model to the final graph. Once the graph is specified, its structure does not get modified during the entire course of the project. Consequently, the situations which result in temporary closing and excluding from active traffic certain road sections, whether due to road accidents, road works or for another reason, are not contemplated. The network specification is considered to be one of the permanent factors in the definition of the addressed problem. The alternative of incorporating into the testing scenarios the possibility of dynamic network design modifications is left to be examined as promising variant in future studies.

The following assumption regards the fact that a potential user of the proposed DSS is granted the access to the real-time data reflecting the evolution of the traffic states in the underlying urban network. Consequently, at any time instant he/she gets acquainted with the current state of the network's performance, as well as with the collection of the historical data on the basis of which it is possible to make projections for the future. Such information in the real life can be provided with high precision by a modern ATIS. The crucial aspect consists of acquisition of the information updates in on-going fashion, so the routing plans do not only rely on historical records, or forecasts created on the basis of past traffic states, but also may be adjusted in accordance with the most recently registered changes. This advanced requirement is indispensable for the propitious fulfilment of the project. However, it does not correspond with the current state reflected by the degree of advancement in application of the novel technological solutions in the real life. Thus, for the purpose of this study, in order to be able to continue with the progressive work, instead of the factual data there were processed the numerical results provided by a microscopic traffic simulator. In this way, there was obtained an accurate representation of both the geometry of the urban network and its performance with all the required high degree of detail. Consequently, although the proposed approach was tested using artificial data it remains valid and can be employed in the future using the adequately extensive and precise real-life information once made available. So, apart from the possibility of building a close-to-reality urban road network model, the microscopic traffic simulator provided the opportunity to create the data base necessary for carrying out the calculations. It facilitated the required detailed information on traffic's evolution, since it was possible to record the changing values of travel times during each time interval of pre-established length and on each street of the underlying city network replica. In this manner, in the present research project, the employed simulation tool serves as a fine substitute of a refined real-life ATIS. The way it is utilized constitutes a novel aspect of the whole approach in comparison to other known records. Notwithstanding, the most desired follow up of the project would be to employ the same data providing device as a validation tool. Unfortunately, until the present day, regardless of the initial objectives, it was not possible to identify a commercially available simulator, which construction would permit to establish an interaction relationship with the proposed routing and scheduling module. In this situation, in order not to discard the simulation as a potential future validating tool, there was designed and implemented a separate module, for which the objective is to emulate the behaviour of the fleet of vehicles in selected urban environment. This application, although it is not graphically supported, performs on a similar basis as simulation. It provides the data required by the employed algorithms and constitutes a good foundation for the validation of the complete approach.

Consequently, the next basic assumption of the project states that the used fleet of freight vehicles is equipped with appliances such as GPS and General Packet Radio Service (GPRS). Both of them are needed due to different functions they perform and type of data they provide. While the first one permits precise localization of an individual car, the other ensures communication between the driver and the dispatcher. Due to the exchange of information, the decision-maker is provided with the dynamic data necessary to optimize the currently performed operations. On the other hand, the novel actions can be directly executed by the vehicles since the newly issued commands are received immediately. That is why the design of the proposed module, to emulate vehicles' performance, puts strong emphasis on careful reproduction of the reactive communication process, since it is essential for the whole approach that the fleet responds immediately to the modifications of the current routing plan and to the changes of the variable environmental factors. It fulfils both of the above described functions and in addition it provides the necessary information on freight vehicles': position, status, size of the currently occupied load carriage space, etc. As a consequence, although in the present thesis project the technical requirement on equipment of the fleet vehicles is fulfilled artificially, it is in accordance with the original objectives.

Another requirement regards the fact that the decision-maker has to be provided with information on customers' requests in the real-time fashion. Hence, it is assumed that there is ensured access to an operating technologically supported unit (e.g. call centre, internet portal supporting the concept of e-commerce, etc.), which gathers data interpreting the changes in customers' demands as they appear contributing to the required DSS's input. The requisite information concerns: the moment arrival of a request call, the specification of both pickup and delivery locations and the quantity of demanded goods. In the real life, many transportation companies permit modifications and cancelation of the orders once they are reported. Normally, this process needs to be performed in accordance with certain constraints representing the company's policies, e.g. the order's cancelation or modification can be done only within the limits of specific time window. Its lower-bound constitutes the moment of order making, while the upper-bound is specified by the arbitrarily imposed time limit. In the present thesis project, orders' modifications or cancellation are not considered. Notwithstanding, the design permits the incorporation of such controlled procedures in the future. Moreover, since there was not found any data base on customers' requests this information was generated artificially. Hence, the required data on customers' requests, delivered to the proposed DSS, depend on the selected alternative of the designed testing scenarios. The details on the process of their creation are provided in Appendix A.2. In addition, the ways in which the customers' data are revealed to the decision-maker depend on the adapted reaction strategy. For example, the information on an individual order may be sent right after it is notified, or to be halted until more requests are gathered and then delivered. As a consequence, the transmission may depend on time (direct or cyclical, which is determined by time interval) or on the number of collected requests.

All the above mentioned requirements are compulsory and sufficient for the implementation of the proposed DSS. Notwithstanding, it needs to be noted that within the collection of obligatory inputs there is included the initial routing and scheduling plan. In the present thesis project there was implemented a complementary module providing the outline of calculated best routes. Consequently, this specific requirement is satisfied and it is not expected from a potential DSS user to employ a separated tool. The construction of the unit providing the initial routing and scheduling plan was undertaken not only due to the input requirements. It does not constitute the integral part of the DSS but its adapted and enriched version was used as its core element.

Although it is not necessary to use it as input, in the proposed DSS there was taken into account the potential solicit of employing the information specifying the future traffic states. Hence, there was implemented an additional module which, even if does not form part of the complete DSS design, substitutes an expert forecasting device and provides the forecasts of vehicles' travel times. In this context, the information stored in the historical data base is interpreted as the long-term forecast, while the matrix containing information on present traffic states is used as the short-term forecast. The two data sources are used simultaneously on the basis of the exponential smoothing technique.

Taking into account all above mentioned necessary basic project input requirements it is possible to create an overview diagram presented in Figure 5.2.

The framework of the undertaken enterprise is based on the assumptions concerning the technical requirements, which today can be met with adequate financial outlays (e.g.: road detectors, blue tooth, GPS, ATIS, etc.), but which, it is believed, soon will constitute standard equipment of each freight vehicle and form part of the serviceable infrastructure of every city. Even so, due to the technical limitations, which were met during the implementation phase of the current project, not all the proposed procedures could be constructed and tested as conceived at the moment. Notwithstanding, the design reckons with them and the shortcomings are highlighted in the document. Moreover, although the collection of the basic assumptions is rigid, there is room for adjustments. For example, beside the above-mentioned requirements for the input data, an assumption, which is essential in the context of the complete undertaking, regards the granted access to highly efficient computers, which allow not only quick calculation, but also the storage of large amounts of data. As was mentioned before, the whole of the current project was carried out on a personal computer. As a consequence, it was necessary to consider the technological limitations, which got reflected both in the design of the proposed DSS and the selection of the testing background. All the modifications related to technical issues and the taken decisions are indicated in the current document since even now with the usage of more sophisticated computing tools they can be overcome.

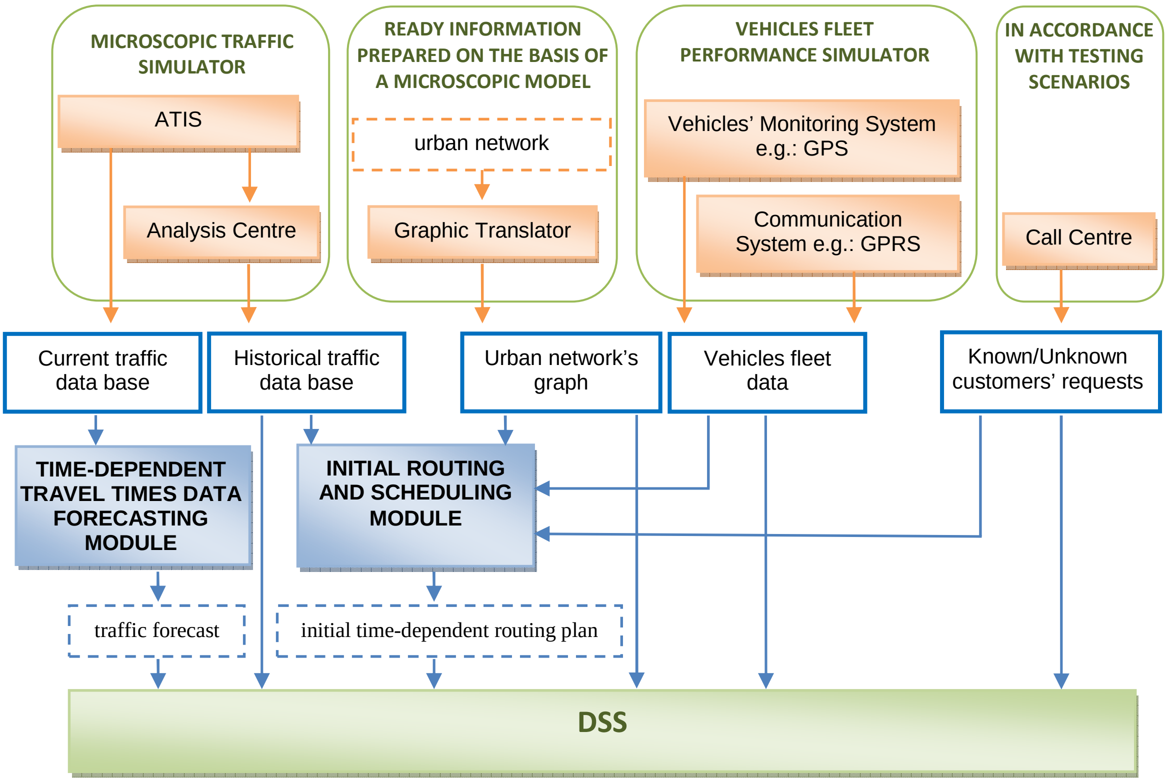


Figure 5.2 Specification of requisite inputs to the proposed DSS

5.3 Proposal of the Decision Support System

The complete overview of the approach employed in the present thesis project is provided in form of a scheme presented in Figure 5.3. Its main intention is to demonstrate mutual dependencies between individual modules. Thus, strong emphasis was put on highlighting what is the output of each implemented segment and by which unit it is used as input.

In the framework diagram there can be distinguished three types of elements. The boxes filled with colour depict individual modules which were designed and developed specifically for the proposed approach. The non coloured cells specify the required feeding data. The squares marked with dotted lines display the different segments' products, which at the same time constitute inputs to subsequently engaged units.

Also, the way in which various colours were introduced into the scheme has its reasoning. The orange indicates required data sets, which are necessary and mandatory. They have been discussed thoroughly in the previous section. In addition, there were marked in orange those modules, which were designed and developed in order to supply the DSS with the required input data. The red colour indicates segments, for which the objective is to provide dynamic information. As a consequence, their output is often and regularly consulted since the obtained data depend on time. The modules constituting the elementary components of the DSS are marked in blue. They are included in the loop of mutual dependencies, which means that they are repetitively activated throughout the complete process of decision assistance.

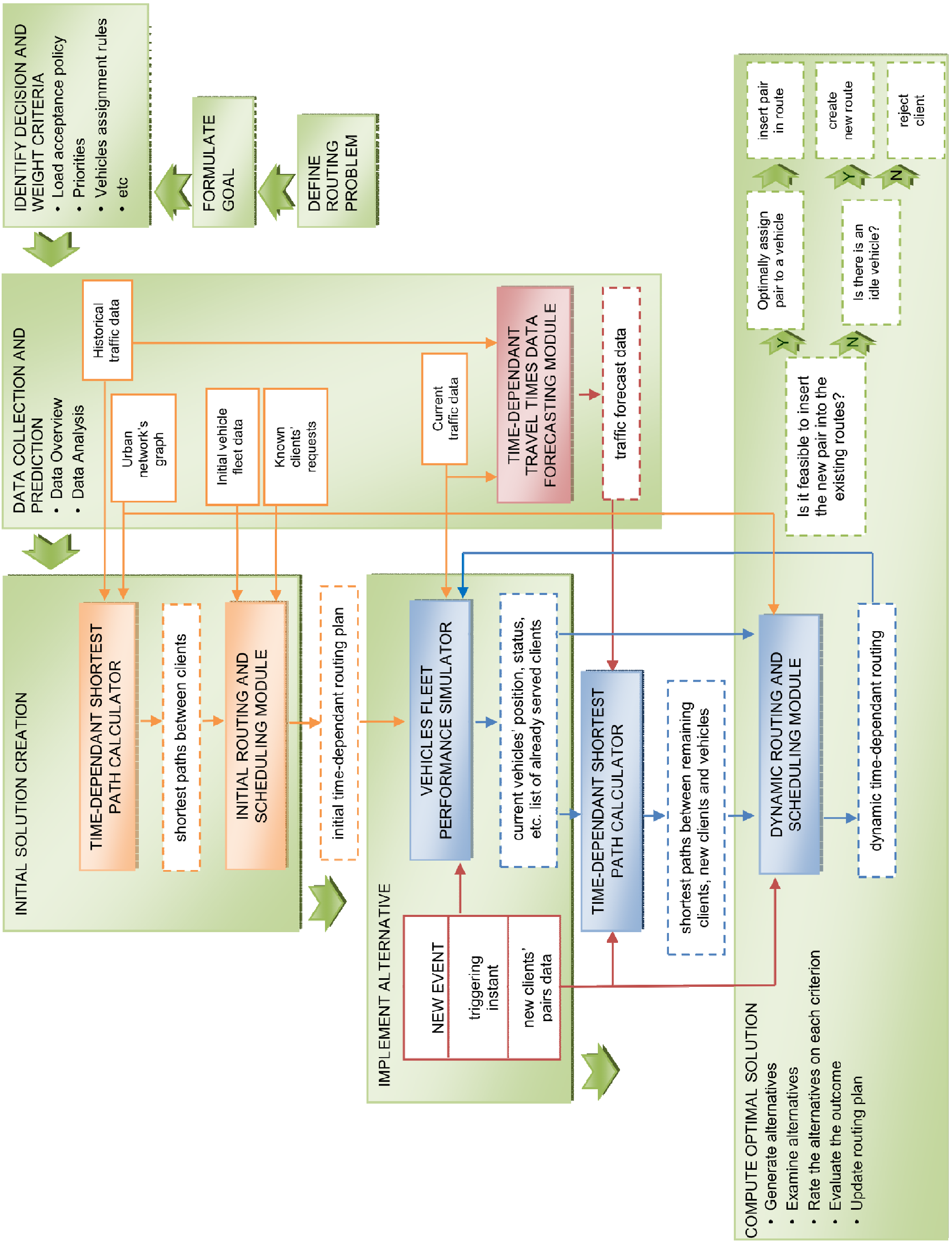


Figure 5.3 Diagram of the project framework

The aim of the TDSP Calculator is to determine the pathway between customers, which corresponds to the minimum value of time required to travel. It is a module which is displayed twice in the scheme of the complete project's framework. For the first time it is used as an appliance providing the input to the IRSM. It uses the historical record of travel times data and the description of the network's graph. On this basis, there are calculated the shortest paths, which are saved in form of arrays specifying the sequence of nodes that a vehicle must pass through, in order to reach the specific next assigned customer. The algorithm employed in this module determines the shortest paths between all the nodes of the graph defining the underlying streets network. However, as input to the IRSM there are used only those which origin and destination constitute locations of customers known to the dispatcher (e.g. customers, which could not be served the previous day) and the depot.

The second time the TDSP Calculator is employed is before the activation of the DRSM. In this context, it constitutes a composite part of the proposed DSS. Its modus operandi is the same as in the previous case. However, the input data it uses are different. Its purpose is to calculate the shortest paths between the customers which were not yet served by the vehicles assigned to them, the new customers who have just made their orders, the vehicles performing the current routing plan and the depot, since it houses a number of still not employed vehicles. Thus, in this case the actual locations of the used fleet vehicles are interpreted as positions of "dummy customers". Moreover, the travel times' values used in the calculation process are provided by the Time-Dependent Travel Times Data Forecasting Module and constitute forecasts of the future states. In contrast to the modified input data, the used description of the network graph remains unchanged.

The objective of the IRSM is to provide as the feeding data to the DSS the initial routing plan for the freight vehicles to perform. Thus, it takes into consideration only the information on the customers known to the dispatcher. The output is constructed by the sequences of customers, which should be visited in a specific order by a single assigned vehicle. The design of this module constituted one of the most challenging parts of the complete project, since the employed algorithm is also used in modified form in the dynamic version of this segment. Thus, the findings of the research carried out in order to specify an optimal approach to solve the addressed PDVRPTW are aggregated and discussed separately in Chapter 6.

The modifications of the selected composite heuristic method, regard the changes in handling the dynamically revealed data on freight vehicles' performance and new customers' characteristics. Hence, the objective of the DRSM is not only to optimize the currently carried out plan in accordance with freshly delivered information on traffic's evolution, but also to introduce the newly reported service orders into the existing routes or in certain cases to create new ones. The employed shortest paths specifications were calculated on the basis of the forecasted travel times. Thus, when the output of the DRSM: the updated routing plan, is executed in the environment of the vehicles' performance simulator there can be found discrepancies between the planned and performed times of travels. Moreover, it can happen that some of the assigned customers will not be served. In this case, they are placed in the set-apart list, which might be used as a basis to determine the accuracy of the proposed method. Besides, in the real life, the information obtained in this way is, as a rule, used for the preparation of the initial routing plan for the next day of work.

The output of the DRSM substitutes the initial input to the VFP Simulator. Its objective is to emulate the operation of the vehicles from the used freight fleet, when they are provided with an update of the routing plan to execute. In practice, the operation of this module consists of estimation of each vehicles location in the underlying road network and determining its status at the moment of re-evaluation of the current routing plan. The additional information obtained in this process concerns the customers. There are created listings defining which customers were served, which ones could not be provided with the service, and which still await it. The information needed for the simulation, beside the specification of the current routes recalculation triggering moment and the composed routing plan regard the travel times data representing the currently evolving traffic states.

In theory, there might be used different events specifications as triggering elements. They may regard customers (e.g.: new orders arrivals, their changes or cancelations, etc.), vehicles from the freight fleet (e.g.: breakages, cut communication with the driver, etc.) or specific changes in traffic (e.g.: road accidents, punctual changes in traffic's organization, etc.). In the present thesis project the main focus is on customers and the moment they report the order. Notwithstanding, the future user of the proposed DSS is free to define the triggering events of different character. In the real life the record of the dynamically arriving customers' requests registered by the private companies is of confidential character. This is why the triggering events employed in the present project were scheduled in an artificial way. Their composition process is explained in details in Appendix A2. Consequently, the New Event cell in the general framework scheme contains a list of new customers' requests, about which it is assumed that the decision-maker had no information about at the moment of preparing the previous routing plan. Every pair of newly appeared customers is characterised by the order's reporting time instant. However, it is not synonymous with the interruption of the VFP Simulator's operation. This stopping moment is specified in the pre-defined experiment's scenario. Thus, each experiment defines how often and when the simulator is suspended in order to recalculate the current routes by the DRSM using new information. The triggering can be done periodically i.e.: at regular intervals, or when a specific number of accumulated requests, is reached. Hence, in the subsequent module, depending on employed scenario there may be introduced into the current routes more than one or no pair of customers.

The lastly implemented segment is the Time-Dependent Travel Times Data Forecasting Module. It does not constitute an integral part of the DSS. However, its implementation was requisite since it provides the necessary updated travel times' data needed to recalculate the current routes. Its modus operandi is based on exponential smoothing. Its objective is to arrange the information provided by two: historical and present traffic data bases, so that the newly obtained composition could be utilised as prediction. Consequently, it substitutes a professional forecasting device, which a potential DSS user may require.

The details on design, implementation and functioning of each of the modules discussed above are described in Chapter 7.

Chapter 6

The objective of this chapter is to present the performed process of design, construction and evaluation of the candidate approaches apt to solve the addressed PDVRPTW. (The mathematical description of the considered problem is presented in Chapter 2 by the equations 2.39-2.52). This part of the project results in selection of one composite procedure, which will constitute a kernel of both Initial and Dynamic Routing and Scheduling Modules.

The collection of variables used to explain the functioning of the algorithms is provided in section 6.1. Next sections present the individual methods examined in order to select the most efficient combination of the processes. Hence, section 6.2 explains the considered data pre-processing routines and the initial solution constructing method. The Parallel Tabu Search common with the two included local search operators are explained in section 6.3. The part 6.4 contains the demonstration of performance of the post-optimization routines. The information on conducted experiments and all the considered problem solving approaches are provided in section 6.5. Finally, the discussion on the obtained results using as a support the summarizing tables, made observations and final resume are presented in section 6.6.

Methods for Initial Routing and Scheduling Module Solving Pickup and Delivery Vehicle Routing Problem with Time Windows

The investigated approaches for solving the addressed PDVRPTW consist of three consecutive steps. The objective of the first one is to construct the initial solution. For this step, there were examined three methods; each starting with a different strategy for ordering customers. There is introduced a new method which organizes the customers depending on the areas they belong to. The separated space sectors and the affiliation of the individual customers to each zone are determined using a *Neighbour Defining Function*. The efficiency of the introduced method was verified on the basis of comparison with other known methods. For that purpose, there were selected two approaches of different level of refinement: Simple Pairing and Sweep Algorithm.

To optimize the initial solution there was implemented an adapted version of the Unified Tabu Search (UTS) heuristic proposed by Cordeau et al., 2001. Originally it was designed and used to solve a VRPTW. It has been adjusted so as to be able to solve the addressed PDVRPTW problem. The main change regards the fact that each modification of a route concerns a pickup-delivery couple instead of an individual customer. This feature affects the architecture and functioning of the UTS structures such as for example the adaptive memory, as well as the general performance of the selected local search operators, which need to consider the additional constraints of pairing and precedence.

In order to raise the efficiency of the PDP adapted UTS it was decided to introduce two local search processes performing synchronized and simultaneous lookup of the next move to execute. As a result, there was developed the Parallel Tabu Search (PTS) heuristic for the PDVRPTW.

It is a usual practice, to complement the Tabu Search heuristic with a post-optimization procedure. It is no different in the current thesis project. Thus, the additional improvement phase determines the third step of the investigated composed strategies. For this step, there were examined two methods: the Normal Pickup and Delivery Pair Rearrange Operator (NPDPRO) and the PDP adapted 2-opt algorithm. Their objective is to improve the solution obtained from the PTS procedure by changing the order of visits of the customers included within each route. The result has to be obligatorily feasible.

All the considered algorithms and heuristics, properly combined, provide varied approaches suitable for solving a PDVRPTW. They are schematically presented in Figure 6.1. The main aim of this study is to observe how each of the individual methods affects the performance of the entire strategy. Also, to compare the quality of operation of the algorithms employed at the same level in order to identify the ones which bring the biggest savings in terms of calculation time and the final solutions' cost.

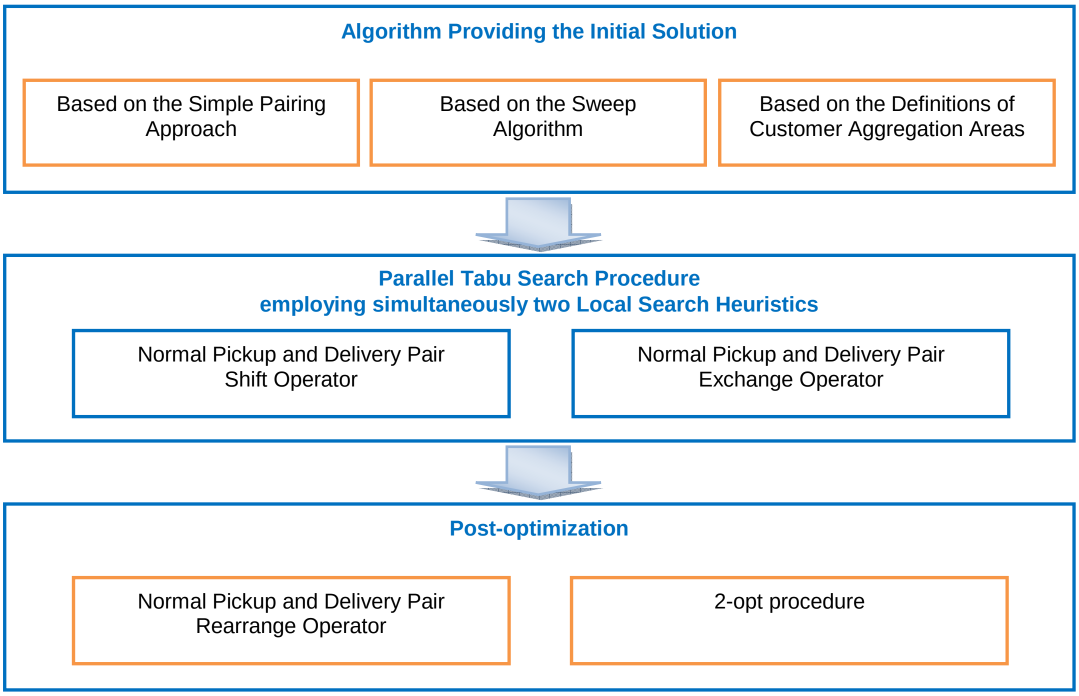


Figure 6.1 Scheme of composite methods considered to construct a complete meta-heuristic solving the addressed PDVRPTW. The orange colour marks the heuristics which constitute examined alternatives

The performed overview of the literature allowed to conclude that so far there has not been proposed and published a summary containing all the results from the implementation of the well-known approaches for solving the PDVRPTW. Such outline can serve as a reference point and not only to help compare the methods among themselves but also allow for assessment of quality of operation of the newly proposed ones. It was also noted that each publication providing a new proposal of a PDVRPTW solving approach in order to estimate its quality compares the obtained results in the output of the method used as a reference, indicating the number of instances in which a better outcome was reached. It is also pointed out by how much the new result is better and how much time was needed in order to conduct the computational tests. However, there was not found a general way of evaluating the complete performance of an approach.

As a consequence, in the final section of the current chapter there is proposed a simple method for which the objective is to estimate the quality of operation of approaches solving the PDVRPTW on the basis of comparison. It permitted to select from all the tested compositions of procedures the one, which in overall performs the best.

The testing benchmarks used to evaluate the performance of each component heuristic and the composed approaches as a whole, consider Euclidean distances. A detailed analysis of the used data and the explanation how they got adapted in order to serve the purposes determined in the present thesis project are provided in Appendix A.

6.1 Notation

Let n denote the number of the customers who require either pickup or delivery service that shall be provided by a fleet of k homogenous vehicles assembled in a single depot. Each customer i is associated a demand d_i, a service duration time s_i, and time window $[e_i, l_i]$. If the customer i requests pickup it is defined as i^+ and as $p(i^+)$ or i^- in the case when the demanded service considers delivery. In figures, the customers are marked as red triangles and described as P - pickup, or D - delivery with a supplementary number denoting a pair to which they belong. The depot is identified as 0 and its demand q_0 and service time s_0 are equal to zero, since neither pickup nor delivery service takes place there. In addition, its time window $[e_0, l_0]$ marks the limits of the available time horizon of realisation of the trips.

Furthermore, let G be a complete graph $G=(V, A)$, where $V=\{0, 1,\ldots, n\}$ is the set of the nodes representing the customers and $A=\{(i, j):i\ j \in V, i \neq j\}$ is the set of arcs constituting the paths that join them. Each arc is associated a nonnegative cost c_{ij} that designates the travel time from customer i to j, where $c_{ij}\neq 0$ and $c_{ij}=c_{ji}$, for every i and j.

The solution is composed by the set of the routes and fulfils the following restrictions:

- each route starts and ends at the depot (the depot's out- and in-degree constraints),
- every pair of the customers belongs exactly to one route (the pairing constraint),
- the pickup customer of the pair is always visited before its corresponding delivery partner (the precedence constraint),
- the accumulated amount of the cargo that might be loaded on the vehicle cannot exceed its capacity (the capacity constraint),
- the service time at the customer i begins and finishes within the time interval $[e_i, l_i]$ (the time window constraint),

- each route is performed within the $[e_0, l_0]$ time interval (the duration constraint), such that $e_0 \le e_i \le l_i \le l_0$,
- the entire routing cost is minimized.

It is also assumed that:

K : is the set of the vehicles in a fleet which number is equal to k,
Q : is the total single vehicle capacity,
N : is the set of customers that $\mathbf{N}=N^+ \cup N^-$,
N^+ : is the set of all the customers that notify a pickup request,
N^- : is the set of all the customers that notify a delivery request,
N_k : is the set of the customers that will be visited by the vehicle k,
m : number of pairs of customers,
d_i : is the size of the customer's demand that will be picked up/delivered at $i^+/p(i^+)$, where $d_{i^+}=d_{p(i^+)}$, $i^+ \in N_k^+$ and $p(i^+) \in N_k^-$,
q_{ik} : is the dimension of the occupancy of the vehicle's k capacity after visiting the customer i,
e_i : instant of time window opening at customer i; it is the earliest moment when vehicle may start giving service to customer i,
l_i : instant of time window closing at customer i; it is the latest moment when vehicle may start giving service to customer i,
a_i : is the arrival time at the customer i,
w_i : is the waiting time at the customer i, that $w_i=\max\{0, e_i - a_i\}$,
b_i : is the start service time at the customer i, that $b_i=a_i+w_i$.

6.2 Description of Heuristics Providing Initial Solution

In the search for an appropriate approach providing the optimal initial solution, there were reviewed three methods based on varied principles regarding the inaugural customers ranking. This process is of special importance due to the fact that the order, in which the individual customers are introduced into the routes, significantly influences the quality of the solution obtained at the end. Although the preliminary data preparation is different for each method, they share the same general organization scheme, which consists of the following steps:

1. Data pre-processing:
    1.1. Construct an ordered list of all the customers.
    1.2. Divide the customers into sub-lists according to one specific rule:
        a. by pair,
        b. by angle,
        c. by area.
2. Construct initial routes.

The initial solution creating procedure, was adapted to the addressed PDP in such a way that both pairing and precedence constraints are respected. Also, the initial solution is always feasible with respect to the vehicles' capacity restrictions. However, it might violate the initial assumption regarding the number of available vehicles. This relaxation is permitted at the early stage of the heuristic since the initial solution will be optimized in the subsequent steps.

The subsequent sections include descriptions of the specific data pre-processing routines. In order to illustrate the characteristic differences between them, on the basis of the same data set, there were prepared graphical examples showing their functioning. The routes constructing step, which is common for all these methods is shown next.

6.2.1 Initial Data Pre-Processing Method Based on Simple Pairing Approach

This preparation process is grounded on a very simple idea. Starting from the complete list containing all the considered customers, there are constructed as many sub-lists as defined customer pairs. The structure obtained in this way determines the input for the routes creation algorithm, which results in building of a collection of routes with a specific feature: each contains only one couple.

customers ordered in sub-lists

sub-list	customers
1	P1, D1
2	P2, D2
3	P3, D3
4	P4, D4

Table 6.1 Result of the data pre-processing method based on simple pairing approach, using the example of four pickup-delivery customer pairs

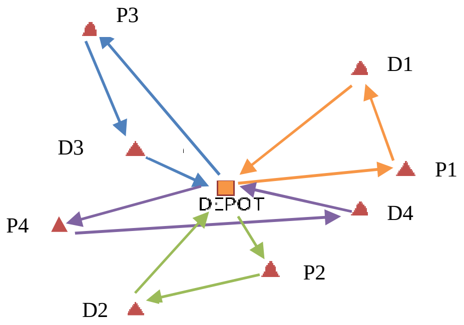


Figure 6.2 Graphical representation of the outcome of the routes' construction process, when the customers are initially ordered by pair

6.2.2 Initial Data Pre-Processing Method Based on Sweep Algorithm

The Sweep Algorithm is a method, in which all the customers are sorted in increasing order of the angle that they make with the depot and an arbitrary radius. Firstly, if it is not already the case, the centre of the Euclidean reference system has to be transferred and settled at the position of the depot. As a result, the coordinates of all the customers' locations must also be updated. Next, there is defined a circulating ray, which fixed end is set in the depot and the depart position of the other, progressing end, is determined either by a randomly chosen or fixed point. Both of these options were tested during the research in various combinations of the composite heuristics. In order to distinguish them within the general description of the approach they were defined as: the Sweep

Algorithm with *random* or *fixed* starting point, accordingly. In the latter case, it was established that the virtual radius always starts its journey from the spot, where the value of the obtained angle is equal to $-\pi$. Consequently, the general span of the considered angles ranges from $-\pi$ to π. While the ray describes a full circle it places in a list all the customers it comes across with during the process. Its motion is anticlockwise.

The next step of the approach regards the division of the prime list of the customers into separated sections. In order to achieve that, the entire circle area drawn by the ray is divided into pieces of equal size. The customers contained in each cut are properly included in a corresponding sub-list. At this stage, there are considered three possibilities regarding the amount of constructed listings equal to the number of: involved customers, available vehicles or one. The objective of this operation was to check in which way the manner of data segmentation affects the whole algorithm constructing the initial solution.

The final information preparation step includes ordering the customers included within each sub-list according to their distance from the depot, so that the iterative process of routes construction would always start from the customers located the farthest. It is due to the fact, that their introduction into the existing routes is the most troublesome.

The functioning of both considered variants of the Sweep Algorithm can be presented on the following scheme:

```
1. Let $L$ be the list of all the customers $L=V\setminus\{0\}$,
2. Sort all the customers by increasing angle $\angle A0S$, where:
       $S$:= current customer,
       0:= depot,
       $A$:= according to the chosen variant is either randomly chosen or fixed reference point = $-\pi$.
3. Divide $L$ into $k$ sub-lists such that each sub-list $l$ satisfies:
       $\angle A0S \in \left( \frac{2l-2-k}{k}\pi, \frac{2l-k}{k}\pi \right], \forall l \in K = \{1,\dots,k\}$
4. Sort all the customers in each sub-list $l$ in decreasing order according to the travel cost between
   the depot and the customer.
```

Algorithm 6.1 Sweep Algorithm with fixed and random starting point

Using the previously introduced example of 4 pickup/delivery customer pairs and 4 available vehicles, which define the number of constructed sub-lists, the complete process might be also presented graphically in Figure 6.3. The initial data, the results of the sweep and the ranging steps for both variants of the algorithm are presented in the corresponding tables.

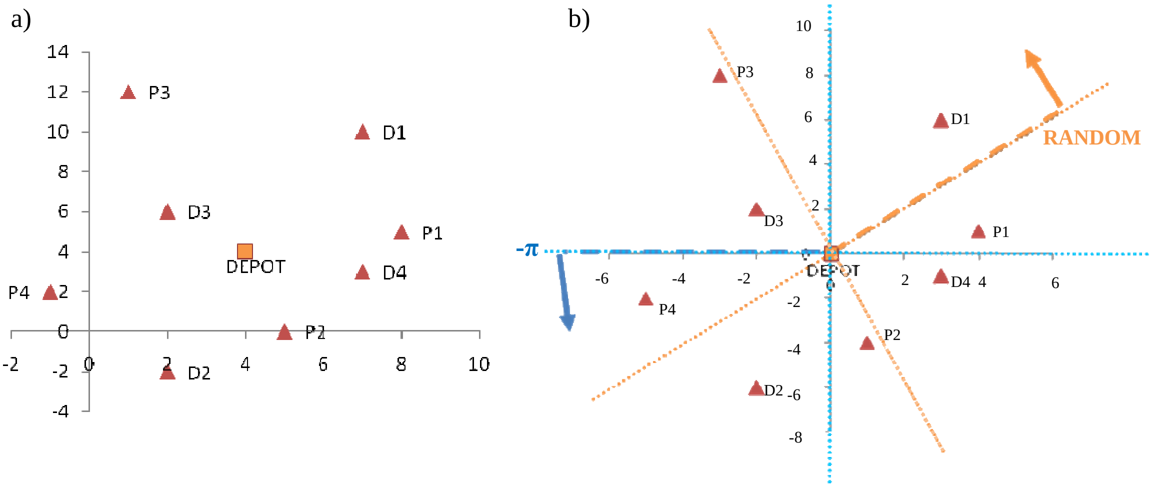


Figure 6.3 Consecutive steps of Sweep Algorithm using the example of four PD customer pairs that might be served by four available vehicles: (a) original data, (b) the intersection of the reference system's axis is placed at the depot; customers' coordinates are updated; two swapping rays characteristic for each method are selected; the space is divided in as many pieces as the number of available vehicles

A

customers	original coordinates x	y
P1	8	5
P2	5	0
P3	1	12
P4	-1	2
D1	7	10
D2	2	-2
D3	2	6
D4	7	3
P1	8	5
P2	5	0
DEPOT	4	4

B

customers	modified coordinates x	y
P1	4	1
P2	1	-4
P3	-3	8
P4	-5	-2
D1	3	6
D2	-2	-6
D3	-2	2
D4	3	-1
P1	4	1
P2	1	-4
DEPOT	0	0

C
customers by sweep angle (fixed start point)

sub-list	customers
1	P4, D2
2	P2, D4
3	P1, D1
4	P3, D3

D
customers by distance from the depot (fixed start point)

sub-list	customers
1	D2, P4
2	P2, D4
3	P1, D1
4	D3, P3

E
customers by sweep angle (random start point)

sub-list	customers
1	D1
2	P3, D3, P4
3	D2, P2
4	D4, P1

F
customers by distance from the depot (random start point)

sub-list	customers
1	D1
2	D3, P3, P4
3	P2, D2
4	D4, P1

Table 6.2 Functioning of Sweep Algorithm. The tables represent correspondingly: (A) initial data of the customers' locations; (B) actualized customers positions; (C, E) result of the sweep step presented as a list of sub-list containing all the customers arranged by the growing angle that they make with the deport and an arbitrary radius; (D, F) final result as a list of sub-lists containing the customers arranged by the decreasing distance from the depot

6.2.3 Initial Data Pre-Processing Method Based on Definitions of Customer Aggregation Areas

When analyzing the benchmark data (presented in Appendix A) it was noticed, that in some test cases it was possible to clearly distinguish aggregations of customers on the plane. This situation is very common in real life, when the customers expecting to send/receive cargo of similar type, are oftentimes located close to each other e.g.: in the case of residential areas, business centres or industrial zones. In this case, a frequent, although intuitive, solution is to assign the nearby customers to the same vehicle route. This reasoning became the inspiration for creating the data pre-processing algorithm, according to which the customers can be arranged depending on the grouping to which they belong. For the purposes of this project, the customer aggregations are denoted as the *neighbourhood areas*.

In order to define the customers as neighbours from the same aggregation area, there was specified a *Neighbour Defining Function* according to which, each customer localised within the range determined by the *reference distance*, are included within the neighbourhood area. The reference distance is calculated in one of the first steps of the algorithm. It is preceded by the determination of the first node, which is placed the closest to the depot and its most proximate neighbour. The doubled value of the distance between these two customers designates the reference distance. Its value is different for each neighbourhood area.

The scheme of performance of the complete method is presented in a form of a pseudo-code as follows:

```
Let $L$ be the list of sub-lists to be obtained
Let $N$ be the list of all the customers $N=V\setminus\{0\}$
Sort all the customers in $N$ by increasing distance from the depot
While $N > 0$
    Let $l$ be the sub-list of initial size = 0
    Let $i$ be the current node and the first of $N$
    Append the current node $i$ to the sub-list $l$
    Remove $i$ from the list $N$
    Let $j$ be the closest node to $i$ from all the nodes of $N$
    Append the closest node $j$ to the sub-list $l$
    Remove $j$ from the list $N$
    Let $d$ be the distance from node $i$ to $j$
    For each node $h \in l$
        For each node $g \in N$
            If distance from $h$ to $g$ is $< 2d$ then
                Append the node $g$ to the sub-list $l$
                Remove the node $g$ from the list $N$
            End If
        End For
    End For
    Append the sub-list $l$ to the main list $L$
End While
```

Algorithm 6.2 Initial data pre-processing method based on the definitions of customer aggregation areas

The functioning of the data pre-processing method based on the definitions of customer aggregation areas may also be presented graphically. The previously used example of four customer pairs is not representative from the point of view of this method since there would be constructed only one neighbourhood area (its result is presented in Table 6.3). For this reason, in order to illustrate the performance of the method there was used a more complex sample shown in Figure 6.4. The circles mark the neighbour search areas, for which the ray is defined as doubled distance between the customer closest to the depot (P1, D6, D5) and his most proximate neighbour (P4, P6, P8 accordingly). Their fading colours indicate the progress made in the sequence of the iterations. For enhanced clarity, the consecutively obtained results are presented in Table 6.4.

order of insertion	customers ordered in sub-list
1	D3
2	P1
3	P4
3	D4
1	P3
2	D1
4	P2
4	D2

Table 6.3 Functioning of the initial data pre-processing method based on the definitions of customer aggregation areas using the example of four customer pairs provided in Table 6.1

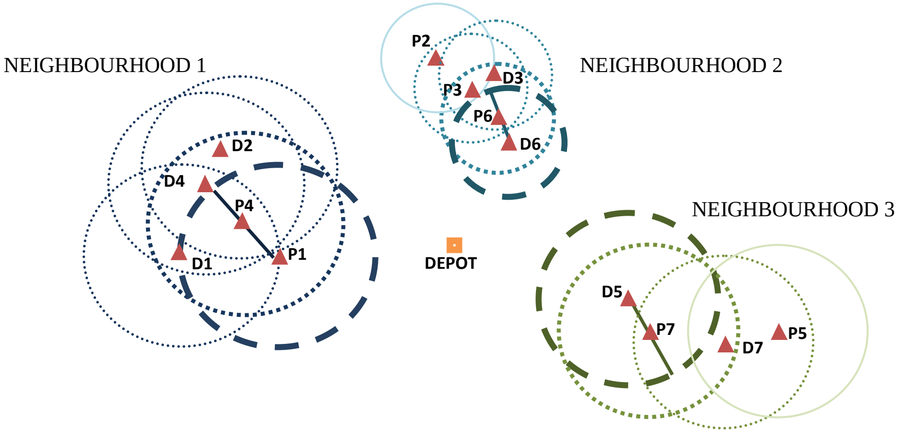


Figure 6.4 Functioning of the initial data pre-processing method based on the definitions of customer aggregation areas

sub-list	customers closest to the depot	closest neighbour	iteration	centre of neighbourhood area result accumulated in a sub-list	customers found within the current neighbourhood area
1	P1	P4	1	P1	P4, D1
			2	P4	D4, D2
			2	D1	-
			3	D4	-
			3	D2	-
2	D6	P6	1	D6	P6
			2	P6	P3, D3
			3	P3	P2
			3	D3	-
			4	P2	-
3	D5	P7	1	D5	P7
			2	P7	D7
			3	D7	P5
			4	P5	-

Table 6.4 Result of the consecutive steps of the initial data pre-processing method based on the definitions of customer aggregation areas

6.2.4 Initial Solution Constructing Method

The second step of the initial solution constructing approach is performed on the ground of the simple insertion procedure, according to which, the pairs of customers are introduced in a route in such a way that the increment of its cost is minimal and the considered constraints regarding: vehicles capacity, TWs, pairing and precedence rules are respected. It is assumed that the number of obtained routes does not have to be smaller or equal to the number of the available vehicles. This may especially be the case when the initial routes are created implementing beforehand the data pre-processing method based on the simple pairing approach.

The initial routes constructing method uses as input, the obtained in the previous step, composed structure containing a sequence of sub-lists. Each sub-list comprises a sequence of customers which are ordered according to their distance from the depot. The procedure may start from the first or the last sub-list in a row and follow the increasing/decreasing order respectfully. Each one of them is assigned with one vehicle.

The first customer, which is located the farthest from the depot, common with its corresponding partner, is used to create the *original route* including: depot-pickup customer-delivery customer-depot. The outcome is in accordance with all the imposed constraints. In the following step, from the current sub-list the next in line customer is selected and its partner is determined. The pickup member of this couple is inserted into the original route first. In order to ensure the automatic compliance with precedence constraint, the customer requiring delivery is always placed in such position in the route, which is localized behind the pickup. For this reason, the feasibility checking routine never verifies if the precedence restriction is fulfilled. It is always respected by default alike the pairing rule. The insertion of customers is an iterative process during which all the possible variants of locations for both customers are checked and evaluated with respect to the final cost of the route. The chosen route alternative is the one, which cost is minimal in comparison with the others and which complies with the imposed restrictions. Once the couple is inserted it is deleted from the sub-lists. However, in the case, when the introduction of a couple into the current route is not feasible, it gets eliminated from the sub-lists and placed in a separated list. Those "problematic" customers will be inserted in new routes at the very end of the process following the same simple insertion procedure. The algorithm's performance is finished when all the sub-lists are empty and every customer is inserted in one original route. The sub-lists, which were empty from the start, are not considered during the process and their associated vehicles might be used to serve the "problematic" customers or simply remain housed at the depot. The final collection of the created routes is used as a starting point of the Tabu Search procedure.

This simple insertion algorithm is presented in a form of a pseudo-code as demonstrated by the Algorithm 6.3.

```
Let $L$ be the list of $k$ organised sub-lists obtained by a chosen data pre-processing method
Let $R$ be the set of routes to be constructed
stopAlgorithm=False
While (stopAlgorithm=False) Do
    Let $Z=\emptyset$ be the set of customers which insertion is not feasible
    For each sub-list $l\in L$
        Let $r_k$ be the route to be constructed and $r_k=\{0, 0\}$
        Let $c_{rk}$ be the cost of the route $r_k$
        For each node $i\in l$
            Find pair partner $p(i)$ of $i$ in $L$
            If $r_k=\{0, 0\}$
                $r_k$=insert node $i^+$ in arc $(0, 0)$
                $r_k$=insert node $p(i^+)$ in arc $(i^+, 0)$
            Else
                Let $r_k*$ be the best feasible route found and $r_k*=\emptyset$
                Let $c_{rk}*$ be the best route cost and $c_{rk}*=\infty$
                For each integer $h\in\{1$, size of $r_k - 1\}$
                    For each integer $j\in\{h+1$, size of $r_k - 1\}$
                        If insertion of nodes $i^+$, $p(i^+)$ in arcs: $(h, h+1)$, $(j, j+1)$ is feasible and $c_{rk}\leq c_{rk}*$
```

```
                            $r_k$*=$r_k$
                            $r_k$*=insert node $i^+$ in arc ($h$, $h$+1)
                            $r_k$*insert node $p(i^+)$ in arc ($j$, $j$+1)
                            $c_{rk}$*= $c_{rk}$
                        End If
                    End For
                End For
                If $r^*$ is empty
                    Remove the nodes $i^+$ and $p(i^+)$ from the list $Z$
                End If
            End Else
            Remove the nodes $i^+$ and $p(i^+)$ from the list $L$
        End For
        If $Z \neq \emptyset$
            $L$=$Z$
        Else
            stopAlgorithm=true
        End Else
    End For
End While
```

Algorithm 6.3 Initial solution constructing algorithm based on simple insertion Greedy method

The graphical representation of the possible result of the initial solution constructing algorithm considering the previously introduced example of four pickup-delivery customer pairs is shown in Figure 6.5. The process starts using as input the sub-list structure obtained by the initial data pre-processing method based on the Sweep Algorithm with both random and fixed starting point. It clearly demonstrates how strongly the data pre-processing affects the final result of the routes creation process.

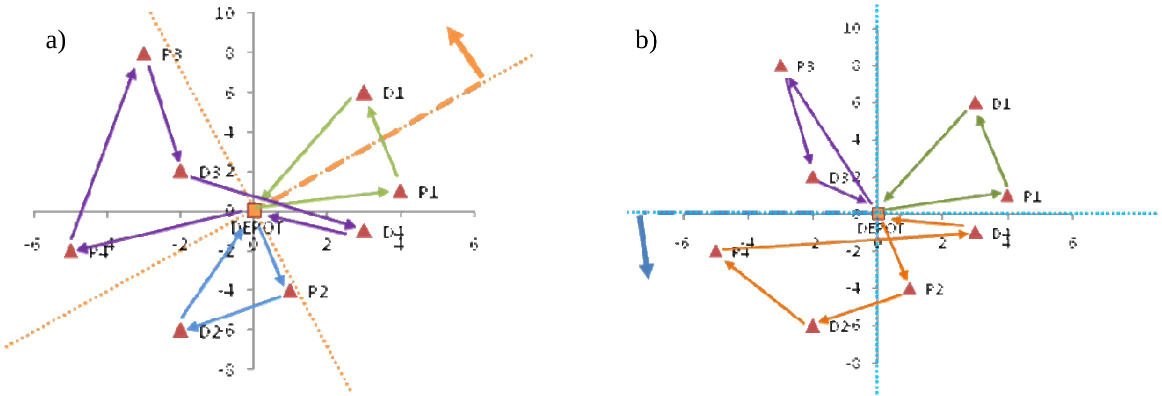


Figure 6.5 Result of initial solution construction algorithm using as input the sub-list structure obtained by the preliminary data pre-processing method based on Sweep Algorithm with: (a) random and (b) fixed starting point (the used example considers four customers pairs and four vehicles)

Sweep Algorithm with random starting point

	routes options	cost
Route 1	P1, D1	13.65974
Route 2	P3, D3, P4, D4	30.85130
	P3, P4, D3, D4	32.73527
	P3, P4, D4, D3	35.46368
	P4, P3, D3, D4	**30.65920**
	P4, P3, D4, D3	35.05924
	P4, D4, P3, D3	33.17527
Route 3	P2, D2	14.05321
Solution Cost		**58.37214**

Sweep Algorithm with fixed starting point

	routes options	cost
Route 1	**P2, D2, P4, D4**	**23.95319**
	P2, P4, D2, D4	25.68101
	P2, P4, D4, D2	31.90554
	P4, P2, D2, D4	25.54862
	P4, P2, D4, D2	28.71089
	P4, D4, P2, D2	26.98308
Route 2	P1, D1	13.65974
Route 3	P3, D3	17.45519
Solution Cost		**55.06812**

Table 6.5 Result of the consecutive steps of the initial solution constructing method using data obtained by the pre-processing method based on Sweep Algorithm with random and fixed starting point accordingly

Considering the same example of four customer pairs, in the case when for the initial routes construction there was used the collection of data pre-processed according to the method based on the definitions of customer aggregation areas, the final result significantly differs from the previously obtained. Since it starts from only one sub-list of ordered customers it creates only one route. Because of that fact, it is possible to clearly present the functioning and the main idea on which the approach of routes constructing is based on. Moreover, it becomes visible that the number of sub-lists prepared at the start is not without significance. That is the reason why, in the performed research, when using the Sweep Algorithm procedure there are considered three scenarios; each defining a different number of ordered sets of customers.

The functioning and the final result of the initial routes constructing method using the data on the customers organized by the area they belong to is shown in Table 6.7.

The data pre-processing method assembled with the routes constructing algorithm determines an opening step of the entire PDVRPTW solving approach. Depending on the chosen routine of ordering customers, the obtained result differs, which has direct impact not only on the initial solution, but also on the final outcome. On the basis of the simple example containing four customer pairs, it was demonstrated how important is the proper selection of the individual methods already at the beginning of the problem solving process. The concluding resume is presented in Table 6.6.

Once the initial routes are constructed they are subjected to the optimization process. In this case the Parallel Tabu Search heuristic is used, including two local search operators.

data pre-processing method based on	initial solution's cost
Simple Pairing Approach	61.77784
Sweep Algorithm with fixed starting point	55.06812
Sweep Algorithm with random starting point	58.37214
Definitions of Customer aggregation Areas	**44.49118**

Table 6.6 Costs of the final results obtained by the initial routes construction algorithm based on three different data pre-processing routines

iteration	customers' pair to insert	routes alternatives										cost
1	P3, D3	**0**	**P3**	**D3**	**0**							**17.45519**
	P1, D1	0	P3	D3	**P1**	**D1**	0					27.1634
		0	P3	**P1**	D3	**D1**	0					37.30444
		0	P3	**P1**	**D1**	D3	0					33.25309
		0	**P1**	**D1**	**P3**	**D3**	**0**					**22.18728**
		0	**P1**	P3	**D1**	D3	0					32.32832
		0	**P1**	P3	D3	**D1**	0					35.96631
2	P4, D4	0	**P4**	**D4**	P1	D1	P3	D3	0			36.39874
		0	**P4**	P1	**D4**	D1	P3	D3	0			37.10619
		0	**P4**	P1	D1	**D4**	P3	D3	0			43.42672
		0	**P4**	P1	D1	P3	**D4**	D3	0			42.49946
		0	**P4**	P1	D1	P3	D3	**D4**	0			38.09942
		0	P1	**P4**	**D4**	D1	P3	D3	0			42.90639
		0	P1	**P4**	D1	**D4**	P3	D3	0			50.64994
		0	P1	**P4**	D1	P3	**D4**	D3	0			49.72268
		0	P1	**P4**	D1	P3	D3	**D4**	0			45.32264
		0	P1	D1	**P4**	**D4**	P3	D3	0			46.05534
		0	P1	D1	**P4**	P3	D4	D3	0			47.93931
		0	P1	D1	**P4**	P3	D3	D4	0			43.53927
		0	P1	D1	P3	**P4**	**D4**	D3	0			40.19576
		0	P1	D1	P3	**P4**	D3	**D4**	0			37.46736
		0	**P1**	**D1**	**P3**	**D3**	**P4**	**D4**	**0**			**35.58339**
3	P2, D2	0	**P2**	**D2**	P1	D1	P3	D3	P4	D4	0	48.18894
		0	P2	P1	**D2**	D1	P3	D3	P4	D4	0	59.65394
		0	P2	P1	D1	**D2**	P3	D3	P4	D4	0	61.19348
		0	P2	P1	D1	P3	**D2**	D3	P4	D4	0	56.43527
		0	P2	P1	D1	P3	D3	**D2**	P4	D4	0	48.48237
		0	**P2**	**P1**	**D1**	**P3**	**D3**	**P4**	**D2**	**D4**	**0**	**44.49118**
		0	P2	P1	D1	P3	D3	P4	D4	**D2**	0	50.71571
		0	P1	**P2**	**D2**	D1	P3	D3	P4	D4	0	54.25949
		0	P1	**P2**	D1	**D2**	P3	D3	P4	D4	0	68.56309
		0	P1	**P2**	D1	P3	**D2**	D3	P4	D4	0	63.80488
		0	P1	**P2**	D1	P3	D3	**D2**	P4	D4	0	55.85198
		0	P1	**P2**	D1	P3	D3	P4	**D2**	D4	0	51.86079
		0	P1	**P2**	D1	P3	D3	P4	D4	**D2**	0	58.08532
		0	P1	D1	**P2**	**D2**	P3	D3	P4	D4	0	57.09809
		0	P1	D1	**P2**	P3	**D2**	D3	P4	D4	0	68.05889
		0	P1	D1	**P2**	P3	D3	**D2**	P4	D4	0	60.10598
		0	P1	D1	**P2**	P3	D3	P4	**D2**	D4	0	56.11479
		0	P1	D1	**P2**	P3	D3	P4	D4	**D2**	0	62.33933
		0	P1	D1	P3	**P2**	**D2**	D3	P4	D4	0	53.75529
		0	P1	D1	P3	P2	D3	**D2**	P4	D4	0	56.85794
		0	P1	D1	P3	P2	D3	P4	**D2**	D4	0	52.86675
		0	P1	D1	P3	P2	D3	P4	D4	**D2**	0	59.09128
		0	P1	D1	P3	D3	**P2**	**D2**	P4	D4	0	45.89714
		0	P1	D1	P3	D3	P2	P4	**D2**	D4	0	47.62496
		0	P1	D1	P3	D3	P2	P4	D4	**D2**	0	53.84949
		0	P1	D1	P3	D3	P4	**P2**	**D2**	D4	0	44.52230
		0	P1	D1	P3	D3	P4	**P2**	D4	**D2**	0	47.68458
		0	P1	D1	P3	D3	P4	D4	**P2**	**D2**	0	45.95677

Table 6.7 Result of the consecutive steps of the initial solution constructing method using data obtained by the pre-processing method based on the definitions of customer aggregation areas

6.3 Parallel Tabu Search

The design of the Parallel Tabu Search approach proposed in the present chapter was inspired by work of Cordeau et al. (2001), where the authors employ the TS meta-heuristic for solving a VRPTW. In order to be able to apply the similar ideas to the PDVRPTW it was necessary to modify the complete procedure and to adapt its concepts to face the emerging challenges. The main change regards the fact that each modification of a route concerns a couple instead of an individual customer. This feature affects TS's structures such as for example the adaptive memory, as well as the general functioning of the selected local search operators, which need to consider the additional constraints of pairing and precedence. However, before explaining the general functioning of the PTS algorithm, it is necessary to introduce the key concepts on which the whole approach is based.

The *solution s* is determined as a set of feasible routes. The cost of the solution $c(s)$ is calculated as the sum of the travel, service and waiting times the vehicles spend on each route in order to satisfy the requests of all the assigned customers. Hence:

$$c(s) = \sum_{r_k \in R} c(r_k) \tag{6.1}$$

$$c(r_k) = a_0 = \sum_{i \in N_{r_k}} c_{i-1,i} + s_{i-1} + w_{i-1} \tag{6.2}$$

where, in addition to the variables presented in section 6.2:

R : set of routes determining solution s,
r_k : route included in solution s performed by vehicle k,
N_{rk} : all customers included in route r_k,
i : customer included in route r_k,
$c(r_k)$: cost of the route r_k,
a_0 : arrival time at the depot after visiting all the customers on the route,
$c_{i-1,i}$: cost of travel from customer i-1 (predecessor of customer i) to i,
s_{i-1} : service time spent at the customer i-1 (predecessor of customer i),
w_{i-1} : waiting time spent at the customer i-1 (predecessor of customer i).

The *solution's neighbourhood N*(s) is defined by a method, whose objective is to remove a pair of customers (i, $p(i)$) from a route and insert it in another one in the most favourable location determined by the minimal increment of the solution's cost. In the present project, this task is performed by the selected PDP adapted local search operators: the Normal Pickup and Delivery Pair Shift Operator and the Normal Pickup and Delivery Pair Exchange Operator, which basic concepts of functioning were presented with details in Chapter 3. Hence, the descriptions provided in the present section consider coding of individual methods, the manner in which they were adapted to the addressed problem and the way they got incorporated into the complete procedure.

The couples are introduced in a new route in such a way, that every delivery customer is always inserted in the customers' sequence in a position located behind its corresponding pickup partner. In this way the precedence constraint is satisfied every time and does not require verification. Similarly, the pairing constraint is fulfilled automatically. The customers of the same couple never get separated.

Consequently, the feasibility check of current solution includes only the verification if either the vehicle's capacity or customers' TWs constraints are violated.

$$w(r_k) = \sum_{i \in N_{r_k}} \max\{0, a_i - l_i\} \tag{6.3}$$

$$q(r_k) = \sum_{i \in N_{r_k}} \max\{0, q_i - Q\} \tag{6.4}$$

where:

$w(r_k)$: aggregated value of the TWs violation occurring in route r_k,
$q(r_k)$: aggregated value of the vehicle's k capacity violation.

Some authors consider also the constraint regarding the limit of the available time the fleet of vehicles has to perform all the transportation tasks. In general, this upper bound corresponds to the instant of depot's time window closing. It is no different in the present project. In the proposed approach, the way in which the individual routes are constructed considers the depot as the first and the last location of the complete sequence. Hence, the violation of the permitted time duration is checked as a part of the verification if all the TW are fulfilled. For this reason, this constraint is not taken into consideration as separate restriction.

The solution is considered to be feasible, when the summarized values of the violations of the TWs occurring in all the routes are equal to zero. Similarly, the aggregated value of all vehicles' capacity violations must not have a positive value. Within the proposed approach there was introduced the *route's valuation function*. It is the most often executed routine, which calculates the values of the constraints' violations, aggregated waiting times and complete cost of the route. The pseudo-code of this procedure is presented in the description of the Algorithm 6.4.

The values of constraints' violations are used in the process of the objective function's calculation, as well as for determining the rate of the penalties, which need to be imposed for not complying with initial restrictions. These costs are calculated according to the following formulas:

$$f(s) = c(s) + \alpha \cdot q(s) + \beta \cdot w(s) \tag{6.5}$$

$$p(s) = \lambda \cdot c(s) \cdot \sqrt{n \cdot k} \cdot \varphi(s) \tag{6.6}$$

$$\Delta = f(s) + p(s) \tag{6.7}$$

where:

$f(s)$: cost evaluating function for the solution s,
$p(s)$: penalties evaluating function for the solution s,
Δ : objective function,
α : parameter related to the violation of the vehicle's capacity constraint,
β : parameter related to the violation of the TWs constraint,
λ : scaling factor,
$\varphi(s)$: parameter controlling the addition frequency.

```
Let $r_k$ be the route to valuate
Let $d_t$=0 be the temporal demand
Let $d_i$ be the value of demand of customer $i$
Let $q(r_k)$=0 be accumulated value of vehicles capacity violation
Let $w(r_k)$=0 be accumulated value of TWs violation
Let $c(r_k)$=0 be the cost of route $r_k$
Let $Q$ be the vehicles capacity
Let customer $j$ be the predecessor of the customer $i$
For each customer $i \in r_k$
    $d_t=d_t+d_i$
    If $d_t>Q$
        $q(r_k)=q(r_k)+(d_t-Q)$
    End if
    Let $e_i$ be the customer's $i$ time window lower bound
    Let $l_i$ be the customer's $i$ time window upper bound
    Let $c_{ji}$ be the cost of travel from customer $j$ to customer $i$
    Let $a_i$ be the arrival time to customer $i$
    Let $s_j$ be the service time spent at customer's $j$
    Let $w_j$ be the waiting time spent at customer's $j$
    $a_i=a_i+c_{ji}+s_j+w_j$
    If $a_i<e_i$
        $w_i=e_i-a_i$
    Else
        $w_i=0$
        If $a_i<l_i$
            $w(r_k)=w(r_k)+(a_i-l_i)$
        End if
    End else
End for
$c(s)=a_i$
```

Algorithm 6.4 Route-valuation function

Some of the above mentioned parameters are dynamically adjusted. At the end of each PTS's iteration the newly obtained solution s is evaluated. If it is feasible according to the vehicle's capacity constraint $q(s)$, the rate of α gets divided by the sum of $(1+\sigma)$, where σ is a parameter of fixed value equal to 0,5. In the contrary case α is multiplied by the same figure. The identical rules apply for updating β related to the violation of the TWs constraint $w(s)$.

The incorporation of penalization in the objective function calculation aims to diversify the search process towards novel or not very thoroughly checked areas, in the situations when the local optimum was reached. Included in the penalty calculating formula factor λ has a fixed value equal to 0,015. Its goal is to control the diversification's intensity. The same objective has the *addition frequency parameter* $\varphi(s)$, which is calculated as the sum of number of times each pair m has been introduced into a route served by the vehicle k during the best solution search process:

$$\varphi(s) = \sum_{(m,r_k)\in B(s)} \rho_{m,r_k} \tag{6.8}$$

where:

$B(s)$: adaptive memory matrix,
ρ_{m,r_k} : number of times the pair m has been introduced into route visited by vehicle k.

The value of $\varphi(s)$ is updated regularly after the completion of each PTS's iteration. The data needed for its calculation is stored in the *adaptive memory structure*, which takes the form of a matrix $B(s)$. Its columns determine all the customers' pairs considered in the problem and the rows define the routes to perform by the assigned vehicles k. Each cell contains two variables: *tabu status* and *permanence memory*. The first one defines the number of iterations θ of the PTS procedure during which it is forbidden to perform the movement of incorporating the selected pair into the determined route. It is when the manoeuvre is considered tabu. The permanence memory determines how many times the pair m has been introduced into the route k. The values of both variables are initially established equal to zero, but they are cyclically updated. When a feasible insertion of a pair m into a new route is executed, the value of the tabu status corresponding to the performed movement (row: route origin, column: removed pair m) is set as θ. It is equal to the integer number closest to the result of the formula included in the square bracket: $\theta=[7.5\log_{10}n]$. At the same time, the permanence memory gets summarized one: $\rho_{m,r_k}=\rho_{m,r_k}+1$ and stored in the appropriate memory matrix cell (row: route destination, column: inserted pair m). Moreover, at the beginning of each iteration, all the tabu statuses of positive value included in the $B(s)$ are reduced by one. It is due to the fact that as the iterations pass the number of the procedure repetitions during which the individual movements are prohibited decreases.

The way in which the adaptive memory structure operates is presented on the example shown in Figure 6.6 There are described three consecutive TS steps, where starting from the initial solution containing three routes, the individual pairs get shifted and placed in new locations. The parameters included within the $B(s)$ memory matrix get updated correspondingly in Table 6.8. The example considers only the pair shifting operator. However, in the case when the exchange of customer's pairs is performed, in order to update the parameters stored within the $B(s)$ matrix, it is necessary to modify four corresponding cells instead of two. Hence, in this context the pairs' exchange process might be seen as double shifting.

Although there was performed an experiments based search of the best initial values of used parameters, at the end there were used the figures proposed by Cordeau et al. (2001), since as a set they have proved to be the most efficient.

In the case, when there was found a move providing a solution, for which the cost is not only the smallest of all the solutions found in the searched neighbourhood, but also is smaller than the best, general solution found so far, although this movement's tabu status value is positive it can be accepted and executed since the ban can be revoked by the *aspiration criteria*. Its main requirement considers not only very favourable cost, but also the unconditional feasibility of the newly obtained outcome. If both of those conditions are satisfied the move is performed, its tabu status gets updated by once again being set equal to θ and the recently created solution is considered as the best found so far.

The whole PTS procedure is stopped when the a priori defined *stopping criteria* is fulfilled. In the case of the present project this was achieved by establishing the maximal number of permitted iterations for the complete PTS routine to execute. This figure is defined as κ and its top value can be no higher than 500. The choice of this number was based on the experiences of other authors studying the PDVRPTW (Chapter 3). Due to the selected stopping criterion the final summary tables of research results contain both the *Central Processing Unit* (CPU) time required to find the best solution, as well as the total CPU time required to execute the whole scenario during κ=500 iterations.

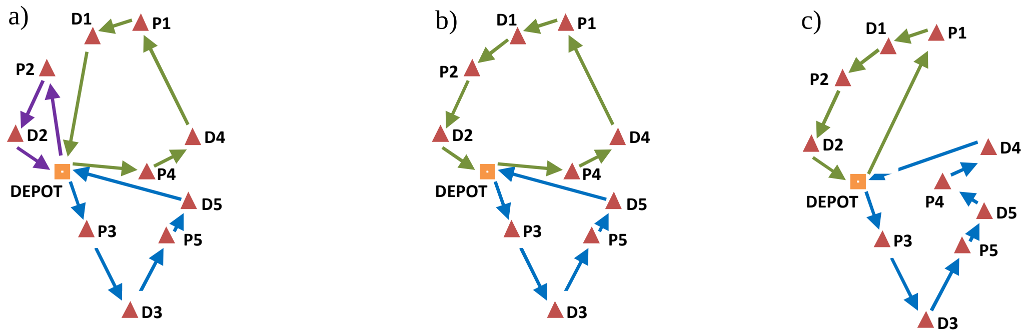


Figure 6.6 Outcomes of the consecutively performed routes' modification steps in TS procedure: a) initial solution containing three routes: R1 = {pair 2}, R2 = {pair 1, pair 4}, R3 = {pair 3, pair5}, b) pair 2 from route R1 got shifted to the route R2, c) pair 4 got shifted from route R2 to route R3

a)

***B*(s)**	**p1**	**p2**	**p3**	**p4**	**p5**
R1	0,0	0,0	0,0	0,0	0,0
R2	0,0	0,0	0,0	0,0	0,0
R3	0,0	0,0	0,0	0,0	0,0

$\varphi(s)=0,$

b)

***B*(s)**	**p1**	**p2**	**p3**	**p4**	**p5**
R1	0,0	**Θ**,0	0,0	0,0	0,0
R2	0,0	0,**1**	0,0	0,0	0,0
R3	0,0	0,0	0,0	0,0	0,0

$\varphi(s)=1,$

c)

***B*(s)**	**p1**	**p2**	**p3**	**p4**	**p5**
R1	0,0	**Θ-1**,0	0,0	0,0	0,0
R2	0,0	0,**1**	0,0	**Θ**,0	0,0
R3	0,0	0,0	0,0	0,**1**	0,0

$\varphi(s)=2$

Table 6.8 The adaptive memory matrix *B*(*s*) containing the record of the tabu status and permanence memory parameters changed according to the movements performed during the TS procedure: a)staring values initializes as zeros, b) updated cells (R1, p2) and (R2, p2) when pair 2 from route R1 got shifted to the route R2, c) updated cells (R1, p2), (R2, p4) and (R3, p4) when pair 4 from route R2 got shifted to the route R3

The parallelism was introduced into the TS routine by executing concurrently two local search operators in each iteration of the TS procedure. As a consequence, two different neighbourhoods of the same, currently best solution are created and searched. The whole exploration space gets expanded and the probability of the complete process to be entrapped within local optima is reduced. Among the best solutions found in each neighbourhood, the one which brings bigger benefits is selected for the final realisation.

Once all the basic concepts are explained the general scheme of the employed PTS procedure might be presented in a form of a pseudo-code as follows:

```
Let $\eta$ be the maximal number of permitted iterations
Let $\alpha$ and $\beta$ be the parameters of pre-established value equal to one
Let $\Delta$ be the value of the objective function supplemented with the values of added penalizations, if any
Let $s$ be the initial solution obtained in the previous step of the approach
```

```
Let $s^*$ be the best solution and $s^*=s$
Let $c(s^*)$ be the cost of the best solution
If the solution s is feasible
    Set $c(s^*)=c(s)$
Else
    Set $c(s^*)=\infty$
Let $B(s)$ be adaptive memory structure, whose arguments are initially set equal to zero
For all the iterations $\kappa<\eta$
    Execute in parallel the operators: NPDPSO and NPDPEO and create two neighbourhoods: $N(s)_S$ and $N(s)_E$ respectfully
    From each neighbourhood select a solution, which minimises the $\Delta$ function: $s_S$ and $s_E$
    Compute $q(s_S)$, $w(s_S)$ and $q(s_E)$, $w(s_E)$
    If solution $s_S$ is feasible and $c(s_S)<c(s^*)$ and $c(s_S)<c(s_E)$
        Set $s^*=s_S$ and $c(s^*)=c(s_S)$
    End if
    If solution $s_E$ is feasible and $c(s_E)<c(s^*)$ and $c(s_E)<c(s_S)$
        Set $s^*=s_E$ and $c(s^*)=c(s_E)$
    End if
    Update $B(s)$ according to the performed movement
    Update $\alpha$ and $\beta$
End for
Apply the post-optimization procedure to $s^*$
```

Algorithm 6.5 Parallel Tabu Search

The basic principles on which both local search operators are based on were presented for the case of the general VRP in Chapter 3. Notwithstanding, they could not be employed in the present project in their basic form and required to be adapted to the PDP. The main modification refers to the fact that instead of moving individual customers it is the couples of customers that get relocated. This fact affects the whole process since in addition to the vehicle's capacity and TWs constraints the complementary pairing and precedence restrictions must be taken into account.

As a consequence, all the operators employed both within the PTS and post-optimization procedures, contain the same part of special character, regarding the search of the best locations to insert the customers from the displaced couple. In each correspondingly introduced pseudo-code, this routine is referred to as: find the best insertion of the pair *m* in route r_k. Its functioning is explained in the presentation of the Algorithm 6.6. The objective is to clearly demonstrate the sequential manner in which first the pickup and then the delivery pair partner is introduced into the route r_k, so that both the pairing and the precedence constraints are always fulfilled.

```
Let $r_k$ be the destination route belonging to the current solution $s$
Let $r_k^*$ be the best route and $r_k^*=r_k$
Make valuation of best route $r_k^*$ => $q(r_k^*)$, $w(r_k^*)$, $c(r_k^*)$
Let $\alpha$ and $\beta$ be the parameters of known, actualized value
Let $f(r_k^*) = c(r_k^*) + \alpha \cdot q(r_k^*) + \beta \cdot w(r_k^*)$ be the value of the objective function of the best route $r_k^*$
Let $n$ be the number of customers in the route $r_k$ including the depot twice as route's source and sink
Let $m$ be the pair of customers $(i, p(i))$ to be inserted into the route $r_k$
Let $pos(h)$ be the position of node $h$ in the sequence of customers of route $r_k$
Let $pos(g)$ be the position of node $g$ in the sequence of customers of route $r_k$
Let $r_k'$ be the route to modify and $r_k'=r_k$
```

```
For each customer $h$ in route $r_k'$
    Insert the pickup customer $i$ behind the node at the position $pos(h)$
    Let $x$=1 be a variable whose maximal value cannot be bigger than $(n-1)$)
    For each customer $g$ in route $r_k'$ and $pos(g)=pos(h)+x$
        Insert the delivery customer $p(i)$ behind the node at the position $pos(g)$
        Make valuation of modified route $r_k'$ => $q(r_k')$, $w(r_k')$, $c(r_k')$
        Let $f(r_k') = c(r_k') + \alpha \cdot q(r_k') + \beta \cdot w(r_k')$ be the value of the objective function of the modified
        route $r_k'$
        If $f(r_k')<f(r_k^*)$ and route $r_k'$ is feasible
            $r_k^*=r_k'$
        End if
        $x=x+1$
        Remove customer $p(i)$ from route $r_k'$
    End for
    Remove customer $i$ from route $r_k'$
End for
```

Algorithm 6.6 Function searching for the best insertion locations in route r_k for the customers of the pair m

6.3.1 Normal Pickup and Delivery Pair Shift Operator

The objective of this operator is to remove a pair of customers from its original route and feasibly insert it in another route of the current solution, in such a way that its total cost is minimized. Its functioning is presented in Figure 6.7, where the origin and the destination routes are defined as A and B, respectively. The pair of customers moved to a new route is marked in orange, just like the arrows, which illustrate new connections. The dashed blue lines denote links between customers, which must be eliminated.

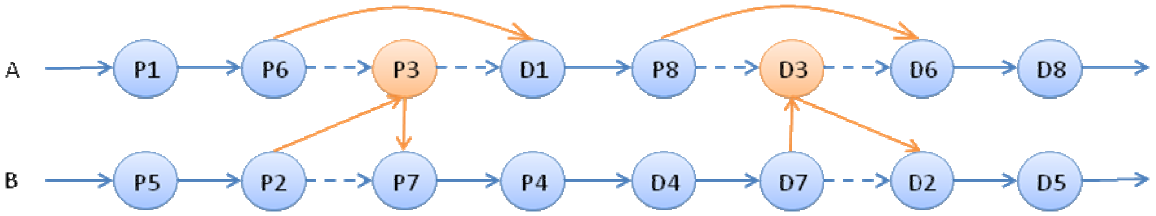


Figure 6.7 Pair Shift Operator

For the purposes of the present work, during the entire process all the pairs are successively moved and all the possible reinsertion locations in the existing routes are checked. Only the manoeuvre which is in accordance with all the a priori imposed restrictions shall be accepted. The fulfilment of the TWs and the capacity constraints need to be checked at the end of each transfer. However, as mentioned in the previous section the precedence and the pairing constraints do not require monitoring since they are automatically brought to completion by the process itself. Firstly, it is always a pair of customers that gets dislocated. And secondly, the pickup customer is consistently inserted as first and its delivery partner is every time introduced in the position placed behind it.

The complete procedure might be presented in a form of a pseudo-code provided by the Algorithm 6.7.

```
Let $n$ be the total number of customers
Let $k$ be the total number of vehicles
Let $s$ be the current solution containing a set of routes $R$
Make valuation of solution $s$ => $q(s)$, $w(s)$, $c(s)$
Let $s^*=s$ be the best solution with a cost $c(s^*)=c(s)$
Let $f(s^*)=\infty$ be the value of the objective function of the best solution $s^*$
Let $\Delta^*=\infty$ be the sum of $f(s^*)$ and the value of assigned penalization
Let $B(s)$ be the memory matrix
For each route $r_1 \in R$
    For each route $r_2 \in R$, such that $r_1 \neq r_2$
        For each customer $i \in r_1$
            Find pair partner $p(i)$ of customer $i$
            Let $m$ be the number defining the pair to which the customers $i$ and $p(i)$ belong
            Remove the customers $i$ and $p(i)$ from route $r_1$
            bool Tabu = FALSE
            If the value of the tabu status stored in $B(s)$ for route $r_2$ and pair $m$ is $\neq 0$
                Tabu = TRUE
            End if
            Find the best insertion of the pair $m$ in route $r_2$
            Make valuation of the newly obtained solution $s'$ => $q(s')$, $w(s')$, $c(s')$
            Let $f(s')$ be the value of the objective function of the newly obtained solution $s'$
            Let $\Delta=0$ be the be the sum of $f(s')$ and the value of assigned penalization
            If $f(s')<f(s^*)$
                $\Delta=f(s')$
            Else
                $\Delta= f(s') + \lambda \cdot c(s') \cdot \sqrt{n \cdot k} \cdot \varphi(s')$
            End if
            Check the feasibility of solution $s'$
            bool AspirationCriteria = FALSE
            If $c(s')<c(s^*)$ and solution $s'$ is feasible
                AspirationCriteria = TRUE
            End if
            If $\Delta<\Delta^*=0$ and (Tabu = TRUE or AspirationCriteria = TRUE)
                $\Delta^*=\Delta$
                The best movement was found
            End if
        End for
    End for
End for
```

Algorithm 6.7 Normal Pickup and Delivery Pair Shift Operator

The process of shifting the customers between the routes appears in the literature under different names. For example, Nanry and Barnes (2000) and Lau and Liang (2001) refer to it as *Single Pair Insertion*. This term defines more precisely the nature of the operator since it clearly indicates that it is the pairs of customers that are moved instead of the individual customers. A more accurate title: the *PD-Shift Operator* was proposed by Li and Lim (2001). However, none of the introduced names defines evidently the relationship between the transferred couple. This argument acquires special significance since there might be distinguished two types of the Shift Operator: normal and reverse (Park et al., 2000), both presented in Figure 6.8. The difference between them regards the fact that in the case of the reverse operator the visiting order between the displaced pair of customers is inverted (marked in red), which violates the precedence constraint of the PDVRPTW formulation. Therefore, the utilization of a more precise name as: *Normal* or *Reverse Pickup and Delivery Pair Shift Operator* (NPDPSO, RPDPSO) is required and justified.

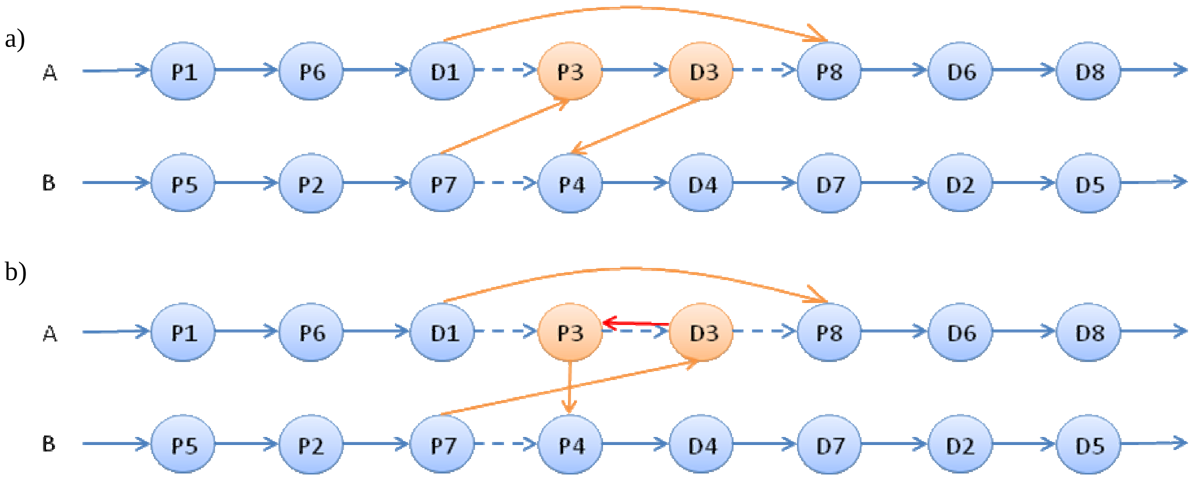


Figure 6.8 Pair Shift Operator: a) normal, b) reverse

6.3.2 Normal Pickup and Delivery Pair Exchange Operator

The purpose of this operator is to modify routes by exchanging the customer pairs between two routes in such a way that the customers removed from their original positions get inserted in new locations providing feasibility and total cost optimization. The performance of the procedure is presented in Figure 6.9, where the customer couple transferred from route A to route B common with the newly introduced links are marked in violet and the elements moved in the contrary direction are coloured in orange. The routes must stay connected, thus the predecessor and the successor of the eliminated customers are properly linked.

The functioning of this operator might also be presented as a pseudo-code defined by the Algorithm 6.8.

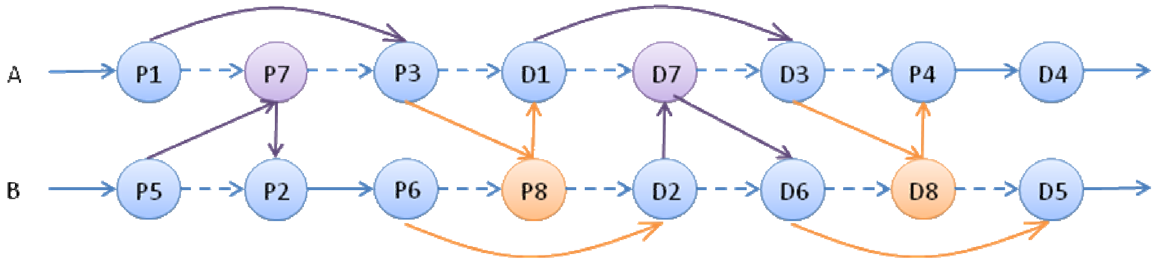


Figure 6.9 Pair Exchange Operator

```
Let $n$ be the total number of customers
Let $k$ be the total number of vehicles
Let $s$ be the current solution containing a set of routes $R$
Make valuation of solution $s$ => $q(s)$, $w(s)$, $c(s)$
Let $s^*=s$ be the best solution with a cost $c(s^*)=c(s)$
Let $f(s^*)=\infty$ be the value of the objective function of the best solution $s^*$
Let $\Delta^*=\infty$ be the sum of $f(s^*)$ and the value of assigned penalization
Let $B(s)$ be the memory matrix
For each route $r_1 \in R$
    For each route $r_2 \in R$, such that $r_1 \neq r_2$
        For each customer $i \in r_1$
            Find pair partner $p(i)$ of customer $i$
            Let $m_1$ be the number defining the pair to which the customers $i$ and $p(i)$ belong
            Remove the customers $i$ and $p(i)$ from route $r_1$
            For each customer $j \in r_2$
                Find pair partner $p(j)$ of customer $j$
                Let $m_2$ be the number defining the pair to which the customers $j$ and $p(j)$ belong
                Remove the customers $j$ and $p(j)$ from route $r_2$
                bool Tabu = FALSE
                If the value of the tabu status stored in $B(s)$ for route $r_2$ and pair $m_1$ is $\neq 0$ and for route $r_1$ and pair $m_2$ is $\neq 0$
                    Tabu = TRUE
                End if
                Find the best insertion of the pair $m_1$ in route $r_2$
                Find the best insertion of the pair $m_2$ in route $r_1$
                Make valuation of the newly obtained solution $s'$ => $q(s')$, $w(s')$, $c(s')$
                Let $f(s')$ be the value of the objective function of the newly obtained solution $s'$
                Let $\Delta=0$ be the be the sum of $f(s')$ and the value of assigned penalization
                If $f(s')<f(s^*)$ and Tabu=FALSE
                    $\Delta=f(s')$
                Else
                    $\Delta= f(s')+\lambda \cdot c(s') \cdot \sqrt{n \cdot k} \cdot \varphi(s')$
                End if
                Check the feasibility of solution $s'$
                bool AspirationCriteria = FALSE
                If $c(s')<c(s^*)$ and solution $s'$ is feasible
                    AspirationCriteria = TRUE
                End if
                If $\Delta<\Delta^*=0$ and (Tabu = FALSE or AspirationCriteria = TRUE)
                    $\Delta^*=\Delta$
                    $f(s^*)=f(s')$
                    The best movement was found
                End if
            End for
        End for
    End for
End for
```

Algorithm 6.8 Normal Pickup and Delivery Pair Exchange Operator

Similarly, as in the case of the Shift Operator, the order of visiting of the reinserted customers' can be reversed. Subsequently there may be obtained four possible outcomes with: both, none and one of the routes reversed in part. As stated before, the crucial consequence of inverting the order of visits is the violation of the precedence constraint. Therefore, it cannot be applied for solving the PDVRPTW problems without introducing a posteriori an additional treatment aiming at such solution's modification so that the restrictions fulfilment is guaranteed. Figure 6.10 demonstrates the differences between the normal and the reverse type of the Exchange Operator.

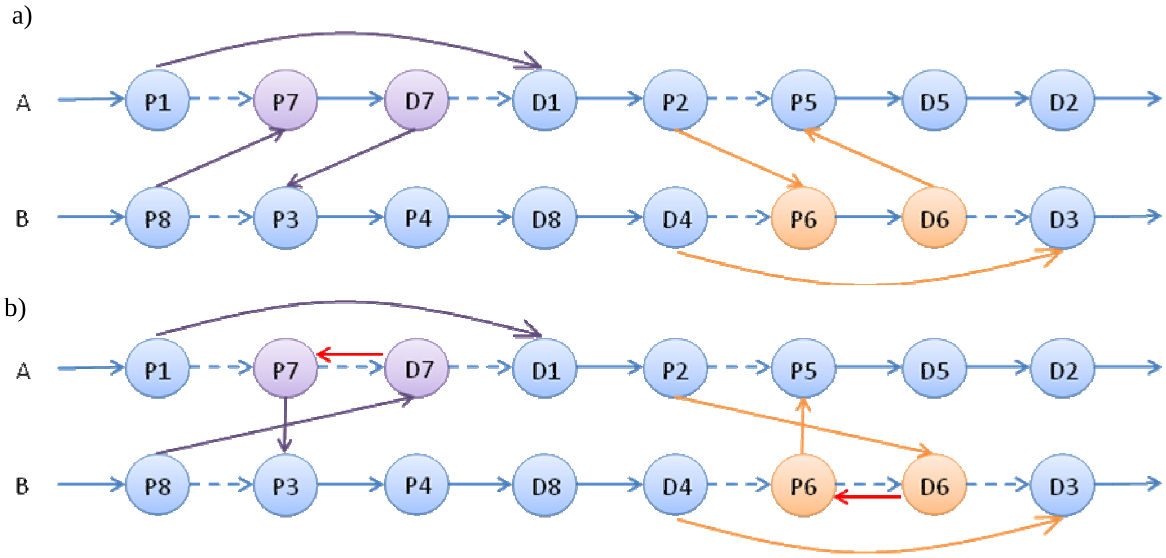


Figure 6.10 Pair Exchange Operator: a) normal, b) reverse

The movements performed by the current operator are also present under different names. For example, Park et.al. (2000) refer to them as the *Interchange Operations*, Nanry and Barnes (2000) define them as *Swapping Pairs Between Routes* and Li and Lim (2001) apply the *PD-Exchange Operator* term. In order to provide higher precision to the definition, the type of the operator used in this work is referred to as the *Normal Pickup and Delivery Pair Exchange Operator* (NPDPEO).

6.4 Post-Optimization Methods

As a last step of the complete approach there was introduced a post-optimization method. The tested candidate routines include: the Rearrange Operator and the 2-opt algorithm, both adapted to the PDP. Their aim is to find such modifications of the collection of routes previously obtained by the PTS, that the newly created result is feasible and characterised by a smaller cost. Each examined process concentrates on individual refinement of each, separate route. Also, they are iterative methods, which repeat their performance until no more improvement movements for the analysed route can be found. These methods provide a set of routes determining the final solution of the entire proposed PDVRPTW solving approach.

6.4.1 Normal Pickup and Delivery Pair Rearrange Operator

The objective of the Rearrange Operator is to recompose the original route by changing the order in which the customers are to be visited by the assigned vehicle, so that a new sequence of customers with a smaller value of the objective function was found. Hence, unlike in the case of the PTS incorporated local search procedures, the changes are performed within the boundaries of only one route instead of two. Moreover, the important point of this routine regards the fact, that only the modifications resulting in a feasible solution are accepted.

The functioning of this PDP adapted Rearrange Operator is presented on an example provided in Figure 6.11. It can also be explained in details in a form of a pseudo-code demonstrated by the Algorithm 6.9.

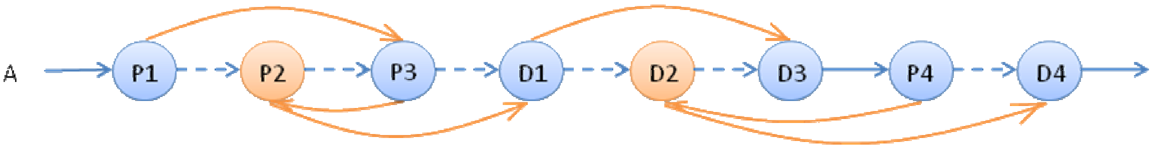


Figure 6.11 Pair Rearrange Operator

```
Let $R$ be the set of routes defining the current solution $s$
For each route $r_k \in R$
    Let $r_k^*$ be the best route and $r_k^* = r_k$
    Make valuation of modified route $r_k^*$ => $q(r_k^*)$, $w(r_k^*)$, $c(r_k^*)$
    While best movement is not found
        For each customer $i \in r_k$
            Find pair partner $p(i)$ of customer $i$
            Remove the customers $i$ and $p(i)$ from route $r_k$
            Find the best insertion of customers $i$ and $p(i)$ in route $r_k$
            Make valuation of modified route $r_k'$ => $q(r_k')$, $w(r_k')$, $c(r_k')$
            Check the feasibility of route $r_k'$
            If $c(r_k') < c(r_k^*)$ and route $r_k'$ is feasible
                $c(s^*) = c(s')$
                The best movement was found
            End if
        End for
        If the best movement was not found
            $r_k^* = r_k$
    End if
    End while
End for
```

Algorithm 6.9 Normal Pickup and Delivery Pair Rearrange Operator

As well as in the case of the previously presented operators, there exists also the reverse version of the Rearrange Operator, which results in the violation of the imposed precedence restriction making the special route-fixing objective invalid, but which may drive the general search into promising areas in terms of the objective function optimization. It might be used as an intermediate step in some heuristics, which monitor and handle the unmet constraints in posterior stages. In the present thesis project, one of the objectives is to exploit the corrective characteristics of this operator in the final post-optimization step, thus the application of its inverted type is not contemplated. Nevertheless, both the normal and the reversed versions of the Rearrange Operator are presented in Figure 6.12.

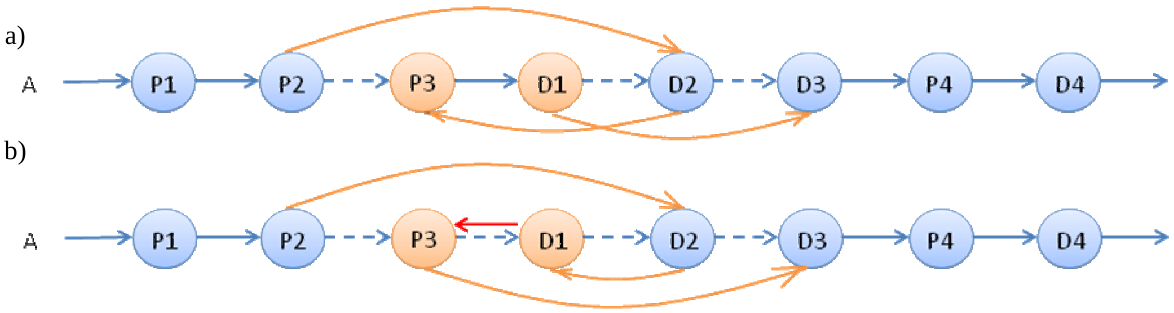


Figure 6.12 Pair Rearrange Operator: a) normal, b) reverse

Li and Lim (2001) refer to the current operator as the *PD-Rearrange Operator* and Nanry and Barnes (2000) use the *Within Route Insertion* name. For the purposes of the present work, the term: *Normal Pickup and Delivery Pair Rearrange Operator* (NPDPRO) shall be used.

6.4.2 2-opt Pickup and Delivery Adapted Method

The functioning of the PDP adapted 2-opt algorithm is based on the same principles as its classical version. It is an iterative process during which two, non-consecutive arcs joining the customers within the same route, get deleted and substituted by new links in such a way that a novel, alternative solution is created. In each repetition there are checked all the possible combinations of arcs and at the end a collection of optional routes is created. The one, which is characterized by the smallest cost, is chosen as a basis for further optimization. The procedure continues until no improved solution can be found. Then, the last, feasible, created route of minimal cost is considered to be final.

In contrast to the classic version of the 2-opt algorithm its PDP adapted version results in smaller number of acceptable alternative routes. It is due to the imposed strict feasibility requirement regarding an extended amount of restrictions. The selected modifications, although characterised with a favourable cost may violate the obligatory precedence constraint, as shown on the example provided in Figure 6.13. Therefore, the whole process must be conducted in such a way that in no circumstances the permitted values of a priori defined restrictions were exceeded. The functioning of the PDP adapted 2-opt method is presented as a pseudo-code defined by the Algorithm 6.10.

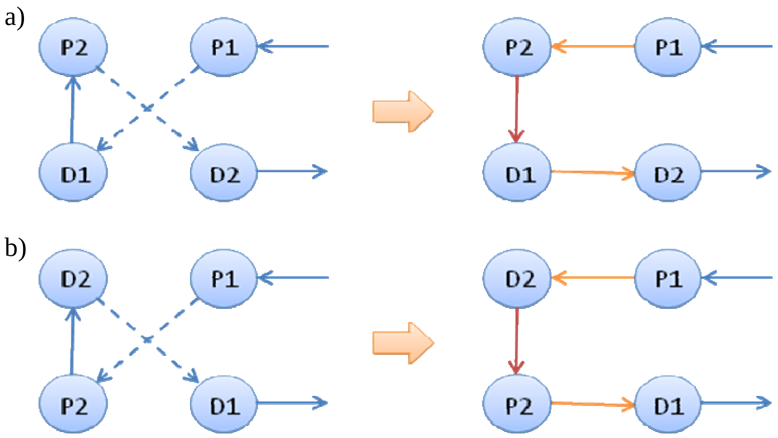


Figure 6.13 Functioning of the 2-opt algorithm adapted for solving a PDP showing the outcome, which is: a) feasible, b) unfeasible. The dashed lines indicate eliminated connections substituted by orange links. The arcs with reveres direction are marked in red

```
Let $R$ be the set of routes defining the current solution $s$
For each route $r_k \in R$
    Let $r_k^*$ be the best route and $r_k^*=r_k$
    Make valuation of modified route $r_k^*$ => $q(r_k^*)$, $w(r_k^*)$, $c(r_k^*)$
    While best movement is not found
        Let $pos(i)$ be the position of node $i$ in the sequence of customers of route $r_k$
        Let $pos(j)$ be the position of node $j$ in the sequence of customers of route $r_k$
        For each customer $i$ in route $r_k$
            For each customer $j$ in route $r_k$ and $pos(j)=pos(i)+2$
                Create new, empty route $r_k'$
                For each customer $h$ in route $r_k$
                    If $pos(h) \le pos(i)$ or if $pos(h) \ge pos(j+1)$
                        Append customer $h$ to $r_k'$
                    Else
                        Append customer at position $pos(i)+pos(i)-pos(h)+1$ to $r_k'$
                    End if
                    Make valuation of modified route $r_k'$ => $q(r_k')$, $w(r_k')$, $c(r_k')$
                    Check the feasibility of route $r_k'$
                    If $c(r_k')<c(r_k^*)$ and route $r_k'$ is feasible
                        $c(s^*)=c(s')$
                        The best movement was found
                    End if
                End for
            End for
        End for
    End while
End for
```

Algorithm 6.10 PDP adapted 2-opt algorithm

6.5 Experiments

As a result of combination of various algorithms there were obtained sixteen composite methods apt to solve the addressed PDVRPTW:

- Simple Pairing Approach/ PTS/ NPDPRO (*pair_rr*),
- Simple Pairing Approach/ PTS/ PDP adapted 2-opt (*pair_2opt*),
- Algorithm based on the Definitions of Customer Aggregation Areas/ PTS/ NPDPRO (*area_rr*),
- Algorithm based on the Definitions of Customer Aggregation Areas/ PTS/ PDP adapted 2-opt (*area_2opt*),
- Sweep Algorithm (with randomly chosen starting point and number of sub-lists equal to the number of customers)/ PTS/ NPDPRO (*angle_r_nCust_rr*),
- Sweep Algorithm (with randomly chosen starting point and number of sub-lists equal to the number of customers)/ PTS/ PDP adapted 2-opt (*angle_r_nCust_2opt*),
- Sweep Algorithm (with randomly chosen starting point and number of sub-lists equal to the number of vehicles)/ PTS/ NPDPRO (*angle_r_nVeh_rr*),
- Sweep Algorithm (with randomly chosen starting point and number of sub-lists equal to the number of vehicles)/ PTS/ PDP adapted 2-opt (*angle_r_nVeh_2opt*),
- Sweep Algorithm (with randomly chosen starting point and number of sub-lists equal to one)/ PTS/ NPDPRO (*angle_r_1_rr*),
- Sweep Algorithm (with randomly chosen starting point and number of sub-lists equal to one)/ PTS/ PDP adapted 2-opt (*angle_s_1_2opt*),
- Sweep Algorithm (with fixed starting point equal to -π and number of sub-lists equal to the number of customers)/ PTS/ NPDPRO (*angle_s_nCust_rr*),
- Sweep Algorithm (with fixed starting point equal to -π and number of sub-lists equal to the number of customers)/ PTS/ PDP adapted 2-opt (*angle_s_nCust_2opt*),
- Sweep Algorithm (with fixed starting point equal to -π and number of sub-lists equal to the number of vehicles)/ PTS/ NPDPRO (*angle_s_nVeh_rr*),
- Sweep Algorithm (with fixed starting point equal to -π and number of sub-lists equal to the number of vehicles)/ PTS/ PDP adapted 2-opt (*angle_s_nVeh_2opt*),
- Sweep Algorithm (with fixed starting point equal to -π and number of sub-lists equal to one)/ PTS/ NPDPRO (*angle_s_1_rr*),
- Sweep Algorithm (with fixed starting point equal to -π and number of sub-lists equal to one)/ PTS/ PDP adapted 2-opt (*angle_s_1_2opt*).

The algorithms and the supporting procedures were programmed in the C++ language, compiled using the Visual Studio 2005, running under using the Windows XP service pack 3. The experiments were performed on a computer with an Intel core 2 duo E6850, at 3Ghz CPU and with 2GB of the RAM.

6.6 Results

The results achieved by all tested methods were compiled in a collection of tables. To ensure transparency of the current document, they were all placed in Appendix B1.

The present section provides final resume of reached outcomes. It explains the way of comparing the individual approaches in terms of their efficiency and provides final conclusions.

The main reflected features regard respectively, the *final schedule cost* of the best obtained solution and the CPU needed to carry out the numerical tests. There were taken into account two variables concerning the time of computation: *actual* and *total cpu*. The first one represents the summarized amount of time needed to: construct the initial set of routes, find the best solution during PTS procedure and implement the post-optimization step. Hence, it does not take into account the PTS time during which no improvement was found for the last best solution. The other variable corresponds to the total duration of the computation process necessary to perform the complete composite routine. The purpose of this distinction was to verify whether it is necessary to perform the initially established number of PTS iterations, and whether the duration of this step could be shortened without much deterioration of the quality of the final solution.

In order to be able to compare the approaches containing in their formulas an incidental factor (i.e. Sweep Algorithm with randomly chosen starting point) with the rest of the methods, it was decided to carry out the experiments testing their performance 100 times and save in a resuming table the expected values of the variables to contrast.

So as to represent the total time needed to perform all these experiments there was created additional summary chart containing the aggregated values of both actual and total cpu variables. The complementary objective of this task was to verify whether it is beneficial to execute a single approach multiple times in order to choose from among all the obtained solutions the one that is the most beneficial.

In addition, to compare with one another the methods containing the random factor, it was decided to substitute it with a fixed value. Thus, all the experiments were run each time starting the process of customers' ordering from the same pre-established point equal to $-\pi$. Similarly as in the previous cases, the quality of performance of each of the approaches was reviewed with respect to the obtained solution's final schedule cost and total cpu.

To assess goodness of reviewed methods, the attention was also paid to the performance of their individual components. Hence, there was created a record presenting the schedule costs of the sets of routes provided by the initial solution constructing algorithms. These data are compared between each other. Due to the fact that each method takes less than one second, there was not prepared an individual listing regarding the CPU.

Similarly, there was evaluated the performance of the algorithms used for post-optimization. The analysis focused on demonstrating the efficiency of the two employed procedures in terms of improvement of the final schedule cost and velocity of calculation. Moreover, there are provided data illustrating for how many instances the specific post-optimization method has improved the original result.

One of the initially addressed tasks in the implementation of the current thesis was to design and create a comparison platform containing the best results obtained by known algorithms, with the objective to evaluate the quality of performance of the examined methods. It was noted however, that none except one (Li and Lim, 2001) of the considered publications (Chapter 3) in addition to the data on travel times provide information on the total schedule including both service and waiting times, which are significant from the point of view of this undertaking. As a consequence, it was decided to use the results obtained by the Li and Lim's (2001) algorithm as a reference.

The comparison of the tested approaches with the one of Li and Lim (2001) is relative due to the fact that there is employed significantly smaller number of iterations in the PTS optimization process. However, this comparison is performed since it allows assessing how far the obtained outputs are from the results which are the best published so far. It brings complementary information on goodness of operation of the reviewed composite heuristics.

It needs to be highlighted that the motivation for all the work carried out and documented in the present chapter was to select a method apt to solve the addressed PDVRPTW providing quickly an outcome of acceptable quality that would permit to continue the work regarding the dynamic approach. The main objective was not to design and construct such meta-heuristic, which would prove to be substantially faster and more efficient than the approaches proposed by other authors but to find a routine good enough from the point of view of the complete undertaking.

This is why the finally chosen method is the one which for the highest number of benchmark cases provides quickly an outcome of the smallest value of the final schedule cost in comparison with the rest of the methods and at the same time is the closest to the reference.

In order to estimate the quality of operation of the tested methods, using the data from Appendix B1, there were first prepared the charts presented in Figures 6.14 and 6.15. The indexes of the instances correspond to the case studies comprised by the following collections: lc_10, lc_20, lr_10, lr_20, lrc_10 and lrc_20 (Appendix A1). In total there were tested 56 benchmarks.

Figure 6.14 shows the final costs of the solutions obtained by each tested method for all the test instances. It puts into evidence, that except for method pair_rr the performance of all the approaches is very similar and therefore it is difficult to clearly indicate which one is the best.

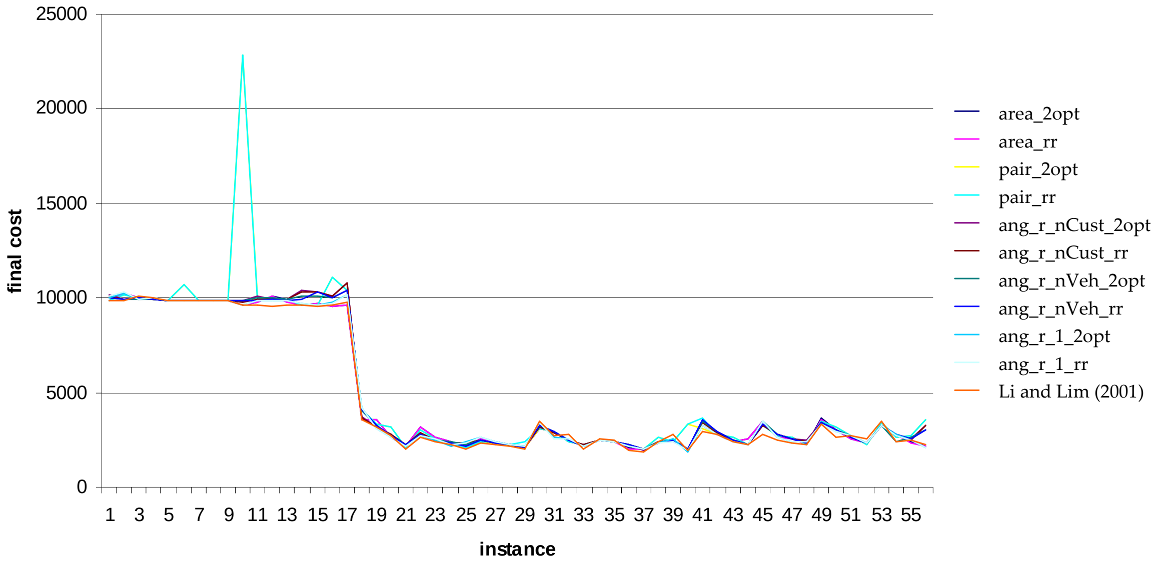


Figure 6.14 Final schedule costs obtained by each method for every benchmark instance

An equivalent conclusion was drawn with respect to the values of the total cpu time. Figure 6.15 outlines how much time each tested approach needed to solve every benchmark instance. It is observable that except of method ang_r_1_2opt and meta-heuristic proposed by Li and Lim (2001), all the rest require comparable amount of time for computation.

The fact that the majority of tested composite heuristics work faster than the method of reference does not mean that they outperform it. Since, they employ much smaller number of iterations in the PTS than the Li and Lim's (2001) algorithm, it is natural that they require less CPU. Nevertheless, at this stage, it is essential to investigate whether it is possible to obtain better or the same final schedule costs, when the time of operation is shortened.

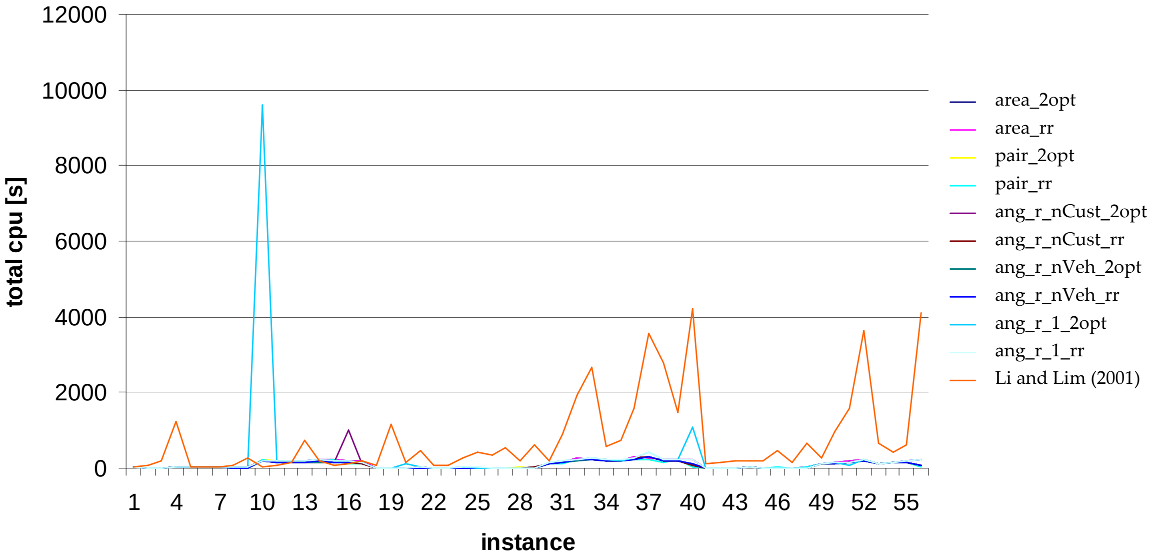


Figure 6.15 Values of total CPU required for solving every benchmark instance by each method

In order to be able to compare the individual methods and to estimate the general quality of their performance, for each two approaches, there was calculated an average difference of the cost and the total cpu values obtained for all benchmark cases. It represents how well one method operates in comparison with another. The computation was performed in accordance with the following formulas:

$$\delta(c(s)_{A,B}) = \frac{\sum_i (c(s)_{i,A} - c(s)_{i,B})}{|i|} \tag{6.9}$$

$$\delta(t(s)_{A,B}) = \frac{\sum_i (t(s)_{i,A} - t(s)_{i,B})}{|i|} \tag{6.10}$$

Where:

i : testing benchmark $i \in I$,
A and B : reviewed methods such that $A \neq B$,
$c(s)_{i,A}$: final schedule cost obtained by method A for instance i,
$t(s)_{i,A}$: final cpu required by method A to solve instance i,

$\delta(c(s)_{A,B})$: average difference between the values of the final schedule cost obtained by method A and B for all instances $i\in I$,

$\delta(t(s)_{A,B})$: average difference between the values of the final cpu time required by method A and B to solve all instances $i\in I$,

The obtained results are comprised by Table 6.9 and 6.10, respectively. For the sake of clarity, all the negative values are marked in red. The case in which method A obtains the best result is highlighted, while the worst outcome is underlined.

method	final schedule cost											
B A	area _2opt	area _rr	pair _2opt	pair _rr	ang_r_ nCust_2opt	ang_r_ nCust_rr	ang_r_ Veh_2opt	ang_r_ nVeh_rr	ang_r_ 1_2opt	ang_r_ 1_rr	Li and Lim (2001)	avg
area_2opt		3.21	-347.29	**-364.87**	-89.69	-72.77	-64.24	-61.62	-0.94	-0.04	86.67	-82.87
area_rr	-3.21		-350.50	**-368.08**	-92.90	-75.98	-67.46	-64.84	-4.16	-3.25	83.46	**-86.08**
pair_2opt	347.29	350.50		**-17.58**	257.60	274.52	283.04	285.66	346.34	347.25	433.96	264.42
pair_rr	364.87	368.08	**17.58**		275.18	292.10	300.63	303.25	363.93	364.83	451.55	**282.00**
ang_r_nCust_2opt	89.69	92.90	**-257.60**	-275.18		16.92	25.44	28.06	88.74	89.65	176.36	6.82
ang_r_nCust_rr	72.77	75.98	-274.52	**-292.10**	-16.92		8.52	11.15	71.83	72.73	159.44	-10.10
ang_r_nVeh_2opt	64.24	67.46	-283.04	**-300.63**	-25.44	-8.52		2.62	63.30	64.21	150.92	-18.63
ang_r_nVeh_rr	61.62	64.84	-285.66	**-303.25**	-28.06	-11.15	-2.62		60.68	61.59	148.30	-21.25
ang_r_1_2opt	0.94	4.16	-346.34	**-363.93**	-88.74	-71.83	-63.30	-60.68		0.91	87.62	-81.93
ang_r_1_rr	0.04	3.25	-347.25	**-364.83**	-89.65	-72.73	-64.21	-61.59	-0.91		86.71	-82.83
Li and Lim (2001)	-86.67	-83.46	-433.96	**-451.55**	-176.36	-159.44	-150.92	-148.30	-87.62	-86.71		**-169.54**

Table 6.9 Resume of the average differences in the final solution cost obtained by each method for all benchmark instances

The way to interpret Table 6.9 is the following: the negative values indicate that method A performs better than method B since it obtains smaller values of the final schedule cost in average for all the tested instances. Thus, e.g.:

- area_rr in comparison with area_2opt reaches in average smaller values of the final schedule cost for all the benchmark instances (-3,21),
- area_rr in comparison with the reference method proposed by Li and Lim (2001) in average obtains bigger values of the final schedule cost for all the benchmark instances (83,46).

Table 6.9 shows that the approach proposed by Li and Lim (2001) in comparison with all the other reviewed composite heuristics provides in average for all the benchmark cases the smallest values of the final schedule cost. This leads to the conclusion that, from the viewpoint of an overall assessment of tested methods, shortening of their time of operation impeded the ability of the proposed methods to reach results as good as the reference.

It does not mean however, that for some benchmark cases there were not obtained better outcomes. In fact, as shown by Table 6.11, each reviewed method was able to improve the results for at least 20% of all the instances.

For example: area_rr was able to improve 38% of instances and deliver better or the same outcome as Li and Lim (2001) for 48%. In each benchmark collection: lc_100, lc_200, lr_100, lr_200, lrc_100 and lrc_200, there were reached at least as good results as these of reference for: 89%, 50%, 17%, 55%, 25% and 63% of instances, respectively. Only in the sets: lc_100 and lc_200 there were reached the same results as these of Li and Lim (2001). They correspond to 44% and 25%, accordingly.

Having in mind that in this case the required CPU time was shortened by 86%, the general performance of this method can be considered as efficient from the point of view of the complete undertaking, where the reaction time is crucial. Besides, it suggests that if allowed to operate longer, it could provide better results.

From all the proposed composite methods the one which is the closest to the reference is area_rr. The worst performing method is pair_rr. The latter conclusion could have been intuitively drawn from the observation of the chart in Figure 6.15.

method	total cpu [s]											
B A	area _2opt	area _rr	pair _2opt	pair _rr	ang_r_ nCust_2opt	ang_r_ nCust_rr	ang_r_ Veh_2opt	ang_r_ nVeh_rr	ang_r_ 1_2opt	ang_r_ 1_rr	Li and Lim (2001)	avg
area_2opt		0.13	18.54	18.59	3.54	18.43	16.30	15.91	**-183.70**	-1.57	-661.68	-68.68
area_rr	-0.13		18.41	18.46	3.41	18.30	16.18	15.79	**-183.82**	-1.70	-661.80	-68.81
pair_2opt	-18.54	-18.41		0.05	-15.00	-0.11	-2.23	-2.63	**-202.23**	-20.11	-680.21	-87.22
pair_rr	-18.59	-18.46	-0.05		-15.05	-0.16	-2.29	-2.68	**-202.29**	-20.16	-680.27	**-87.27**
ang_r_nCust_2opt	-3.54	-3.41	15.00	15.05		14.89	12.77	12.38	**-187.23**	-5.11	-665.21	-72.22
ang_r_nCust_rr	-18.43	-18.30	0.11	0.16	-14.89		-2.13	-2.52	**-202.13**	-20.00	-680.11	-87.11
ang_r_nVeh_2opt	-16.30	-16.18	2.23	2.29	-12.77	2.13		-0.39	**-200.00**	-17.88	-677.98	-84.99
ang_r_nVeh_rr	-15.91	-15.79	2.63	2.68	-12.38	2.52	0.39		**-199.61**	-17.48	-677.59	-84.59
ang_r_1_2opt	183.70	183.82	202.23	202.29	187.23	202.13	200.00	199.61		**182.13**	-477.98	115.01
ang_r_1_rr	1.57	1.70	20.11	20.16	5.11	20.00	17.88	17.48	-182.13		-660.11	-67.11
Li and Lim (2001)	661.68	661.80	680.21	680.27	665.21	680.11	677.98	677.59	**477.98**	660.11		**593.00**

Table 6.10 Resume of the average differences in the total cpu time required by each method to solve all benchmark instances

The way to interpret Table 6.10 is similar as in the previous case. The negative values indicate that method A performs faster than method B since it obtains smaller values of the final cpu time in average for all the tested instances. Thus, e.g.:

- method area_rr in comparison with area_2opt performs faster in average for all the benchmark instances (-0,13),
- method area_rr in comparison with pair_rr performs slower in average for all the benchmark instances (18,46).

Table 6.10 shows that the fastest is pair_rr. It outperforms the reference approach by 88%. The method of Li and Lim (2001) requires in average the highest amount of CPU time. The second slowest approach is ang_r_1_2opt. The two last conclusions are consistent with what is shown in Figure 6.16.

In order to complement the assessment of performance of the tested approaches there were prepared Tables 6.11 and 6.12. They contain information on the number of the benchmark cases in which smaller values of the final schedule cost and the final cpu time were obtained by one method in comparison with another. Thus, e.g.:

- area_rr in 22 instances obtained smaller values of the final schedule cost than area_2opt,
- area_rr in 12 instances reached smaller values of the final cpu time than area_2opt.

Method	final-schedule cost											
B A	area _2opt	area _rr	pair _2opt	pair _rr	ang_r_ nCust_2opt	ang_r_ nCust_rr	ang_r_ Veh_2opt	ang_r_ nVeh_rr	ang_r_ 1_2opt	ang_r_ 1_rr	Li and Lim (2001)	avg
area_2opt		**8**	25	26	35	35	34	31	25	23	20	23.82
area_rr	22		26	26	36	36	35	34	27	24	**21**	26.09
pair_2opt	27	24		**9**	28	29	29	30	27	24	15	22.00
pair_rr	26	24	23		25	25	27	28	23	20	**14**	21.36
ang_r_nCust_2opt	21	20	28	31		18	25	20	19	**14**	**14**	19.09
ang_r_nCust_rr	21	20	27	31	38		30	28	21	16	**13**	22.27
ang_r_nVeh_2opt	22	21	27	29	31	26		21	20	18	**11**	20.55
ang_r_nVeh_rr	25	22	26	28	36	28	35		20	18	**12**	22.73
ang_r_1_2opt	26	25	27	31	37	35	36	36		22	**18**	26.64
ang_r_1_rr	27	23	29	33	42	40	38	38	27		**19**	**28.73**
Li and Lim (2001)	31	**29**	37	38	42	41	44	44	35	33		**34.00**

Table 6.11 Number of instances in which method A obtained lower value of the final solution cost than method B

Method	total cpu [s]											
B A	area _2opt	area _rr	pair _2opt	pair _rr	ang_r_ nCust_2opt	ang_r_ nCust_rr	ang_r_ Veh_2opt	ang_r_ nVeh_rr	ang_r_ 1_2opt	ang_r_ 1_rr	Li and Lim (2001)	avg
area_2opt		**8**	14	13	10	10	9	10	23	24	49	15.45
area_rr	12		15	13	10	10	**9**	10	23	23	49	15.82
pair_2opt	36	36		**13**	23	24	24	26	40	40	50	28.36
pair_rr	39	39	**16**		24	25	25	25	41	41	51	**29.64**
ang_r_nCust_2opt	36	36	22	24		**20**	27	28	39	37	50	29.00
ang_r_nCust_rr	35	34	21	22	**9**		23	24	38	36	51	26.64
ang_r_nVeh_2opt	36	37	21	22	**14**	16		17	42	40	51	26.91
ang_r_nVeh_rr	36	37	21	21	15	15	**13**		43	41	51	26.64
ang_r_1_2opt	21	21	13	14	10	10	**8**	9		19	50	15.91
ang_r_1_rr	20	19	14	14	11	11	**9**	11	**9**		50	15.27
Li and Lim (2001)	7	7	**5**	**5**	**5**	**5**	**5**	**5**	6	6		5.09

Table 6.12 Number of instances in which method A obtained lower value of the final cpu time than method B

The approach of Li and Lim (2001) in comparison with all the rest of the methods was able to obtain the smallest values of the final schedule cost in the highest number of instances. In average this number corresponds to 61%.

ang_r_1_r is the second best. For the average of 51% of the total number of the instances, it was able to improve the final schedule cost. It is followed by area_rr, which reaches 47%. Notwithstanding, these two approaches are one of the most time consuming.

pair_rr for the highest average of 53%, was able to improve the final cpu. The approach of Li and Lim (2001) is the slowest. Only for the average of 9% of the total number of the instances it is able to perform faster than the other methods.

The least time consuming approach pair_rr for each benchmark case requires in average 12,15 seconds less than the algorithm proposed by Li and Lim (2001). area_rr which is one of the slowest performing approaches, but which improves the most the final schedule costs values, for each benchmark case requires in average 11,82 seconds less than the algorithm of reference. Regarding the CPU, the comparison of these two methods indicates that they perform on a similar level. Hence, it is more justified to select one approach on the basis of comparison of the final schedule costs instead of the final cpu. Hence, the approach which was ultimately chosen as a basis for both IRSM and DRSM in the continuation of the project is area_rr.

The value of actual cpu obtained by each reviewed method in each instance is shorter than total cpu by an average amount of 58%. PTS finds the best solution after an average number of iterations equal to 248. These observations suggest that a reduced number of iterations performed by PTS might result in significant savings of CPU, while the quality of final solution is deteriorated in small degree.

The study of the individual components of the tested approaches and the manner, in which they affect each other, shows that the initial solution has strong impact on the final output.

None of the initial solution creating algorithms, executed independently, without the optimization and post-optimization steps, generally performs better than the algorithm used as a reference. However, the methods: organizing the customers by aggregation area and by angle with one sub-list, for an average of 7% of the instances, were able to reach a better result than the one obtained by the Li and Lim's (2001) algorithm. These two methods also reached the highest score if it comes to the number of instances with the smallest schedule cost obtained in comparison with the others. In addition, they provide the best initial schedule costs. However, they take the longest to perform the complete approach from all the reviewed routines.

Hence, there can be drawn the following conclusion: the division of customers into many sub-sets results in higher number of initial routes, which requires less CPU to solve the addressed problem completely but at expense of the quality of the final solution's schedule cost.

In the case when it is not possible to perform the entire composite heuristic due to e.g.: time limitation, the method which organizes the customers by angle with one sub-list proves to be the most proficient.

The evaluation of performance of the methods proposed and implemented to post-optimize the solution delivered by PTS indicates that the NPDPRO is both more efficient and faster than the PDP adapted 2-opt routine. For all the revised methods, it provides higher decrement of the solutions' schedule cost. Also, for all the tested methods, the NPDPRO leaves without improvement lower number of instances. Except of the method, which initially orders customers by pairs, the execution time, when solving all the considered benchmark instances, is the smallest for the NPDPRO post-optimization step.

The analysis of the time of performance of the approaches, which initially organise the customers using Sweep Algorithm with randomly chosen starting point, shows that none of them can be executed 100 times in order to solve all the instances in time shorter or at least equal to the one of the Li and Lim's (2001) meta-heuristic. However, ang_r_nCust_rr is the only method able to execute 100 times 14% (8) of all the instances in the total time shorter than the one necessary to perform once the Li and Lim's (2001) approach. For 9% (5) there was found a result better than the one of the reference. These instances belong to the lr_10 set (Appendix A1). Since the complete collection comprises 12 instances it is worth to consider such solving strategy, for similar cases.

From all the tested methods with random ingredient, ang_r_nCust_rr proves to be the fastest. It is also the second best if it comes to the percentage of the instances which were solved 100 times in the shortest time (27%). ang_r_nCust_2opt reaches a greater number (30%).

ang_r_1_rr obtains the lowest values of the final schedule cost in comparison with the other approaches with random ingredient. It also improves the greatest number of the instances.

The analysis of the same approaches, but which initially organise the customers using Sweep Algorithm starting from a fixed point equal to -π, leads to similar conclusions. The method angle_s_nCust_rr performs the fastest, while the ang_s_1_rr obtains the lowest values of the final schedule cost in comparison with the rest of the methods.

Table 6.13 provides results of comparison between the two types of the same method, which organizes the customers using the Sweep Algorithm. It shows that only ang_s_1_rr and ang_s_1_2opt, provide in average for all tested benchmark cases better outcome in terms of both final schedule cost and total cpu, than their random versions.

Random staring point Fixed starting point equal to –π	final schedule cost	final cpu [s]
ang_nCust_rr	25.72	-17
ang_nCust_2opt	38.64	-3
ang_nVeh_rr	**-22.72**	2
ang_nVeh_2opt	-20.69	1
ang_1_rr	-6.68	**-185**
ang_1_2opt	-8.92	-4

Table 6.13 Resume of the average differences in final solution cost and final cpu time obtained by two variants of the same approach, which initially organizes the customers using Sweep Algorithm (starting from a random or a fixed point equal to $-\pi$)

The observation of the approaches which employ the Sweep Algorithm allowed to draw the same conclusions as these brought by the analysis of all the methods providing the initial solutions and their impact on the final outcome. The higher the number of initial sub-lists of ordered customers and by consequence the higher the number of initial routes, the shorter the total amount of required CPU time to perform the complete routine, but for the price of improvement of the final schedule cost.

In sum, among all the tested composite approaches, area_rr was chosen to be implemented in continuation of the thesis. It includes the original initial solution creating algorithm based on the definition of customer aggregation areas, which performs the best in comparison with other reviewed alternatives. Similarly, the NPDPRO post-optimization process proved to work better than the PDP adapted 2-opt routine.

Due to fact, that PTS employed smaller number of iterations than the approach used as reference, it was not possible to clearly define if the tested methods can outperform it, although they all require less CPU. However, there could be specified the number of iterations which in much shorter time brought solutions with the same or better final schedule cost. area_rr in around 15% of the time required by the algorithm of Li and Lim (2001) can solve similarly or better almost 50% of studied cases.

Since, area_rr includes the initial solution creating procedure which pays special attention to customers' locations it works best solving instances where the customers are clustered (sets lc_100 and lc_200). In the cases where the customers are distributed at random or mixing both random with grouped locations, area_rr is less efficient. Especially, when there are considered short scheduling horizons (sets lc_100 and lrc_100). However, when elongated scheduling horizons are considered (sets: lr_200 and lrc_200) the performance of area_rr is much improved. These observations allow concluding that the solving method has to be well matched to the addressed problem.

Chapter 7

The aim of the current chapter is to specify the design and functioning of all the individual modules composing the proposed DSS. It also provides the description of the selected background network, the outline of the arranged testing scenarios and the final resume of obtained results.

The first section 7.1 presents the TDSP Calculator. It demonstrates the construction of the structures used for data storing, explains the functioning of the employed algorithm and outlines the challenges met during the implementation process. Next, the designs of both the IRSM and DRSM are presented in sections 7.2 and 7.3, respectively. The description focuses on specific modifications made on the original version of the approach selected in accordance with the findings explained in Chapter 6. The Time-Dependent Travel Time Data Forecasting Module is defined in section 7.4. Although it does not form part of the proposed DSS it fulfils a complementary function relevant from the point of view of the complete undertaking. The information on functioning of the VFP Simulator is explained in section 7.5. The last sections of the current chapter provide the description of the chosen urban network (7.6), the design of testing experiments (7.7) and the concluding resume of collected results (7.8).

Decision Support System for Real-Time Freight Management

In short, a modern DSS might be defined as a computer-based system that assists the process of decision-making. In this context, any computer application which improves user's ability to make decisions might be specified as DSS. Thus, as rightly noted by pioneering research of Alter (1980), a DSS can "*take on many different forms and can be used in many different ways*". It can focus on data, documents, knowledge, models or communications. It might be created with the intention to serve a specific, single user or a group or organization. In the latter case it could be employed as inter or intra organizational structure. It can be designed to be utilised by the final decision-maker or by the person placed in an intermediate position in the chain of decision-making process such as for example the analyst. It can be provided as a complete off-the-shelf product or a custom-made application. In some cases in order to make the DSS function it is sufficient to utilise a personal computer, while in others it is necessary to utilise more extensive tool as networked environment. It may be used at any level in an organization supporting:

operations, management and strategic resolutions. The targeted purpose could be specified as broad or narrow. In this context, the employed DSS can be defined as function (task) or industry specific, accordingly. The addressed tasks might regard: information gathering, model building, sensitivity analysis, collaboration, alternative evaluation, decision implementation, etc.

This wide range of factors and the consequent possible ways to characterize the DSS result in lack of agreement on formulation of its universal definition. However, in the literature there might be found precise conceptualisation proposals. Power and Sharda (2009) specifies the DSS as an "*interactive computer-based system that helps people use computer communications, data, documents, knowledge, and models to solve problems and make decisions*". Turban (1995) determines it as "*interactive, flexible, and adaptable computer-based information system especially developed for supporting the solution of a non-structured management problem for improved decision making. It utilizes data, provides an easy-to use interface and allows for the decision maker's own insights*".

In any case, the objective of a DSS is to inform, facilitate the task of solving the addressed problems and support the decision-making processes. In main, it focuses on quantitative analysis and modelling of the current and future states performed on the basis of the available historical internal and external information. The result of such analysis in a form of a concise resume helps to understand the observed phenomena or studied problem and decide on most appropriate actions to undertake. In addition, it needs to be noted that it is not the DSS's intention to substitute the presence of experienced decision-maker by completely automating the decision-making process, but to complement his skills enabling quick reaction and assure flexibility.

Analogously, as it is challenging to put into words the taking-everything-into-account definition of the DSS, it is not easy to come up with a universal taxonomy. The literature provides the following proposals for categorising the DSS (Power, 1997, Power and Sharda, 2009, Haettenschwiler, 1999):

at the user level:

- *passive* – although it supports the decision-making process it does not provide definite solutions or suggestions,
- *active* – able to bring explicit decisions suggestions or solutions,
- *cooperative* – permits the user to modify, improve or complete the DSS's proposal and send it back to the system, which is able to do the same; this cyclical process is repeated until the final common solution is created.

at the technical level:

- *enterprise-wide* – linked to large data warehouses and serve many users,
- *desktop* – intended for a singular user working on an individual personal computer.

at the conceptual level:

- *communication-driven* (or *group-driven*) – its objective is to facilitate the interactive process of problems' solving performed by the group of decision-makers. Hence, its main focus is on communication and collaboration in order to enhance the efficiency and support the decision-making operations. It assists in such activities as: electronic communication, scheduling, documents sharing, etc.

- *data-driven* (or *data-oriented*) – it concentrates on accessing and managing the available both internal and external data. Consequently, it includes applications apt to efficiently: search, manipulate, transfer, report, warehouse, analyse and display data.
- *document-driven* – in contrast to the predecessor, it specializes in management of unstructured information, which might be presented in many different formats. Thus, it incorporates the data processing technologies and applications permitting the manipulation and analysis of: documents containing descriptions, listings, records, correspondence, etc.
- *knowledge-driven* – its objective is to provide a specialized problem-solving expertise prepared on the basis of extensive knowledge of the addressed area. It might take the form of listings of facts, rules, procedures or similar arrangements. In essence, it suggests or recommends actions.
- *model-driven* – it works on the data and parameters provided by the user by employing the models, which gathered in a collection form a wide range of alternatives. Among many the variety includes: accounting, financial, statistical, analytical, representational, and optimization models.

The different types of the DSS also make it difficult to specify a standard guideline design to follow while building one. However, the analysis of the various authors proposals (Power and Sharda, 2009, Power, 2002, Sprague and Carlson, 1982) indicate that there might be distinguished three elements, which are perpetually mentioned in all the schemes (Figure 7.1):

- information management system,
- model base management system,
- module responsible for the communication dialogue, e.g.: user interface.

In essence, the information management system is responsible for the administration of data accumulated in storage structures such as the data-bases or data-warehouses. The latter term, in contrast to the first one, specifies the data depository constituent of immense size and complex architecture. The information can come from a number of both internal and external sources containing current (i.e.: freshly updated) and historical material. It needs to be kept in order and organized in a way that guarantees quick and easy: access, extraction and analysis. The format of used information does not have to be uniform and can include for example: documents (in document-driven DSS), collection of rules (in knowledge-driven DSS), data (in data-driven DSS), etc.

The model base management system administrates a collection of models and models' operating applications. This package contains alternatives, which vary depending on the addressed problem and solving objective, e.g.: defining relationships, information processing, analysis, etc. The singular selected approach must be able to handle data of special type and amount. The finally provided output is analysed and evaluated by the decision-maker, hence it needs to be delineated in a format both manageable by the user interface and legible for the user himself. As a consequence, the selection of one the most appropriate modelling approach constitutes the fundamental issue.

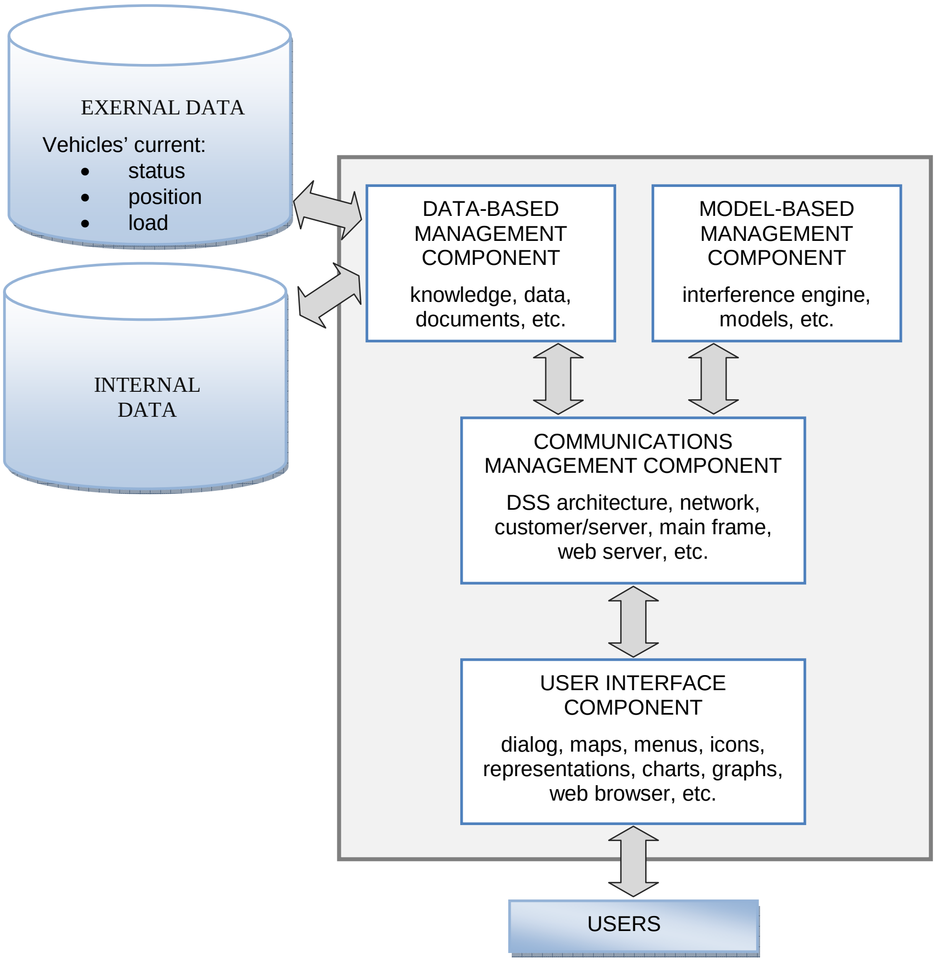


Figure 7.1 Key elements of a DSS framework (Power and R. Sharda, 2009)

In the design of the module responsible for the communication it is indispensable to pay special attention to the architecture of both hardware and software component parts. The efficiency of the entire DSS's operation depends on factors such as: organization of the technical equipment, manner in which the data is distributed and facilitated, the way in which the individual system's units are connected and allocated, etc. All these proceedings depend on the purpose, character and outcome the DSS is to provide. The complementary specifications such as e.g.: number of presupposed users and the scope of access into the decision-making process raise a question of security, which has to be addressed by the designer. This issue is of special importance having in mind the constant development of technologies and software. On this account, it is to expect that the networks environment and internet will constitute a standard foundation employed for communication purposes in the DSS's architecture. Because of the same reason, a special attention must also be paid to the design of user interface responsible for efficient information intercourse.

In addition to the above mentioned elements, the user himself might also be considered as fourth staple component in the structure of the DSS. In this context, there can be distinguished three basic processes which realization is substantial and which highlight the contribution of the decision-maker in the complete decision-making process confirming the necessity of his engagement:

- specification and collection of necessary data,
- selection of required methods to manage the data,
- evaluation or learning which results in comparison and exam of decisions in order to see if there is a need to change either the data being used or the data management methods.

With this point of view in mind, the general layout of the DSS could be formulated on the basis of the analysis of the addressed decision-making process and the decision-maker's participation. This strategy is presented in Figure 7.2. In this approach, the essential DSS's components would be: input data to analyse, user's knowledge for expertise, obtained outputs and taken decisions, while the collection of procedures would include: data management, learning and evaluation process. First, the decision-maker needs to select the necessary data. Their format and quality influence the decision if and what pre-processing methods should be used. In addition, the choice of the analytical tool and methodology depends both on the character of the data and the expected outcome. Once the information has been processed, the decision-maker studies the obtained result by comparing possible alternatives and deciding whether it is necessary to repeat the study with modified data set or by implementing another method. Finally, among all the possible solutions there is chosen one alternative to be executed.

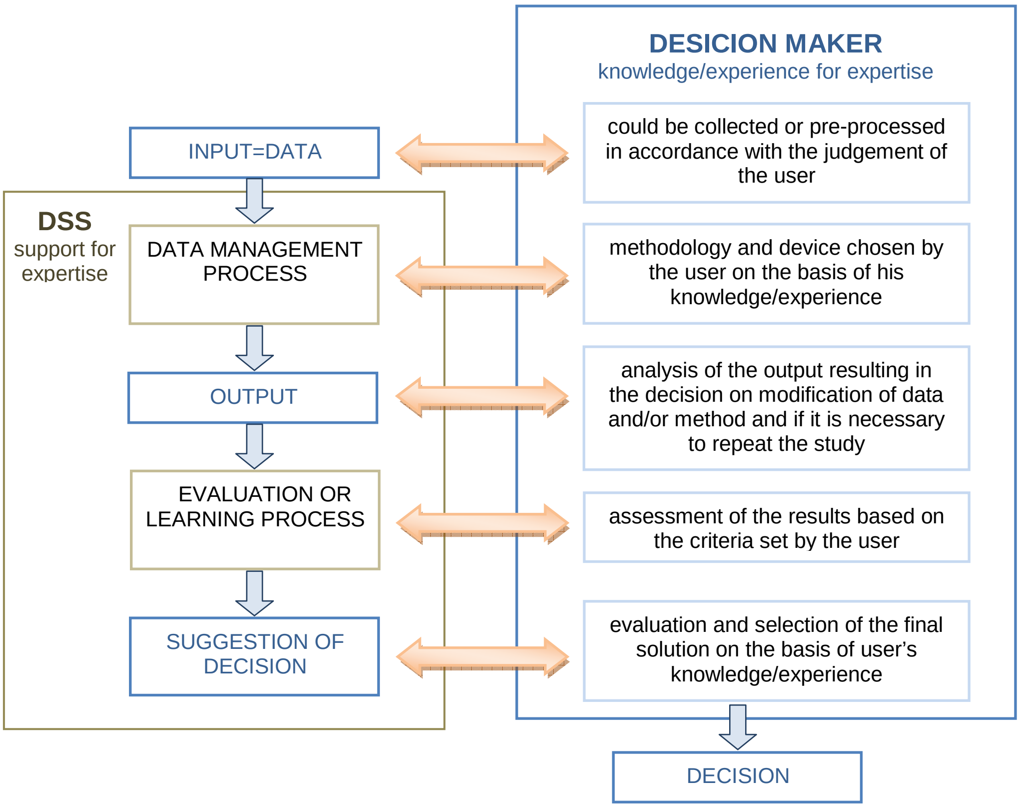


Figure 7.2 Decision-making process using a DSS

In sum, the DSS functioning depends on the effective performance of three functions:

- information management,
- data quantification,
- model manipulation.

On that account, the design of a modern DSS needs to take into consideration the specification of a software tool that meets user's needs and provides appropriate notification. The delivery of information has to be well-timed, which in practice means that it is available on demand. Also, the given data has to be up-to-the-minute, precise, applicable and sufficiently complete to provide the user with sufficient support when deciding. In this context, the format of the provided material is not without significance. It must be simple enough to be quickly interpreted and, when necessary, processed and transferred. Thus, it might take various forms. It could be displayed as: numerical inform (e.g.: statistics, forecasts, etc.), verbal record (e.g.: opinion, report, etc.), graphic feedback (e.g.: charts, schemes, maps, etc.) or other. The direct consequence of the choice regarding the data format is the selection of an appropriate application permitting its efficient management and modification, if necessary. Moreover, it is required from the DSS's information management process to be cheap. With respect to this, the emerging technological opportunities and resources allow achieving high-performance at the same time promising low operating costs in addition to flexibility and speed.

In the present thesis project, the framework of the proposed DSS has been arranged on the basis of the previously mentioned key elements. Notwithstanding, in order to specialise the design, there was paid a special attention to the dynamic aspect of the proposed CL optimization application. The urban network's dynamics, resulting in significant and constant variability of traffic conditions affecting the quality of freight's performance, impose consideration of the time-dependent travel time values. There should also be taken into account other variables resulting from the changeable nature of the addressed problem and which get revealed with the elapse of time (e.g.: new customers' requests). Hence, the efficient fleet management in city areas should be based on integration of the vehicle routing models and the real-time traffic information, while reckoning with the complementary dynamically revealed data. Consequently, the proposed DSS is to assist the freight manager in his choices on modifications of the current routing and scheduling plans in accordance with the freshly updated knowledge.

So, as presented by the example provided in Figure 7.3, it is assumed that part of the information is available at the very beginning of the decision-making process. It is used to create the initial time-dependent routing and scheduling plan (three routes in the example). While it is being executed according to the current traffic evolution, the new data regarding the addressed problem defining factors are registered (travel times, new customers' demands, fleet operational conditions, etc). As a consequence, the present plan can be updated at any moment and with the support provided by proposed DSS.

Hence, in the case when the new service requests are reported at time *t* the fleet manager may consult the solution suggestions offered by the DSS. The first decision that must be taken regards the acceptation of the new service task. If the new request is authorised, the second decision to take concerns the fact if it is feasible and profitable to insert the new couple of customers into the existing routes or if it is needed and possible to create a new route. When the first option is valid, there must be selected candidates of routes to incorporate new requests into. Next, in the case when the customers are to be introduced into the existing sequence of customers to visit, there need to be determined the most profitable and feasible positions to do so. Once all the necessary decisions are taken and all the specified modifications are performed, the newly updated routing plan is being executed. This cyclic procedure repeats until the end of the working day of the company delivering the goods.

The details regarding both the general design of the proposed DSS to be used by freight managing companies in city areas and the addressed decision-making process were presented in Chapter 5. The twofold objective of the current chapter is to provide description of each of the individual components designed and developed in terms of the approach, and to demonstrate the potential benefits resulting from enhanced efficiency, which affects company's competitiveness and profits.

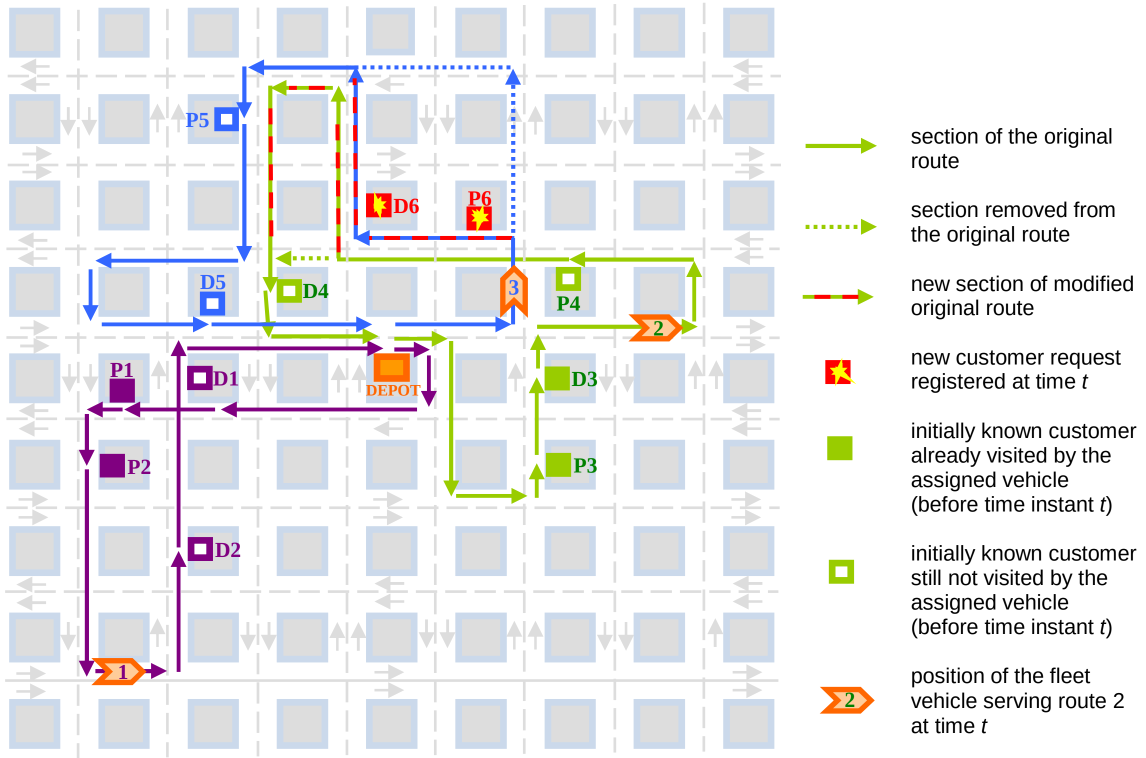


Figure 7.3 Dynamic modification of the current routing and scheduling plan on the basis of the real-time information in the city logistics environment (there are contemplated two alternatives: adjustment of route 2 - green and 3 - blue)

7.1 Time-Dependent Shortest Path Calculator

The objective of the TDSP Calculator is to provide quality information supporting the dynamic traffic assignment. A dispatcher may use the produced outcome of estimation as feedback for optimising the current routing and scheduling plan in a real-time fashion. Hence, the obtained result constitutes an essential input of the module defining freight routes of the proposed DSS.

The applications addressing the time-dependent (TD) shortest path problems might be found in many publications regarding logistics and distribution. Consequently, it was decided that the construction of the designed TDSP Calculator will be based on a known approach. As a core element, there was chosen the algorithm proposed by Ziliaskopoulos and Mahmassani (1993). It is due to the fact that when implemented on commercially available computers it can efficiently calculate the TD shortest paths for large street networks. Moreover, it was tested not only on four different sets of random networks, but also on a real street network. The main motivation of the original study was to calculate the shortest paths in a real-time environment, taking the advantage of a possible connection to the Intelligent Vehicle Highway System (IVHS), which corresponds with the set of objectives determined in the present thesis project.

The original objective of the employed algorithm is to calculate the TD shortest paths leading from all the nodes of the underlying network to one, specified as destination point. Hence, the obtained result might be defined as many-to-one (M2O). We propose to extend this approach in such a way, that the final outcome is of the many-to-many (M2M) type. It mainly involves modification of the data storing structures. On the other hand, the format of used input data is maintained. It is a matrix of arcs' costs estimated for all the existing network links and for every time interval over a time horizon of pre-established length.

7.1.1 Notation and Data Structures

Let G be a finite directed graph $G=(V, A)$, where $V=\{0, 1,\ldots, n\}$ is the set of the nodes representing the nodes of the networks and $A=\{(i, j): i, j \in V, i \neq j\}$ is the set of arcs designating the links that connect them. Each arc is associated a nonnegative cost $c_{ij}(t)$ that denotes the travel time from node i to j, when the departure time from node i is equal to the time instant t and where $c_{ij}(t) \neq 0$, for every i and j. The function $c_{ij}(t)$ is defined for every $t \in S$, where $S=\{t_0, t_0+\delta, t_0+2\delta,\ldots, t_0+M\delta\}$ and where:

- t_0 is the earliest possible departure time from any origin node of the network,
- δ designates a small time interval during which some noticeable changes in traffic conditions might be observed,
- time interval from t_0 to $t_0+M\delta$ constitutes the complete time horizon considered in the shortest paths evaluation process; hence M stands for a large integer number.

Moreover, it is assumed that:

- $c_{ij}(t)$ for $t > t_0+M\delta$ is constant and equal to $c_{ij}(t_0+M\delta)$,
- $c_{ij}(\tau) = c_{ij}(t_0+k\delta)$ for every τ in the interval $t_0+k\delta < \tau < t_0+(k+1)\delta$.

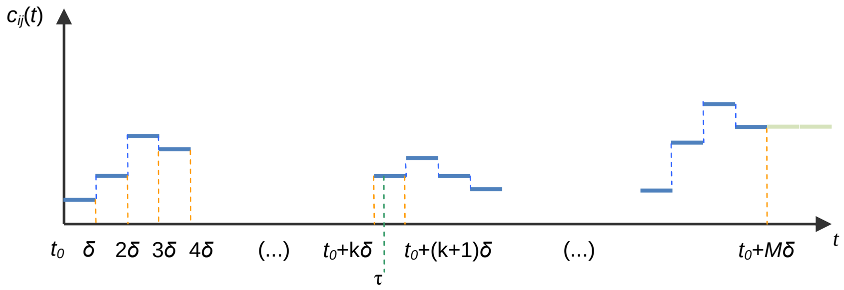


Figure 7.4 Example of graphical interpretation of the TD travel time $c_{ij}(t)$

Furthermore, as in the case of Ziliaskopoulos and Mahmassani (1993), there is also used a term of a *label* denoted as $\lambda_i(t)$. It corresponds to the total travel time of the current shortest path from node i to the singular, pre-established destination point N at time instant t. Its value is actualised at every step of the computational process. All the labels $\lambda_i(t)$ calculated at each time interval $t \in S$ are stored in the structure of a M-long vector: $\Lambda_i=[\lambda_i(t_0), ,..., \lambda_i(t_0+M\delta)]$. In order to support the M2M extended design of the algorithm this composition was modified. Instead of a vector we use a three-dimensional matrix: node origin i per node destination N per time interval. It is referred to as the *labels' cube*. The scheme of this structure is shown in Figure 7.5. The labels of the shortest paths which origin and destination constitutes the same node are marked as zero. Analogously, in the case when there is no existing path between two different nodes the value of its label is set equal to ∞.

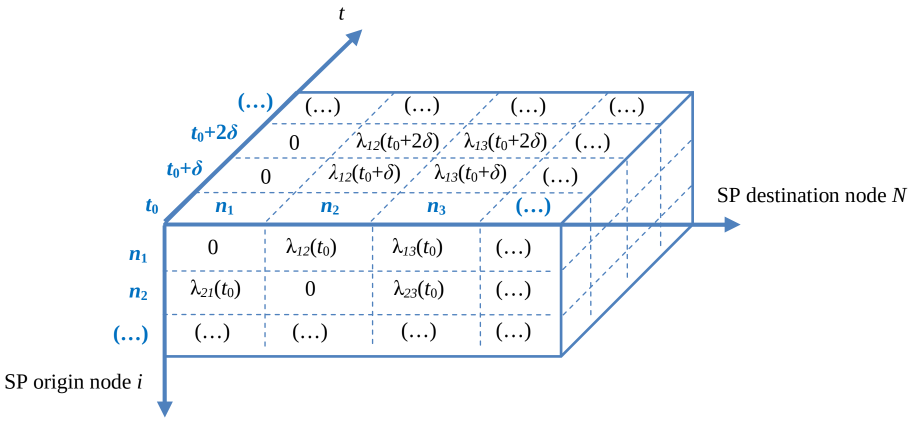


Figure 7.5 Scheme of the three-dimensional structure holding the values of the TDSPs (labels)

Moreover, in order to be able to specify the sequence of nodes n to pass through when following the shortest path departing from node i to reach the node N, Ziliaskopoulos and Mahmassani (1993) use another vector structure: $P_i=\{n_1, n_2,\ldots, n_m\}$, where $n_1=i$ and $n_m=N$. Similarly as before, this arrangement was modified and substituted by a three-dimensional matrix denoted the *SP cube*. It is presented in Figure 7.6 The substantial difference lays in the fact that each cell stores an identification of the closest node to visit at instant t, that we call *target* $T_{iN}(t)$. It takes the following values:

- 0 - if there is no existing connection (an arc or a path) between the two nodes,
- integer number - identification of the target node.

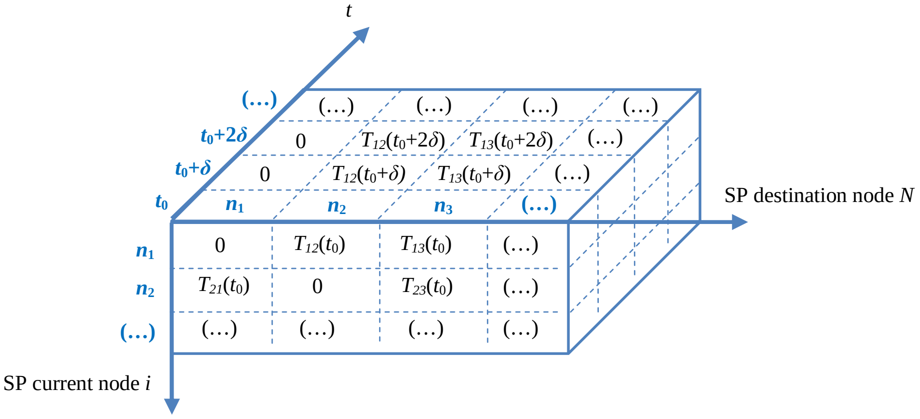


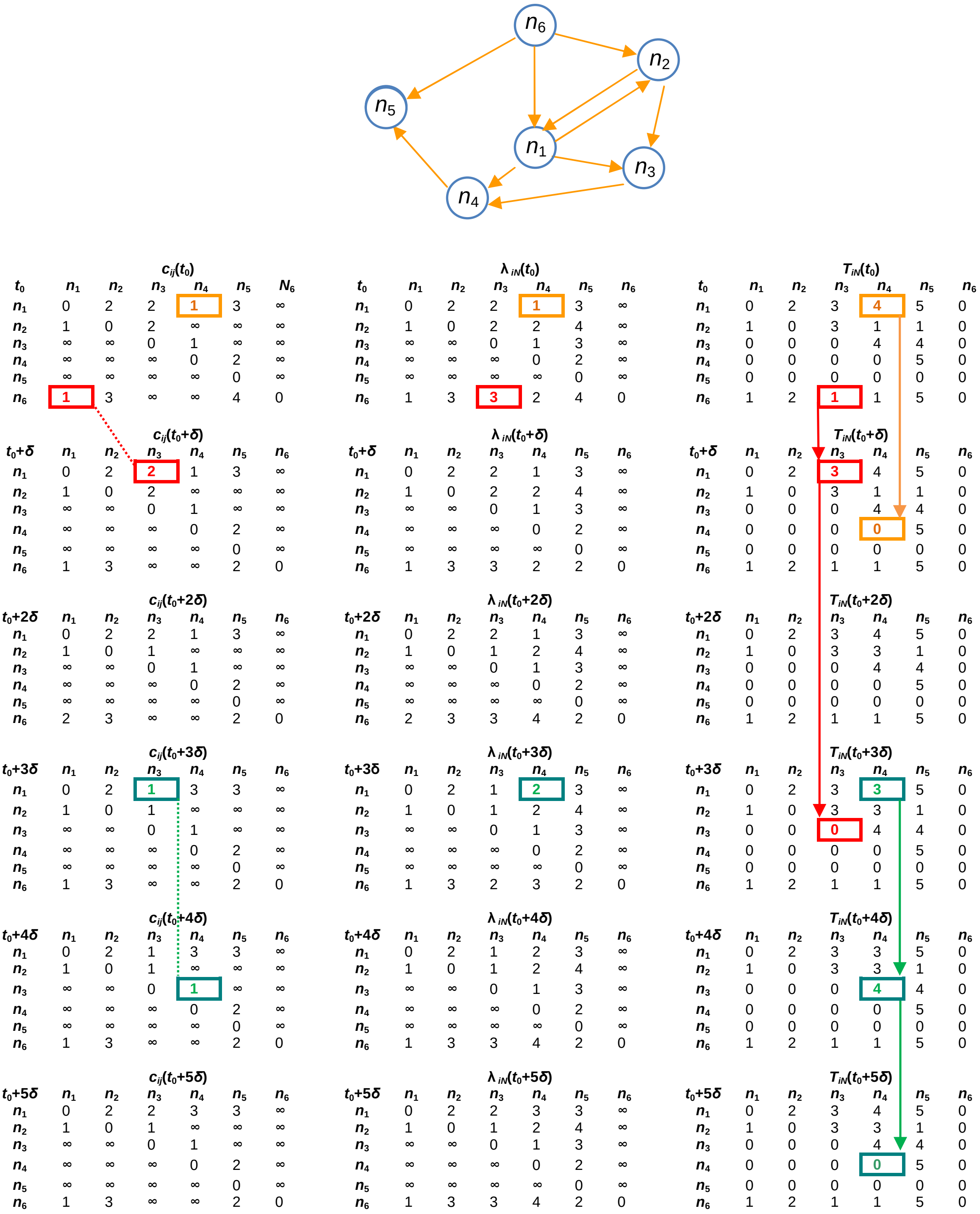
Figure 7.6 Scheme of the three-dimensional structure holding the target nodes defining the TDSPs

If the target node is directly reachable from the current node *i* it is necessary to pass through it in order to eventually arrive at the destination node *N* of the shortest path. This information is time-dependent, thus it may change as the time evolves. Consequently, the notation of the shortest path as a sequence of nodes is not straightforward and requires an additional search function, which output is an easily read array of nodes of the shortest path between the two nodes of interest: origin *i* and destination *N*. In order to clarify more the design and functioning of the above-mentioned structures, there is provided a simple example in Figure 7.7. Besides the graphical description of the exemplary network, it contains a collection of individual matrices showing at each time interval the original values of the TD travel cost $c_{ij}(t)$, the current shortest path value $\lambda_{iN}(t)$ and the record of the current target nodes to go through $T_{iN}(t)$.

In order to avoid scanning of all the nodes in every iteration Ziliaskopoulos and Mahmassani (1993) use a list of scan eligible nodes called: *SE list*. The SE list is designed as a *deque* and contains nodes with ability to improve the labels. The used structure permits insertion of elements both at the end and at the beginning of the listing. However, it is assumed that only the nodes located at the top of the record can be removed. All the manoeuvres in the SE list are performed in accordance with a pre-established strategy. The SE list is also used in the TDSP Calculator proposed in the present project.

The deque is implemented as a one-dimensional array and may contain the following values:

- -1 - if the node *i* has been introduced into the SE list at least once, but it is not there anymore,
- 0 - if the node *i* has never been introduced into the SE list,
- *j* - if the node *i* is currently present in the SE list and *j* is the next node to it in the list,
- ∞ - if the node *i* is the last node in the SE list.



$c_{ij}(t_0)$

t_0	n_1	n_2	n_3	n_4	n_5	N_6
n_1	0	2	2	1	3	∞
n_2	1	0	2	∞	∞	∞
n_3	∞	∞	0	1	∞	∞
n_4	∞	∞	∞	0	2	∞
n_5	∞	∞	∞	∞	0	∞
n_6	1	3	∞	∞	4	0

$\lambda_{iN}(t_0)$

t_0	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	2	1	3	∞
n_2	1	0	2	2	4	∞
n_3	∞	∞	0	1	3	∞
n_4	∞	∞	∞	0	2	∞
n_5	∞	∞	∞	∞	0	∞
n_6	1	3	3	2	4	0

$T_{iN}(t_0)$

t_0	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	3	4	5	0
n_2	1	0	3	1	1	0
n_3	0	0	0	4	4	0
n_4	0	0	0	0	5	0
n_5	0	0	0	0	0	0
n_6	1	2	1	1	5	0

$c_{ij}(t_0+\delta)$

$t_0+\delta$	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	2	1	3	∞
n_2	1	0	2	∞	∞	∞
n_3	∞	∞	0	1	∞	∞
n_4	∞	∞	∞	0	2	∞
n_5	∞	∞	∞	∞	0	∞
n_6	1	3	∞	∞	2	0

$\lambda_{iN}(t_0+\delta)$

$t_0+\delta$	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	2	1	3	∞
n_2	1	0	2	2	4	∞
n_3	∞	∞	0	1	3	∞
n_4	∞	∞	∞	0	2	∞
n_5	∞	∞	∞	∞	0	∞
n_6	1	3	3	2	2	0

$T_{iN}(t_0+\delta)$

$t_0+\delta$	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	3	4	5	0
n_2	1	0	3	1	1	0
n_3	0	0	0	4	4	0
n_4	0	0	0	0	5	0
n_5	0	0	0	0	0	0
n_6	1	2	1	1	5	0

$c_{ij}(t_0+2\delta)$

$t_0+2\delta$	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	2	1	3	∞
n_2	1	0	1	∞	∞	∞
n_3	∞	∞	0	1	∞	∞
n_4	∞	∞	∞	0	2	∞
n_5	∞	∞	∞	∞	0	∞
n_6	2	3	∞	∞	2	0

$\lambda_{iN}(t_0+2\delta)$

$t_0+2\delta$	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	2	1	3	∞
n_2	1	0	1	2	4	∞
n_3	∞	∞	0	1	3	∞
n_4	∞	∞	∞	0	2	∞
n_5	∞	∞	∞	∞	0	∞
n_6	2	3	3	4	2	0

$T_{iN}(t_0+2\delta)$

$t_0+2\delta$	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	3	4	5	0
n_2	1	0	3	3	1	0
n_3	0	0	0	4	4	0
n_4	0	0	0	0	5	0
n_5	0	0	0	0	0	0
n_6	1	2	1	1	5	0

$c_{ij}(t_0+3\delta)$

$t_0+3\delta$	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	1	3	3	∞
n_2	1	0	1	∞	∞	∞
n_3	∞	∞	0	1	∞	∞
n_4	∞	∞	∞	0	2	∞
n_5	∞	∞	∞	∞	0	∞
n_6	1	3	∞	∞	2	0

$\lambda_{iN}(t_0+3\delta)$

$t_0+3\delta$	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	1	2	3	∞
n_2	1	0	1	2	4	∞
n_3	∞	∞	0	1	3	∞
n_4	∞	∞	∞	0	2	∞
n_5	∞	∞	∞	∞	0	∞
n_6	1	3	2	3	2	0

$T_{iN}(t_0+3\delta)$

$t_0+3\delta$	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	3	3	5	0
n_2	1	0	3	3	1	0
n_3	0	0	0	4	4	0
n_4	0	0	0	0	5	0
n_5	0	0	0	0	0	0
n_6	1	2	1	1	5	0

$c_{ij}(t_0+4\delta)$

$t_0+4\delta$	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	1	3	3	∞
n_2	1	0	1	∞	∞	∞
n_3	∞	∞	0	1	∞	∞
n_4	∞	∞	∞	0	2	∞
n_5	∞	∞	∞	∞	0	∞
n_6	1	3	∞	∞	2	0

$\lambda_{iN}(t_0+4\delta)$

$t_0+4\delta$	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	1	2	3	∞
n_2	1	0	1	2	4	∞
n_3	∞	∞	0	1	3	∞
n_4	∞	∞	∞	0	2	∞
n_5	∞	∞	∞	∞	0	∞
n_6	1	3	3	4	2	0

$T_{iN}(t_0+4\delta)$

$t_0+4\delta$	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	3	3	5	0
n_2	1	0	3	3	1	0
n_3	0	0	0	4	4	0
n_4	0	0	0	0	5	0
n_5	0	0	0	0	0	0
n_6	1	2	1	1	5	0

$c_{ij}(t_0+5\delta)$

$t_0+5\delta$	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	2	3	3	∞
n_2	1	0	1	∞	∞	∞
n_3	∞	∞	0	1	∞	∞
n_4	∞	∞	∞	0	2	∞
n_5	∞	∞	∞	∞	0	∞
n_6	1	3	∞	∞	2	0

$\lambda_{iN}(t_0+5\delta)$

$t_0+5\delta$	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	2	3	3	∞
n_2	1	0	1	2	4	∞
n_3	∞	∞	0	1	3	∞
n_4	∞	∞	∞	0	2	∞
n_5	∞	∞	∞	∞	0	∞
n_6	1	3	3	4	2	0

$T_{iN}(t_0+5\delta)$

$t_0+5\delta$	n_1	n_2	n_3	n_4	n_5	n_6
n_1	0	2	3	4	5	0
n_2	1	0	3	3	1	0
n_3	0	0	0	4	4	0
n_4	0	0	0	0	5	0
n_5	0	0	0	0	0	0
n_6	1	2	1	1	5	0

Figure 7.7 Example of calculation and data storage of the TDSPs. There are highlighted three of all obtained sample paths: $SP_{1\text{-}4}(t_0)=\{1,4\}$, $\lambda_{1,4}(t_0)=1$; $SP_{1\text{-}4}(t_0+3\delta)=\{1,3, 4\}$, $\lambda_{1,4}(t_0+3\delta)=1+1=2$; $SP_{6\text{-}3}(t_0)=\{6, 1,3\}$, $\lambda_{6,3}(t_0)=1+2=3$

The first and the last node are indicated by two moving pointers denoted as: *FIRST* and *LAST*, accordingly.

Finally, the collection of neighbour nodes which are directly connected with arcs with a specific node *i*, is denoted as: $\Gamma^{-1}\{i\}$.

7.1.2 Time-Dependent Shortest Path Algorithm

As mentioned before, the proposed TDSP Calculator is based on the algorithm introduced by Ziliaskopoulos and Mahmassani (1993). However, in order to support the M2M extended design of the algorithm, its original composition was modified. The fundamental difference lies in the fact that the original process is performed multiple times and in each repetition a different node is chosen and set as a destination. In addition, the values of all the obtained labels and targets are stored in the amplified structures.

Once a destination node *N* is specified, in the first step of the algorithm, the SE list is initialised. We implement it as a fixed-size array, which length is specified by the number of all the nodes in the considered background network. At the position of the destination node *N*, the stored value is set equal to -1, while all the rest of the nodes are assigned with zero. Both pointers: FIRST and LAST indicate the same object on the list: the destination node *N*. Moreover, the label vectors are initialised as a part of the assembling cubic structure. For all the time intervals, the values of labels $\lambda_{NN}(t)$ are set equal to zero:

$$\Lambda_{NN} = [\lambda_{NN}(t_0) = 0, \lambda_{NN}(t_0 + \delta) = 0,..., \lambda_{NN}(t_0 + M\delta) = 0] \qquad (7.1)$$

For the rest of the nodes the label values are initialized as ∞. Therefore:

$$\Lambda_{iN} = [\lambda_{iN}(t_0) = \infty, \lambda_{iN}(t_0 + \delta) = \infty,..., \lambda_{iN}(t_0 + M\delta) = \infty] \qquad \forall\, i \in \{1, 2, ..., N\text{-}1\} \qquad (7.2)$$

The following step constitutes the *insertion procedure*. It starts with *removal* of the first node from the SE list. It is then called: the *current node*. Its corresponding value in the deque is set equal to -1. Then, at each time interval $t \in S$, all the direct neighbours *j* of the current node *i* (note that in the first iteration $i=N$) are examined in concordance with the equation:

$$\lambda_{ji}(t) = \min \{\lambda_{ji}(t), c_{ji}(t) + \lambda_{iN}(t + c_{ji}(t))\} \qquad j \in \Gamma^{-1}\{i\}, \qquad (7.3)$$

If the old value of $\lambda_{ji}(t)$ is greater than the one obtained by calculating: $c_{ji}(t) + \lambda_{iN}(t + c_{ji}(t))$, the figure previously saved in the label vector Λ_{ji} of the assembling structure is substituted with the new result. Moreover, if at least one of the components of this label vector is modified the node *j* is inserted in the SE list. The place of insertion: at the beginning or at the end of the deque, depends on the already stored value:

- if deque(*j*) = 0, the node *j* is inserted at the end of the SE list, consequently:
  - the value assigned at the position deque(LAST) is set equal to *j*,
  - the value assigned at the position deque(*j*) is set equal to ∞ ,
  - the pointer LAST gets updated and indicates *j*,

- if deque(*j*) = -1, the node *j* is inserted at the beginning of the SE list, consequently:

- the value assigned at the position deque(*j*) is set equal to the figure indicated by the FIRST pointer,
- the pointer FIRST gets updated and indicates *j*.

At this point, the information on the found closest neighbour *j* of the current node *i* is recorded in the SP cube defining the shortest paths.

When all the existing neighbours have been examined the routine is repeated. The first node in the SE list is processed in another iteration of the insertion procedure starting with its removal. The complete process lasts until the SE list remains empty. The obtained output is a matrix, which rows constitute *M*-dimensional label vectors Λ_{iN} containing the values of the TD shortest paths calculated for each time instance $t \in S$ from every node *i* to the pre-established destination node *N*.

The complete procedure is presented in a form of a pseudo-code shown by the Algorithm 7.1.

```
Let $N$ be the set of all the nodes
Let $\Lambda$ be the labels' cube containing labels $\lambda_{ij}(t)$ to be obtained for all the nodes origin $i$, destination $j$ and instance $t$
Let $SP$ be the SP cube containing target nodes to be obtained for all the nodes origin $i$, destination $j$ and instance $t$
For each node $i \in N$
    Let $destN$ be the destination node = $i$
    Initialise $\Lambda[destN][j][t] = \infty$ for all the nodes $j \in N$ and all time instances $t \in S$
    Initialise $SP[destN][j][t] = \infty$ for all the nodes $j \in N$ and all time instances $t \in S$
    For each time instance $t \in S$
        $\Lambda[destN][destN][t] = 0$
        $SP[destN][destN][t] = 0$
    End For
    Let $SE\_list$ be the deque of scan eligible nodes
    Initialise $SE\_list[j] = 0$ for all the nodes $j \in N$
    $SE\_list[destN] = -1$
    Let $FIRST$ be a pointer indicating the first node in the $SE\_list = destN$
    Let $LAST$ be a pointer indicating the last node in the $SE\_list = destN$
    Let $curN$ be the current node = $destN$
    While $FIRST \neq \infty$ and $FIRST \neq -1$
        Let $N\_list$ be the list of all the neighbours of node $curN$
        For each node $n \in N\_list$
            For each time instance $t \in S$
                Let $c_{n,curN}(t)$ be the cost of the arc joining node $n$ and $curN$ at instant $t$
                $\lambda_{n,destN}(t) = \Lambda[n][destN][t]$
                $\lambda_{n,destN}(t)^* = c_{n,curN}(t) + \lambda_{curN,destN}(t + c_{n,curN}(t))\}$
                If $\lambda_{n,destN}(t)^* < \lambda_{n,destN}(t)$
                    $\Lambda[n][destN][t] = \lambda_{n,destN}(t)^*$
                    $SP[n][destN][t] = n$
                    If $SE\_list[n] = 0$
                        $SE\_list[LAST] = n$
                        $LAST = n$
                        $SE\_list[n] = \infty$
                    Else
                        If $SE\_list[n] = -1$
```

```
                            SE_list[n] = FIRST
                            FIRST = n
                        End If
                    End Else
                End If
            End For
        End For
        curN = FIRST
        FIRST = SE_list[curN]
        SE_list[curN] = -1
    End While
End For
```

Algorithm 7.1 Algorithm performed by the TDSP Calculator

7.2 Initial Dynamic Routing and Scheduling Module

The output provided by the TDSP Calculator constitutes an input to the next segment of the proposed DSS: the Initial Routing and Scheduling Module. The construction of this component is based on the modified version of the meta-heuristic solving the PDVRPTW, which was selected from several tested alternatives presented in Chapter 6. The original algorithm needed to be adjusted due to the fact that the problem addressed at present has different characteristics.

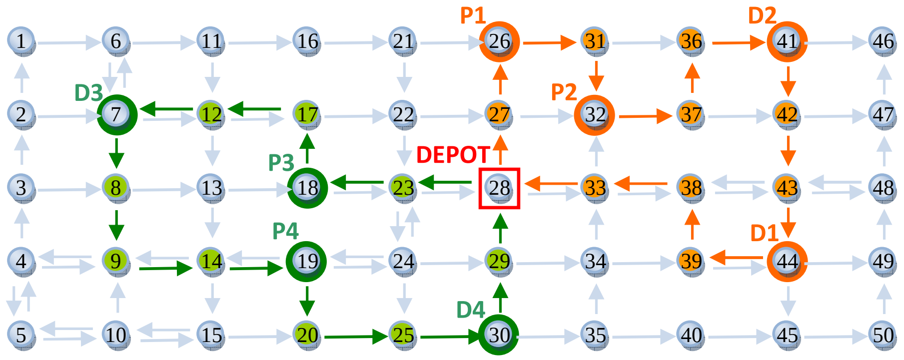
The studied problem is no longer static in a sense that the cost of a trip between two customers does not correspond to the Euclidean distance between them. Instead, there is considered the amount of time required to perform the TD shortest path. Consequently, the geographical location coordinates x, y are no longer needed. Each individual customer's location is determined by the numeric identification of the network graph's node to which it is assigned.

Moreover, the initial step of the original procedure in which the Euclidean distances are calculated and put into the costs matrix is omitted. In its place, there is performed a substitute process. On the basis of the result provided by the TDSP Calculator, it selects and stores in a multidimensional matrix the collection of values of the TD shortest paths between the nodes, to which the customers are assigned.

Besides modifying the costs data storing structures, all the functions and the mechanism using it needed to be adjusted to take into account their TD character. Hence, each time a travel time cost between two customers is consulted it is checked with respect to the time instant the vehicle is to leave the corresponding origin customer.

Consequently, the produced output constitutes a collection of TD routes used as the initial routing and scheduling plan. A graphical example of the IRSM outcome is presented in Figure 7.8. All the routes start and end at the singular depot and are constructed in a way that all the pre-specified constraints regarding: TWs, vehicles' capacity, customers' precedence and pairing are respected. Each sequence of customers is complemented with the queue of successive nodes specifying the shortest paths between them that a vehicle needs to go through.

For this reason, there was implemented an additional data structure holding the sequence of nodes specifying each shortest path. Although it is not used at this stage of the complete approach it needs to be kept in order to be employed in the subsequent step performed by the VFP Simulator.



Route 1: 28 (DEPOT), 27, 26 (P1), 31, 32 (P2), 37, 36, 41 (D2), 42, 43, 44 (D1), 39, 38, 33, 28 (DEPOT)
Route 2: 28 (DEPOT), 23, 18 (P3), 17, 12, 7 (D3), 8, 9, 14, 19 (P4), 20, 25, 30 (D4), 29, 28 (DEPOT)

Figure 7.8 Graphical example of the IRSM's outcome

7.3 Dynamic Routing and Scheduling Module

The basic objective of the Dynamic Routing and Scheduling Module is to update the current routing and scheduling plan in accordance with the newly revealed information regarding: customers' requests and service conditions (demands, TWs, etc.), operational conditions of employed fleet (vehicles' availability, status, positions, current occupancy of the carriage space, etc.) and the traffic conditions.

The procedure developed for the IRSM was used as a base for construction of the DRSM. Thus, it consists of three consecutive steps: initial solution creation procedure, PTS optimization process and NPDPRO post-optimization routine. Notwithstanding, all the algorithms needed to be modified so that the new dynamic elements of the addressed problem were taken into account.

One of the essential differences between the initial and the dynamic routing and scheduling module is the composition of the routes. In the case of the IRSM, the depot is determined as the first element in the sequence of location points to be visited by the assigned vehicle. Also, the number of customers contained by each route is even. The DRSM manages routes, for which the first element is specified by the current location of the vehicle performing the circuit. The subsequent destination points are the customers, which have not yet been served. Thus, a single route does not have to contain an even number of customers and does not have to consist of the complete pairs since a part of the route may have already been performed. As a consequence, the delivery customers for which pickup partners have been served cannot be moved to different routes in any of the optimization and post-optimization processes. This is inconsistent with the imposed pairing constraint.

Next fundamental difference between the two modules regards the description of the freight vehicles. For the needs of the DRSM there was introduced an additional vehicle defining feature called the *vehicle status*, v_{stat}. Its objective is to specify the action which is being performed by the vehicle at the time instant t triggering the recalculation of the current routing and scheduling plan. The listing of possible tasks includes:

- v_{stat}=*SERV* : if the vehicle is currently providing a customer with the service,
- v_{stat}=*WAIT* : if the vehicle is currently waiting at customer's location for his time window to be opened,
- v_{stat}=*MOVE* : if the vehicle is currently on its way to the next customer,
- v_{stat}=*IDLE* : if the vehicle is currently housed at the depot.

The procedure developed for the IRSM does not require specification of the vehicles' status. Notwithstanding, since all the considered vehicles are housed at the depot, their status can be defined as *IDLE*.

For the DRSM purposes, in relation to the v_{stat} specifications, there were also introduced additional variables regarding the remaining time to finish the currently carried activity. They are marked with a hat.

In contrast to the IRSM, which is executed only once, the DRSM is initiated multiple times. It is activated by a specified trigger referred to as the *event*. The collection of the events was selected in a way to ensure the immediate response to the major dynamic factors affecting the studied problem. They are: changes in the record of the customers requesting service, changes in the intensity of the traffic and the changes in the efficiency of the vehicle fleet's performance. Thus the listing of events includes:

- external event : registration of a call from a new pair of customers requesting service,
- interval events :
  - end of providing a current customer with requested service,
  - arrival to a scheduled customer after his TW was closed.

In the latter case, due to the traffic being more intense than expected, it was not possible to serve the scheduled customer. If this customer requests pickup, it is placed common with its delivery partner in a set-apart *list of unfulfilled assignments* U_{cv}. If it is the delivery customer, it is also removed from the current route and it is not taken into account when updating the routing plan. At the end of the complete experiment the summarised number of elements in the U_{cv} list serves as indication of the proposed approach's efficiency. In the real life the information on non-served customers is kept with the intention to be used to create the initial routing plan at the very beginning of the next working day. In addition, depending on the company's policy there are employed measures aiming at compensating the customer for the occurred delay. Also, the freight company must ensure safekeeping of the picked up goods, which could not be delivered, or to renegotiate the terms of fulfilment of the troublesome order. Thus, to the general costs of transport there need to be added the additional costs associated with the storage and/or modification of the contract with the customer.

If a new request for service appears while the routing plan is already being executed it is valid and necessary to modify the original graph by adding an additional node representing the new customer's position and redefining the arcs. However, in the present thesis project it is assumed that the new service call is always made by a customer, whose location can be specified by one of the already existing network nodes. In this way, the structures and the data variables specifying the customers, such as their: TWs, demand, service time, etc., maintain the same, original format.

The biggest change made in the design of the DRSM with respect to the architecture of the IRSM regards the initial solution creation procedure. The IRSM composes the initial routing and scheduling plan from scratch, in accordance with the rule of minimal increment of the solution's cost, using the record of historical travel times and the data specifying known customers' requests. In contrast, the DRSM focuses on optimal modification of the existing routes in accordance with: the updated forecast of traffic conditions, the current report on vehicles performance and the information on newly reported customer's demands.

Thus, at the time instant *t* triggering the recalculation of the current routing and scheduling plan, the first operation performed by the DRSM is to verify both the number of routes that are being executed and the current status of each vehicle. Next, depending on the v_{stat} for each newly planned route there is specified the initial location point:

- if v_{stat}=*SERV* : the first customer of the novel route is the currently served customer (once the serving activity has been started it cannot be aborted),
- if v_{stat}=*WAIT* : as the first customer of the novel route there is created a "dummy" depot which is a copy of the customer the vehicle is currently waiting at (this approach allows redirection of the vehicle while it is waiting),
- if v_{stat}=*MOVE* : as the first customer of the novel route there is created a "dummy" depot; its location corresponds to the destination node of the arc it is currently on (the vehicle is not obliged to visit the lastly assigned next customer; once it reaches the end of the section it can follow a newly proposed path),
- if v_{stat}=*IDLE* : in the case when a new route is created the depot is its first customer.

Subsequently, in accordance with the specified v_{stat}, for each route there is calculated the value of remaining time to finish the currently carried activity.

In continuation, there are reviewed all the customers which still have not been provided with the requested service. In the case when there are identified delivery customers whose pickup partners' loads have already been collected, they are featured as the customers that need to be served obligatorily by the initially assigned vehicle. Thus, for each identified original route there is defined a list of mandatory delivery locations to visit.

The following operation is the initial solution creation procedure. At this stage, there are contemplated two alternatives: the *Dynamic Complete Solution Reconstruction Method* (*CSR*) and the *Dynamic Single Pair Insertion Procedure* (*SPI*).

The objective of the first approach, similarly as in the case of the IRSM algorithm, is to build a new routing and scheduling plan from scratch but with special consideration of the delivery customers which must be obligatorily visited by the originally assigned vehicles.

The dynamic SPI procedure does not remove any of the customers from the originally planned sequences, except from these that have already been served or which could not have been served since their TW was missed. Its objective is to introduce the new pair of customers in the most favourable location in the current routes respecting all the imposed constraints. In the case when the feasible insertion is not possible, there is created a new route containing the new pair.

In both of the reviewed methods the input constitutes of:

- the original routing and scheduling plan,
- a list containing newly reported pairs of customers requesting service (it can be empty),
- information on travel times delivered by the TDSP Calculator computed on the basis of the data provided by the Time-Dependent Travel Time Data Forecasting Module.

7.3.1 Notation

In the description of the two contemplated initial solution creating procedures for the DRSM there is employed the following notation:

t : time instant of the event,
i : a customer that was not served by assigned vehicle v before time instant t, if:
  i=0 – location i is a customer that at time instant t is being provided with the service or hosts waiting vehicle,
  i=1 – location i is the first customer in the current sequence, that was not reached by the assigned vehicle v before time instant t,
D : node in the graph defining the position of the depot,
D' : dummy depot,
v_{stat} : vehicle status denoted as either: *MOVE*, *SERV*, *WAIT* or *IDLE*,
v_{r_pos} : location defining current position of the vehicle performing route r when at time instant t its v_{stat}=*MOVE*,
$T^F_{i,j}(t)$: forecasted value of the TD travel time between customers i and j when the trip starts at time instant t,
$\hat{T}^F_{i,j}(t)$: forecasted remaining TD travel time between customers i and j when the trip starts at time instant t,
a^F_i : forecasted arrival time to customer i,
w^F_i : forecasted waiting time at customer i,
$\hat{w}^F_i$: forecasted remaining waiting time to perform at customer i, when v_{stat}=*WAIT*,
s_i : service time of customer i,
$\hat{s}_i$: remaining service time to perform at customer i, when v_{stat}=*SERV*,
d_i : demand of customer i,
e_i : lower-bound of time window of customer i; it is the earliest moment when vehicle may start giving service to customer i,
l_i : upper-bound of time window of customer i; it is the latest moment when vehicle may start giving service to customer i,
$q_v(i)$: current occupancy of vehicle's v capacity after serving customer i,
Q_v : total capacity of vehicle v.

7.3.2 Time-Dependent Computation

Both alternative methods considered as basis for construction of DRSM, create a new routing plan reckoning with dynamic factors affecting the problem: current traffic development, new requests and freight vehicles' operational state. Hence, in contrast to the static approach, the variables specifying: travel, arrival and waiting time for all not visited customers are calculated with respect to the triggering instant *t* and depend on the moment a trip between two customers starts.

The value of the forecasted arrival time to the first customer *i* in the updated sequence, which has not been served by the assigned vehicle *v* before the time instant *t*, is estimated taking into consideration its present status. Depending on the v_{stat}, there needs to be evaluated the remaining time of the activity performed at the moment. Either it is waiting, serving or being on the move.

Thus, in order to determine a_i^F where *i* is the first customer in the new sequence, in each case it is necessary to employ a corresponding equation:

if v_{stat}=*MOVE*,

$$a_i^F = t + T_{V_{r\_pos},i}^F(t) \qquad \text{for } i=1 \qquad (7.4)$$

if v_{stat}=*SERV*,

$$a_i^F = t + \hat{s}_{i-1} + T_{i-1,i}^F(t + \hat{s}_{i-1}) \qquad \text{for } i=1 \qquad (7.5)$$

if v_{stat}=*WAIT*,

if a vehicle is not diverted:

$$a_i^F = t + \hat{w}_{i-1}^F + s_{i-1} + T_{i-1,i}^F(t + \hat{w}_{i-1}^F + s_{i-1}) \qquad \text{for } i=1 \qquad (7.6)$$

if a vehicle is diverted

$$a_i^F = t + T_{i-1,i}^F(t) \qquad \text{for } i=1 \qquad (7.7)$$

if v_{stat}=*IDLE*,

$$a_i^F = t + T_{D,i}^F(t) \qquad \text{for } i=1 \qquad (7.8)$$

The forecasted arrival time to the customers subsequent to the first non-served customer *i* is estimated independently from the current vehicle status:

$$a_{i+1}^F = a_i^F + s_i + w_i^F + T_{i,i+1}^F(a_i^F + s_i + w_i^F) \qquad \text{for } i>0 \qquad (7.9)$$

Similarly, the forecasted waiting time for all not served customers *i* is evaluated in accordance with equation:

$$w_i^F = \max\{0, e_i - a_i^F\} \qquad \text{for } i>0 \qquad (7.10)$$

The forecasted remaining waiting time for the first not served customer *i*, when v_{stat}=*WAIT* is calculated as follows:

$$w_i^F = e_i - t \qquad \text{for } i\text{=0} \qquad (7.11)$$

The remaining service time for the first not served customer *i*, when v_{stat}=*SERV*, is provided by the formula:

$$\hat{s}_i = \max(a_i, e_i) + s_i - t \qquad \text{for } i\text{=0} \qquad (7.12)$$

7.3.3 Dynamic Complete Solution Reconstruction Method

This method destroys the current routes and reconstructs them paying special attention to the delivery customers whose pickup partners have already been served.

In the first step of the method there is created a list of all the customers V_S, static and dynamic, which requested service before event *t*. From this record, there are removed all customers which have already been served. There are also eliminated the customers which were visited by the assigned vehicles, but could not be served since their TW was closed. If these customers demanded pickup their delivery partners are erased as well. Next, from the current listing there are removed the customers *i* for which $l_i<t$. Their corresponding pair partners are also eliminated. The final list V_S will be used to create the new routing and scheduling plan.

Subsequently, the current status of each vehicle is checked. There are created dummy depots if necessary. Each dummy depot requires pickup service, but it is not assigned a delivery partner. There are estimated the values of remaining times of the activities that were being performed at time instant *t* of the event. This process is presented in the form of a pseudo-code by Algorithm 7.2.

```
Let $V$ be the set of all the vehicles in the fleet
Let $N$ be the set of all the customers
For each $v \in V$ and $v_{stat} \neq$ IDLE
    If $v_{stat}$=WAIT at customer $i$ assigned to graph node $g$
        Create dummy depot D' assigned to graph node $g$, such that:
        D' = N+1
        $d_{D'} = q_v(i-1)$
        $s_{D'} = 0$
        N=N+1
    Else if $v_{stat}$=MOVE to node $g$
        Create dummy depot D' assigned to graph node $g$ such that:
        D' = N+1
        $d_{D'} = q_v(i-1)$
        $s_{D'} = T_{g-1,g}(a_{g-1}) - (t - a_{g-1})$
        N=N+1
    Else if $v_{stat}$=SERV customer $i$
        $\hat{s}_i = \max(a_i, e_i) + s_i - t$
    End if
End for
```

Algorithm 7.2 Dummy customers' creation procedure

Next, there is executed the forecasting module, which provides data on TD travel times between customers to be served and nodes defining current positions of the vehicles, both dummy and actual.

For each vehicle there is created a route which starts at the node defining its location and ends at the depot. Then, there are inserted the mandatory delivery customers whose pickup partners have already been served by it. Once introduced, they are sorted in accordance with the growing value of their TW's upper-bound. The customers which TW closes the soonest will be visited first. Consequently, the initial solution consists of routes containing only the mandatory delivery customers. The number of routes can be smaller than in the original routing plan.

Next, one by one, all customer pairs from list V_S, are inserted into the existing routes fulfilling the: pairing, precedence, TWs and capacity constraints. The first two restrictions are enforced as a matter of course of the design of the insertion process. Thus, the feasibility check regards verification if both the TWs and the capacity constraints are violated.

The route *r* is still feasible after the insertion of the customer *n* between customers *i* and *i*+1 if:

$$a_j^F \le l_j \qquad \text{for all customers } j\in r \text{ and } j=\{n, i+1,\dots,D\} \tag{7.13}$$

and

$$q_v(j) \le Q_v \qquad \text{for all customers } j\in r \text{ and } j=\{n, i+1,\dots,D\} \tag{7.14}$$

Each route, in which it is feasible to introduce a specific pair of customers, is determined as a *candidate*. Among all the candidates there is selected the one, which characterizes with the smallest value of the increment of the total cost. In the case when it is not feasible to introduce a pair in any of the existing routes a new route is created. The entire dynamic CSR method is provided by the Algorithm 7.3.

```
Let $R$ be the set of initial routes containing mandatory delivery customers
Let $R'=0$ be the set of candidate routes
Let $V_S$ be the list of pairs $P$ to be visited
For each pair $P\in V_S$
    Let $p$ be a pickup customer from pair $P$ and $d$ be its delivery partner
    For each $r\in R$
        Calculate $a_i^F$ for all $i\in r$
        For each $i\in r$ and $i\neq D$
            Insert $p$ after $i$
            Update $a_i^F$ for all $i=\{p, i+1,\dots,D\}$
            Perform feasibility check
            For each customer $j\in r$ and $j=\{p, i+1,\dots,D-1\}$
                Insert $d$ after $j$
                Update $a_j^F$ for all $j=\{d, i+1,\dots,D\}$
                Perform feasibility check
                If it is feasible to insert the pair $P$ in $r$
                    Define $r$ as a candidate and add it to the list $R'$
                End if
```

```
            End for
        End For
    End For
    From all $r\in R'$ pick the route which $a_D^F$ is minimal and substitute the corresponding original route
    If the insertion of $P$ in any $r\in R$ is not feasible
        Create new route {D-p-d-D}
    End if
End For
```

Algorithm 7.3 Dynamic Complete Solution Reconstruction Method

7.3.4 Dynamic Single Pair Insertion Procedure

The SPI method is based on the idea to keep the original routing and scheduling plan as little changed as possible. This strategy is commonly used in the real life since it is preferred by the freight drivers. Thus, the objective of the dynamic SPI procedure is to incorporate a dynamic pickup/delivery pair of customers in the most favourable location in one of the original routes without violating any of the pre-established constraints.

The method starts with removal from the original routes the customers which have already been served and those which although visited were not served since their TW was closed. In the latter case, non-served pickup customers are removed along with their corresponding delivery partners. Next, similarly as in the case of CSR method, there is reviewed current status of each freight vehicle and there is created a dummy depot when necessary.

For each vehicle there is specified a list of mandatory delivery customers to be visited. It is then checked if they are part of the route to be performed by this vehicle. If this is not the case, those customers are removed from their current locations and inserted in the routes of the vehicles they have to be served by, following the rule of the minimal increment of the route's cost.

In continuation, for all the present routes there are identified both the most profitable and feasible locations to insert the pickup and the delivery customers of the dynamic pairs. If it is not feasible to insert a pair a new route is created. The complete dynamic SPI process is explained in form of a pseudo-code by the Algorithm 7.4.

```
Let $R$ be the set of all original routes
For each $r\in R$
    Remove served customers
    Remove customers which were visited but could not be served since their TW was closed
    If removed customer is pickup
        Remove also its delivery partner
    End if
    Verify $v_{stat}$ and create dummy depot if necessary
    Let $C_r$ be the list of mandatory delivery customers of route $r$
    If mandatory customer $c\in C_r$ and is $c\notin r$
        Insert $c$ in $r$
    End if
End For
Let $V_D$ be the list of dynamic pairs requesting service
```

```
For each pair $P \in V_D$
Let $p$ be a pickup customer from pair $P$ and $d$ be its delivery partner
    For each $r \in R$
        Calculate $a_i^F$ for all $i \in r$
        For each $i \in r$ and $i \neq D$
            Insert $p$ after $i$
            Update $a_i^F$ for all $i = \{p, i+1, \ldots, D\}$
            Perform feasibility check
            For each customer $j \in r$ and $j = \{p, i+1, \ldots, D-1\}$
                Insert $d$ after $j$
                Update $a_j^F$ for all $j = \{d, i+1, \ldots, D\}$
                Perform feasibility check
                If it is feasible to insert the pair $P$ in $r$
                    Define $r$ as a candidate and add it to the list $R'$
                End if
            End for
        End For
    End For
    From all $r \in R'$ pick the route which $a_D^F$ is minimal and substitute the corresponding original route
    If the insertion of $P$ in any $r \in R$ is not feasible
        Create new route {D-p-d-D}
    End if
End For
```

Algorithm 7.4 Dynamic Single Pair Insertion Procedure

In the present thesis project, both dynamic CSR and SPI methods deal with one customer and one pair at a time. However, at the time instant *t* of an event, there can be registered more than one new request of service. We consider cases when 2 requests arrive at the same time. The pair that is inserted first is picked up at random.

Notwithstanding, in the cases when high number of requests are registered at once there should be defined and implemented an additional process specifying the order in which the newly reported pairs of customers are to be inserted into the existing routes.

7.3.5 Dynamic Modifications of Both Parallel Tabu Search and Normal Pickup and Delivery Pair Rearrange Operator

Once the initial dynamic solution is determined it is subjected to PTS optimization procedure followed by the NPDPRO post-optimization method. The functioning of these processes is explained in details in Chapter 6. The DRSM respects the general architecture of both of these methods. However, due to the fact that the addressed problem is dynamic there are taken into consideration additional restrictions.

As mentioned before in the current chapter, at the time instant *t* of the event, some customers in each route might have already been served. Thus, the PTS local search operators NPDPSO, NPDPEO as well as the post-optimization procedure NPDPRO shall only consider replacements of complete pairs of non-served customers. The delivery customers which pickup partners have already been served remain assigned to the same route.

Also, there was modified the way of calculating the variable defining the number of iterations θ of the PTS procedure during which it is forbidden to perform the movement of incorporating the selected pair into the determined route. In the IRSM it is equal to the integer number closest to the result of the following formula: $\theta=[7.5\log_{10}n]$, where n corresponds to the number of all the customers. The value of n is fixed since it is known in advance and there are no new requests considered. For the purposes of the DRSM, θ is calculated using the same formula. However, the value of n is not fixed and it is equal to the current number of customers still left to be provided with the service. It is updated before the execution of the PTS procedure and it includes the newly reported pairs of customers if they were inserted in the current routes in the previous operation.

The most important difference between the PTS and NPDPRO algorithms presented in Chapter 6 and their modified versions used in the DRSM regards the format of used travel time data. In the static version, the cost of a trip between two customers is represented as Euclidean distance or as fixed value of time. In the DRSM, this cost is defined as the amount of time spent on performing the TD shortest path. As a consequence, in each operation of both the PTS and the NPDPRO there must be paid careful attention to the moments when the vehicles start the trips.

7.4 Time-Dependent Travel Time Data Forecasting Module

Having in mind, the progress of technological development resulting in faster access to data, it is reasonable to assume the possibility of admission to detailed traffic information of the selected network sections in real-time. Beside the observation of the current states, the more efficient tools and mechanisms for data storage and analysis permit also the examination of the historical records and preparation of effective forecasts of future changes. On that account, in the present thesis project, it is assumed that the user of the proposed DSS is granted the access to the traffic data provided by an ATIS. Consequently, at any time instant he/she gets acquainted with the current state of the network's performance, as well as with the collection of the historical data on the basis of which it is possible to make projections for the future. In this context, it is expected from the decision-maker to utilise a forecasting device informing on the possible future changes in the networks' operation.

In order to emulate the functioning of such forecasting appliance, there was developed the Time-Dependent Travel Time Data Forecasting Module. It does not constitute an integral part of the proposed DSS and can be substituted by any other professional travel time data forecasting device. Notwithstanding, it is necessary to reckon with this module since it provides the essential input to the DSS. Its objective is to arrange the information provided by two data bases representing the historical and the current network states accordingly, so that the newly obtained composition could be utilised as forecast. Hence, the design of the forecasting module was based on exponential smoothing - a simple technique, which can be applied to the time series data in order to make forecasts. It employs the moving average, which is able to smooth the short-term fluctuations and highlight the long-term trends. It is called exponential, since the weighting factor α decreases in exponential fashion. The values of α change within the (0, 1) limits. If it is close to one the data smoothing effect is lighter and a greater weight is given to the recent changes in the data. In the contrary case, when it is closer to zero, a greater smoothing effect is obtained and the historical report is more important.

There is no specific way to rate α. Its value might be determined in accordance with the statistician's judgment and experience or as a conclusion of analysis of the result of the empirical tests. For the purposes of the present thesis project, it was decided to represent α in terms of number of remaining intervals T and by that link it with the variable of time:

$$\alpha(t) = \frac{2}{T+1} \tag{7.15}$$

where:

$\alpha\,(t)$: weighting factor depending on remaining time intervals T,
t : specific time interval in the future,
T : number of the time intervals left until the end of the complete horizon $T \leq \tau$,
τ : complete number of the time intervals within the complete horizon.

The interpretation of the idea behind the proposed Time-Dependent Travel Time Data Forecasting Module is presented in Figure 7.9. It employs the following additional notation:

t_0 : current time interval, that $t_0 \leq t$,
j : arc of the network's graph,
A : set of all the arcs of the network's graph,
$c_j^H(t)$: travel time on arc j at time interval t stored in historical data base,
$c_j^P(t)$: travel time on arc j at time interval t stored in data base representing present,
$c_j^F(t)$: the forecasted value of the travel time on arc j at time interval t.

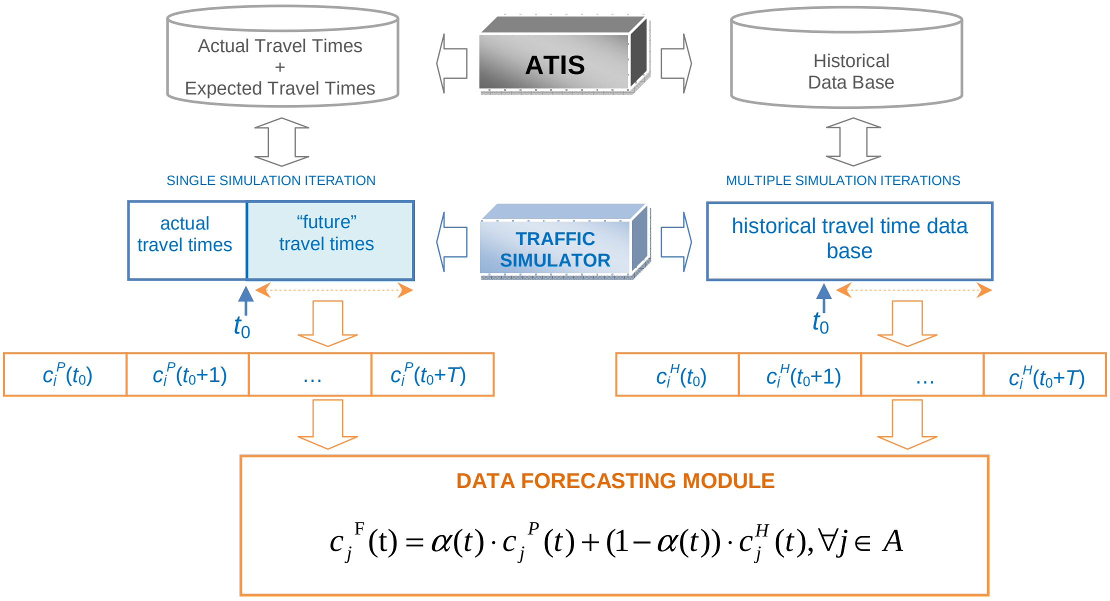


Figure 7.9 Time-Dependent Travel Time Data Forecasting Module

In order to illustrate the functioning of the proposed Time-Dependent Travel Time Data Forecasting Module, Figure 7.10 provides as an example the collection of graphs demonstrating the obtained forecasting result, when considering different number of time intervals T. There is also presented the adaptation of $\alpha\,(t)$ function for each alternative accordingly.

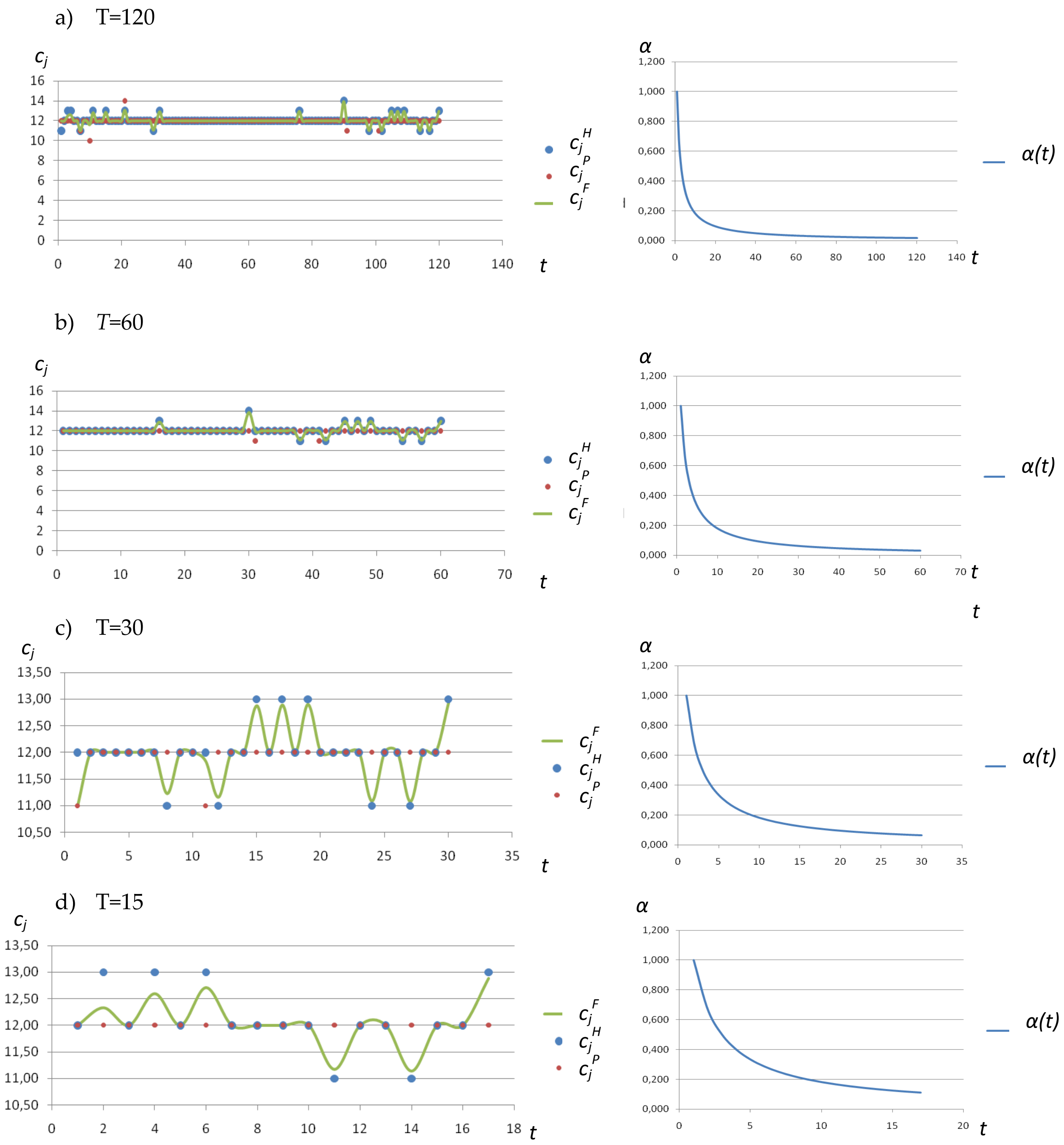


Figure 7.10 Example demonstrating the functioning of the Time-Dependent Travel Time Data Forecasting Module for one, randomly chosen arc *j*

7.5 Vehicle Fleet Performance Simulator

Once the routing plan is created it is to be performed by the freight fleet. We assume that the used vehicles are equipped with both GPS and GPRS or another device permitting to specify their exact location, the activity they currently perform and the amount of carried load. At this point of the project, the most desirable alternative for testing the proposed DSS, keeping in mind the limited possibilities of employing the proposed approach in the real-life environment, would be to link the previously explained routing and scheduling modules to a commercially available traffic simulator with particular features. The employed simulator has to permit specification of attributes defining: customers, depot and group of vehicles belonging to the fleet. It has to be able to execute the created routing plan and to permit tracking of the individual cars within the urban traffic environment. Besides, it has to guarantee the possibility of stopping the simulation experiment at any time instant and once the performance is retaken, follow up with the modified version of the routing plan. Therefore, it needs to provide an output consisting of a collection of data defining the vehicles behaviour, which in the real life would be given by systems such as the GPS and GPRS. This information is necessary to adjust the current routing plan.

In the present day, the commercially available traffic simulators do not characterise with all the above-mentioned features, which are essential for the undertaken project. Moreover, they do not permit the users to introduce necessary modifications that would enable the fulfilment of the specified list of requirements. It is due to the fact that, in order to execute the adjustments, it is inevitable to obtain a wide access to the kernel of the software of such simulator, which the owning companies are not willing to or cannot provide. As a consequence, it was decided to take up the tasks of design and development of a simple fleet behaviour simulator that would cope with the requisite demands. In the present thesis project it is referred to as the Vehicle Fleet Performance (VFP) Simulator. Since, in certain sense it constitutes a motor of the proposed DSS it got incorporated in its structure. The main objective of the developed simulator is to provide the information, which in the real life would be facilitated by special fleet monitoring device (e.g.: GPS, GPRS). In order to shorten the time required for its implementation, unlike the commercial simulators, the proposed implement does not represent graphically the emulation of the behaviour of the vehicles. Its main focus is on delivering the numerical data.

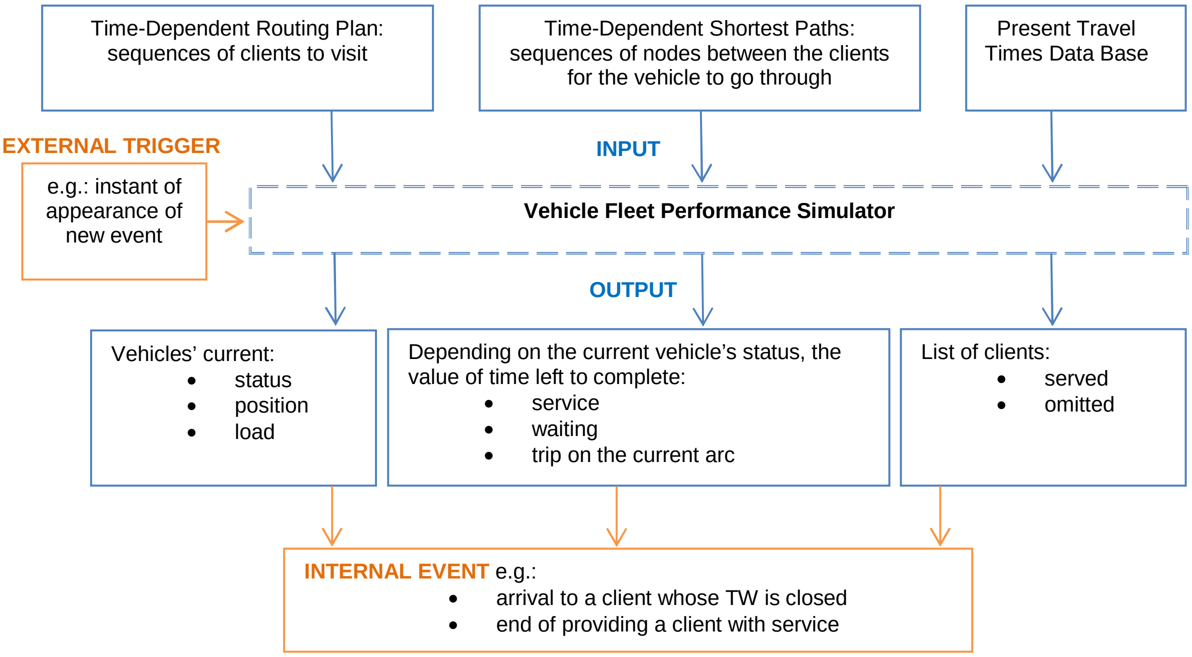


Figure 7.11 Required input and produced output of the VFP Simulator

As described in Figure 7.11, the inputs to the designed VFP Simulator constitute:

- the sequences of nodes representing the shortest paths between the consecutive customers,
- the routing plan consisting of the sequences of customers that need to be provided with either pickup or delivery service,
- the present travel time matrix, in accordance with which the routing plan is being performed.

On the other hand, the produced output includes the details on:

- the current fleet vehicles': position, status and amount of loaded cargo,
- the amount of time each vehicle needs to finish the currently performed action,
- the list of already served customers, on the basis of which one can define which of the service demanding customers, although originally included in the executed routing plan, were not provided with the service due to traffic.

There are two main functions included in the present module. The first one regards summing up for each individual vehicle the performed: travel, waiting and service times, while the second one keeps updated the variables defining the vehicles. The complete procedure lasts until reaching the time instant specifying the moment of new event occurrence. The functioning of the proposed VFP Simulator is explained using the block scheme presented in Figure 7.12. It employs the following notation:

T_e : event time,
T_v : vehicle time,
i : current node,
i+1 : next node,
i_{cv} : graph node defining the location of customer c_v,
b_v : last node of the complete route visited by vehicle v,
D_i : node defining the location of depot centre,
D : depot centre,
c_v : last customer visited by vehicle v,
c_v+1 : next customer to be visited by vehicle v,
A_{cv} : arrival time of vehicle v at customer c_v,
w_{cv} : waiting time at customer c_v,
s_{cv} : service time of the customer c_v,
$e(c_v+1)$: time window lower-bound of the next customer to be visited by vehicle v,
$l(c_v+1)$: time window upper-bound of the next customer to be visited by vehicle v,
τ : remaining time to finish the current activity (either waiting or giving service or travelling),
$t_{i,\,i+1}(T_v)$: TD travel time between node i and subsequent node i+1 when the departure moment from the origin node i is equal to T_v,
Z_{iv} : list of visited nodes i by vehicle v,
Z_{cv} : list of visited customers c_v by vehicle v,
Z_{iv}(last) : last element from the list Z_{iv},
Z_{cv}(last) : last element from the list Z_{cv},

Z_{Aiv} : list of arrival times to the nodes i visited by vehicle v,
Z_{Acv} : list of arrival times to the customers visited by vehicle v,
L_{cv} : list of customers served by vehicle v,
U_{cv} : list of customers c_v that could not be served by vehicle v,
Q_v : current load carried by the vehicle v,
d_{cv} : demand of the customer c_v served by the vehicle v,
startSim : the instant of starting the complete simulation.

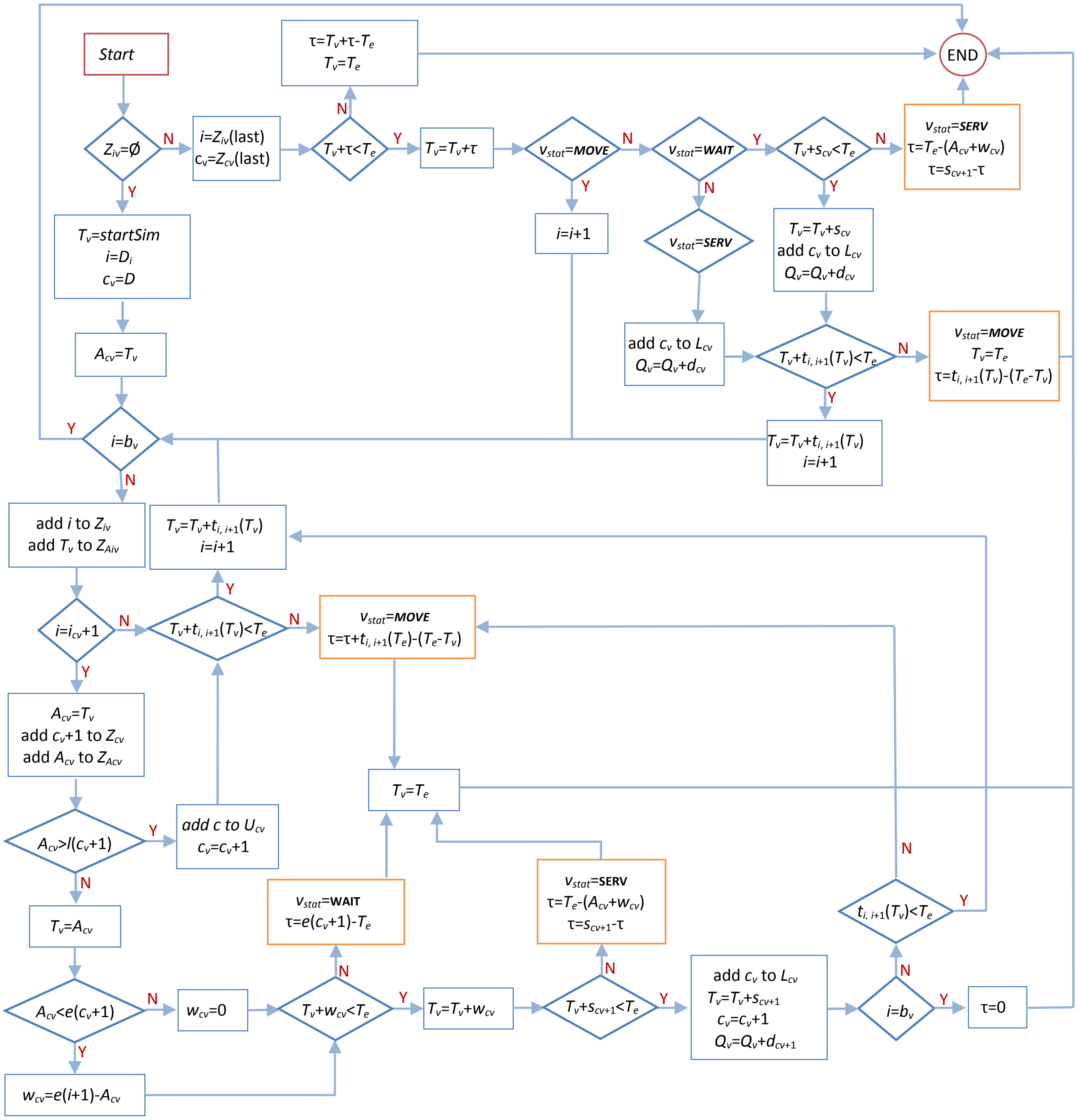


Figure 7.12 Block scheme of the VFP Simulator

7.6 Study case

One of the basic intentions of the undertaken thesis project was to examine the performance of the proposed approach on a real-life street network instead of an artificial background, which is a strategy most frequently encountered in other publications. Hence, initially the area of the city of Barcelona was chosen as the testing site.

Barcelona is a town with 46.500 establishments, where every day there are performed around 100.000 loading and unloading operations, which require 4.000 accessible parking spaces (Robusté Anton, 2005). Consequently, the number of circulating vehicles distributing goods is extensive. The occurring delays represent a substantial fraction of incurred costs and impact negatively the productivity. In the year 1993 it was estimated that each day the value of truck delay due to traffic congestion is of 2,5 hours, which within one year sums up to 166,8 million of Euros of total average cost.

Cost	Million of Euros per year	%
Delay cost (driver)	68,6	41,1
Delay cost (merchandise)	90,2	54,1
Additional operating cost	5,5	3,3
Additional cost of pollution	2,5	1,5
Total	166,8	100

Table 7.1 Cost of traffic congestion for urban distribution vehicles in Barcelona in 1993 (Robusté Anton, 2005)

Nowadays, such big optimization problem requires the usage of very potent computational tools. Due to the fact that the whole of the work was executed on a personal computer with limited properties it was necessary to reduce the size of the considered background to one quarter. Under these circumstances, the downtown area of the Barcelona city: l'Eixample was finally selected as the testing network. It is the most populated district of Barcelona and of all the Spanish cities both in absolute (262.485 inhabitants) and in the relative terms (35.586 inhabitants/km²). The original site of this 7,46 km² large area is presented in Figure 7.13.

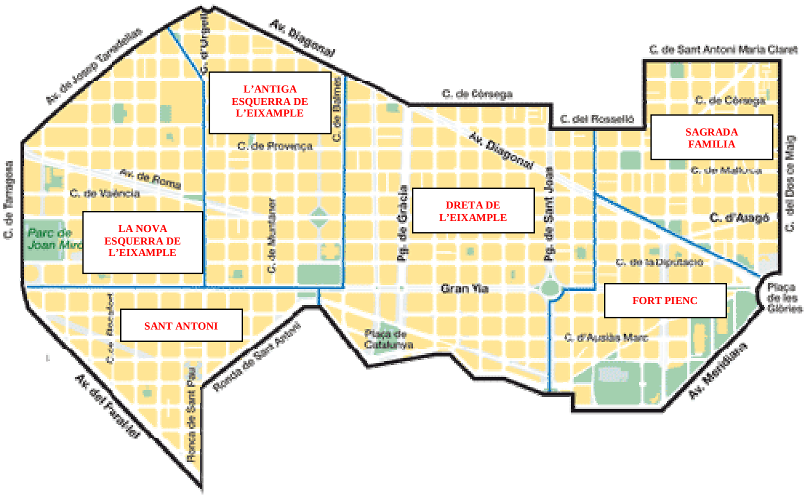


Figure 7.13 L'Eixample - testing site of the proposed approach

It should be noted, that although within the current project there was utilised as background a segregated fraction of the complete city network, the proposed approach supported with larger outlays on employed computation tools can be also implemented for a much larger network such as the one of an entire town.

The scope of the selected road network was modelled using a graphic editor of a microscopic traffic simulator. It is called AIMSUN and plays a subsidiary role in the whole thesis project. However, in its place there could be used any other software or tool able to represent in detail the addressed system and to deliver the record of variable travel times on each replica of the original sections. The complete model of the selected network consists of around 700 junctions and 1.550 street sections. It is presented in Figure 7.14.

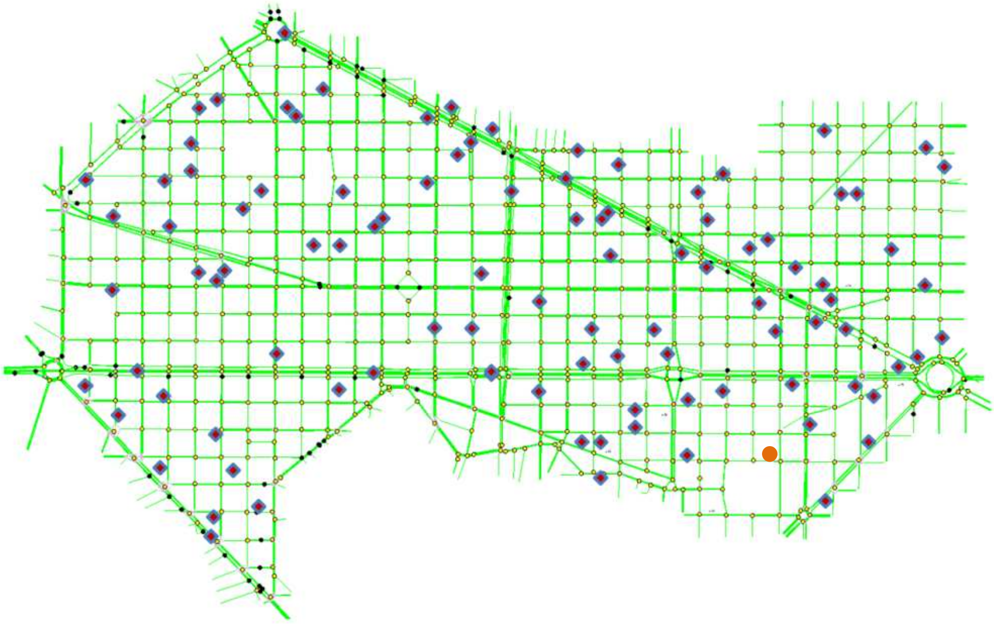


Figure 7.14 Microscopic model of the L'Eixample network

The collection of 100 customers was placed on the map at random. They are marked as blue lined squares. The singular depot was located in the spot, which seems to be very probable in the real life: close to the big train station. Its position is indicated by the orange circle. The generation of the variables specifying the employed collection of the customers was based on the customers' description proposed by Barcelo and Orozco (2010b) for the VRPTW. The process of data adaptation is described in details in Appendix A2. Notwithstanding, the main difference lies in the fact that it was necessary to add the identification specifying the pair to which each customer belongs to and the index defining if it is the pickup or delivery service that is required.

In order to serve the purposes of the present thesis project, the network of L'Eixample needed to be translated into a graph. (The challenges related with this task were explained in details in the introduction part of Chapter 2.) As a consequence, in the final result, each original road section can be represented graphically by more than one arc, for which the origin node is located at the beginning of the current section and the corresponding destination point constitutes the entrance to the subsequent street. (The network's translation procedure is presented on an example shown in Figure 2.2). On the other hand, the ultimate graph can also be represented as a matrix of adjacencies, where the stored, non-zero values indicate the existing directed arcs joining the nodes. In the presented study case, the graph constitutes of around 1.570 nodes and 2.797 arcs.

The value of the cost assigned to each individual arc of the studied network corresponds to the TD travel time. It includes the amount of time a vehicle needs to cross the original section, plus the time necessary to perform the corresponding turning movement. In the real life this information could be provided by an ATIS. Nonetheless, in the present study, there were employed the numerical results provided by a microscopic traffic simulator. Hence, the travel time data were collected during numerous series of microscopic simulation experiments. In addition, in order to obtain a result close to reality, the simulations were taking into account the demand variations, so that the morning and afternoon rush hours stand out.

The travel time data were collected every five minutes in each simulation experiment and were finally used to generate average values calculated in seconds. The created aggregated matrix containing TD information on network's performance was used as a record of past traffic states. Consequently, in the present document it is referred to as the *historical data base*. On the other hand, the simulation result of one, randomly chosen experiment replica was used to represent the present. Hence, it is called the *present data base*.

As explained in section 7.1.3, due to the difficulties regarding the precision of the calculation of the TD shortest paths, although the original travel time data were recorded every five minutes, they were adjusted and kept in shorter intervals of 1 and 10 seconds. The registered values were adapted using interpolation.

The graph as well as the considered historical travel time matrix is available at (http_3). The information on the used collection of pickup/delivery customers and the present data base can be obtainable at (http_8).

7.7 Experiments

In order to evaluate the performance of the proposed DSS and its methods, there was designed a collection of testing scenarios, in which the main focus is put on the efficiency of the fleet of freight vehicles in executing the assigned tasks.

The selection of the general assumptions that are valid for all the experiments includes the specification of the number of vehicles in the fleet and its uniform capacity. It is supposed that the fleet consists of 8 identical vehicles which load carriage space may comprise maximal amount of 100 units of transported goods.

Moreover, each trip shall start and end at the singular depot and its final cost is defined as the time necessary to perform the route. The depot does not have a specified demand or pair partner. Its opening hours determine the complete time horizon during which all the routing tasks need to be completed. In order to realistically represent the working hours of a real-life urban shipping company the TW of the depot opens at 7 am until 5pm.

Also, in every testing scenario there is considered the same number of customers, which in total summarises to 100. It corresponds to 50 pickup and delivery pairs. All the customers demand the same amount of commodity equal to 10 units. The positive or negative sign indicates if the requested service regards loading (+) or unloading (-) of goods. In addition, the service time duration is the same for each customer and takes 10 minutes.

If it comes to customers' characteristics that differentiate the specific scenarios, there were taken into account dissimilar spans of customers' TWs. There are defined *narrow* TWs, which might take the value either of one hour or half an hour, and *wide* TWs of possible lengths of: 4, 4.5, 5, 5.5 and 6 hours. The narrower the TW the more difficult it is to introduce the pair of customers into the existing routes. The employed values were selected in a way to reproduce the real life.

Another main difference between the individual scenarios regards the fact that there are considered different percentages of two types of customers. There are distinguished *static customers* about whom all the information is known at the time of making the initial routing plan and the *dynamic customers*, which are those whose request is registered when the initial routes are already being executed. The considered proportions include: 100, 80, 60, 50, 40 and 20 per cent of static customers. The higher the number of dynamic requests the more dynamic is the addressed problem.

In the case when there are considered only static customers there were tested two alternatives regarding different types of traffic information: *static* and *real-time*. The objective was to evaluate the impact that the real-time information has on the ultimately created solution in comparison with the constant approximate values of the travel time.

In the definition of each testing scenario there is specified the type of travel-times information that was used by IRSM to create the initial routing and scheduling plan. There are considered three alternatives:

- TD information gathered in the historical data base,
- average static travel time values (AS) calculated for the whole day for each section of the underlying city road network on the basis of the same historical data base,
- *perfect* information provided by the present data base.

The scenarios using the perfect travel time information assume that the dispatcher has perfect knowledge on the future travel times at the moment of defining the initial routing plan. These scenarios serve as a reference point in the process of assessment of goodness of other approaches which employ different types of traffic information.

The original travel time data were recorded in seconds and collected on every arc for every time interval of length δ equal to five minutes. These time periods were divided into shorter one-second-long epochs. Next, the travel time data were adjusted on the basis of interpolation. As a consequence of these proceedings there was obtained enhanced precision of calculation but for the price of increment of both the CPU and the usage of memory space. For that reason, in order to accelerate the computation it was decided to perform the operations of the TDSP Calculator for different destination nodes in parallel on two processors.

Also, in order to explore the possibility to reduce travel time data precision in order to speed up the simulation and be able to deploy the algorithms in a real-life application more easily, in the last 24 testing scenarios TDSP Calculator uses travel time data adjusted to 10 seconds long intervals.

TDSP Calculator can be activated only *once* during the performance of the testing scenario, before triggering the IRSM, or *multiple times.*

In the cases when the perfect travel time information is used the dynamic recalculation of the shortest paths is not required. Similarly, there is no need to use the Time-Dependent Travel Time Data Forecasting Module.

In the scenarios, where the AS travel time information is used, there is considered single activation of TDSP Calculator. While in this case it is of no use to employ the Time-Dependent Travel Time Data Forecasting Module, it is launched regularly when solving the tests considering TD traffic data. The objective is to show the impact that the time-dependant information and dynamic modifications of current routing plan have on final outcome.

As explained in section 7.3, the repetitive activation of both TDSP Calculator and DRSM is due the occurrence of an event belonging to the pre-specified collection including:

- a new call, requesting service for a pair of customers, is registered,
- a vehicle terminates providing a current customer with requested service,
- a vehicle arrives to a scheduled customer when its TW is already closed.

All designed scenarios were executed twice. Each time in the DRSM there was employed a different dynamic initial solution constructing method: dynamic CSR method or SPI procedure. The objective was to verify which of the algorithms is more efficient and provides a better final solution.

In the real life it is not uncommon for the dispatchers to take into account an additional amount of time, when defining the freight travel times. This surplus is called a *buffer* and serves as collateral in case something unexpected happens and delays the vehicles. Commonly, the original travel time values get incremented by 20%. In order to investigate the efficiency of this approach, there were performed testing scenarios, which take into consideration the buffers.

Originally it is assumed that the underlying road network presents normal traffic conditions during the simulation. However, in order to complement the research there are also considered the situations when traffic conditions are suddenly altered for example due to a major incident. Hence, one arc of the graph was picked at random and set as the traffic obstruction starting point. Next, there were selected the adjacent arcs which in sum constitute 10% of the total underlying road network. The cost of the trip on the chosen arcs was set equal to a very high number during one hour, starting form a randomly picked up moment in time, forcing the rerouting algorithms to find a feasible alternative. The travel time data base created in this way can be obtained at (http_8). The aim of this operation was the evaluation of performance of the proposed solving strategies in worsened traffic conditions.

In summary, the main experimental design factors and their levels are:

- solving methods (SPI and CSR),
- travel times (perfect, average static and time-dependent),
- TWs specifications (narrow and wide),
- percentage of customers’ requests known in advance.

The significant combinations and levels define the computational experiments. Definite collection of testing scenarios consists of 84 different cases. These combinations are illustrated in Figure 7.15. The computational results for the static case achieved in Chapter 6, which are used as input, are shown in the head box of the figure.

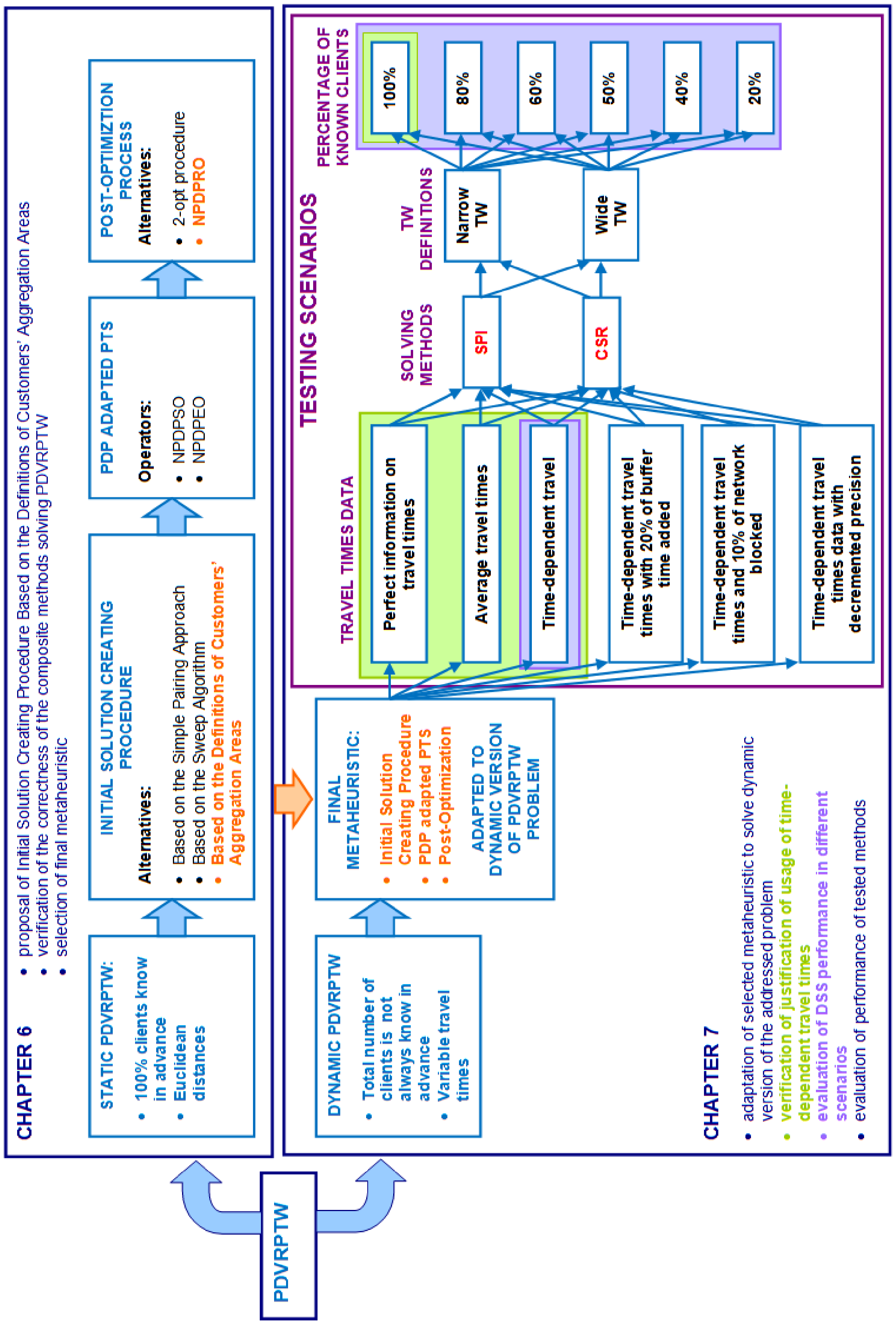


Table 7.15 Design of experiments

The tables explicitly describing the combinations of the factors for each experiment are:

N° scenario	TW	N° of static customers	Method	Travel time data	TDSP Calculator used	Forecaster used
1	narrow	100	SPI	perfect	once	-
2	wide	100	SPI	perfect	once	-
3	narrow	100	SPI	AS	once	-
4	wide	100	SPI	AS	once	-
5	narrow	100	SPI	TD	multiple times	multiple times
6	wide	100	SPI	TD	multiple times	multiple times
7	narrow	80	SPI	TD	multiple times	multiple times
8	wide	80	SPI	TD	multiple times	multiple times
9	narrow	60	SPI	TD	multiple times	multiple times
10	wide	60	SPI	TD	multiple times	multiple times
11	narrow	50	SPI	TD	multiple times	multiple times
12	wide	50	SPI	TD	multiple times	multiple times
13	narrow	40	SPI	TD	multiple times	multiple times
14	wide	40	SPI	TD	multiple times	multiple times
15	narrow	20	SPI	TD	multiple times	multiple times
16	wide	20	SPI	TD	multiple times	multiple times

Table 7.2 Listing of testing scenarios, using SPI procedure and where δ=1 sec

N° scenario	TW	N° of static customers	Method	Travel time data	TDSP Calculator used	Forecaster used
17	narrow	100	CSR	perfect	once	-
18	wide	100	CSR	perfect	once	-
19	narrow	100	CSR	AS	once	-
20	wide	100	CSR	AS	once	-
21	narrow	100	CSR	TD	multiple times	multiple times
22	wide	100	CSR	TD	multiple times	multiple times
23	narrow	80	CSR	TD	multiple times	multiple times
24	wide	80	CSR	TD	multiple times	multiple times
25	narrow	60	CSR	TD	multiple times	multiple times
26	wide	60	CSR	TD	multiple times	multiple times
27	narrow	50	CSR	TD	multiple times	multiple times
28	wide	50	CSR	TD	multiple times	multiple times
29	narrow	40	CSR	TD	multiple times	multiple times
30	wide	40	CSR	TD	multiple times	multiple times
31	narrow	20	CSR	TD	multiple times	multiple times
32	wide	20	CSR	TD	multiple times	multiple times

Table 7.3 Listing of testing scenarios, using CSR procedure and where δ=1 sec

N° scenario	TW	N° of static customers	Method	Travel time data	TDSP Calculator used	Forecaster used	Buffer
33	narrow	100	SPI	TD	multiple times	multiple times	20%
34	wide	100	SPI	TD	multiple times	multiple times	20%
35	narrow	80	SPI	TD	multiple times	multiple times	20%
36	wide	80	SPI	TD	multiple times	multiple times	20%
37	narrow	60	SPI	TD	multiple times	multiple times	20%
38	wide	60	SPI	TD	multiple times	multiple times	20%
39	narrow	50	SPI	TD	multiple times	multiple times	20%
40	wide	50	SPI	TD	multiple times	multiple times	20%
41	narrow	40	SPI	TD	multiple times	multiple times	20%
42	wide	40	SPI	TD	multiple times	multiple times	20%
43	narrow	20	SPI	TD	multiple times	multiple times	20%
44	wide	20	SPI	TD	multiple times	multiple times	20%

Table 7.4 Listing of testing scenarios, using SPI procedure, where δ=1 sec and there is added 20% buffer time

N° scenario	TW	N° of static customers	Method	Travel time data	TDSP Calculator used	Forecaster used	Buffer
45	narrow	100	CSR	TD	multiple times	multiple times	20%
46	wide	100	CSR	TD	multiple times	multiple times	20%
47	narrow	80	CSR	TD	multiple times	multiple times	20%
48	wide	80	CSR	TD	multiple times	multiple times	20%
49	narrow	60	CSR	TD	multiple times	multiple times	20%
50	wide	60	CSR	TD	multiple times	multiple times	20%
51	narrow	50	CSR	TD	multiple times	multiple times	20%
52	wide	50	CSR	TD	multiple times	multiple times	20%
53	narrow	40	CSR	TD	multiple times	multiple times	20%
54	wide	40	CSR	TD	multiple times	multiple times	20%
55	narrow	20	CSR	TD	multiple times	multiple times	20%
56	wide	20	CSR	TD	multiple times	multiple times	20%

Table 7.5 Listing of testing scenarios, using CSR procedure, where δ=1 sec and there is added 20% buffer time

N° scenario	TW	N° of static customers	Method	Travel time data	TDSP Calculator used	Forecaster used	Traffic blocked
57	narrow	100	SPI	TD	multiple times	multiple times	10%
58	wide	100	SPI	TD	multiple times	multiple times	10%
59	narrow	100	CSR	TD	multiple times	multiple times	10%
60	wide	100	CSR	TD	multiple times	multiple times	10%

Table 7.6 Listing of testing scenarios, using either SPI or CSR procedures, where δ=1 sec and when 10% of network is blocked

N° scenario	TW	N° of static customers	Method	Travel time data	TDSP Calculator used	Forecaster used
61	narrow	100	SPI	TD	multiple times	multiple times
62	wide	100	SPI	TD	multiple times	multiple times
63	narrow	80	SPI	TD	multiple times	multiple times
64	wide	80	SPI	TD	multiple times	multiple times
65	narrow	60	SPI	TD	multiple times	multiple times
66	wide	60	SPI	TD	multiple times	multiple times
67	narrow	50	SPI	TD	multiple times	multiple times
68	wide	50	SPI	TD	multiple times	multiple times
69	narrow	40	SPI	TD	multiple times	multiple times
70	wide	40	SPI	TD	multiple times	multiple times
71	narrow	20	SPI	TD	multiple times	multiple times
72	wide	20	SPI	TD	multiple times	multiple times

Table 7.7 Listing of testing scenarios, using SPI procedure and where δ=10 sec

N° scenario	TW	N° of static customers	Method	Travel time data	TDSP Calculator used	Forecaster used
73	narrow	100	CSR	TD	multiple times	multiple times
74	wide	100	CSR	TD	multiple times	multiple times
75	narrow	80	CSR	TD	multiple times	multiple times
76	wide	80	CSR	TD	multiple times	multiple times
77	narrow	60	CSR	TD	multiple times	multiple times
78	wide	60	CSR	TD	multiple times	multiple times
79	narrow	50	CSR	TD	multiple times	multiple times
80	wide	50	CSR	TD	multiple times	multiple times
81	narrow	40	CSR	TD	multiple times	multiple times
82	wide	40	CSR	TD	multiple times	multiple times
83	narrow	20	CSR	TD	multiple times	multiple times
84	wide	20	CSR	TD	multiple times	multiple times

Table 7.8 Listing of testing scenarios, using CSR procedure and where δ=10 sec

7.8 Results

The results of all the conducted tests were collected and placed in tables, which consist of two main segments. The first one provides the description of the initial routing and scheduling plan which was prepared by IRSM. It includes:

- number of designed routes,
- number of customers, which were known at the time of preparing the initial routing and scheduling plan,
- summarised amount of pure travel time to be performed by all utilised vehicles,
- summarised amount of waiting time to be performed by all utilised vehicles,
- complete cost of solution, which includes the total time of: travel, waiting and service.

The second section outlines the plan which was actually performed by the vehicles fleet. Its description comprises:

- number of performed routes,
- summarised amount of pure travel time performed by all utilised vehicles,
- summarised amount of waiting time performed by all utilised vehicles,
- complete cost of solution, which includes the performed time of: travel, waiting and service,
- service level, which defines the percentage of customers which were successfully provided with requested service.

All the obtained results are presented separately in Appendix B2. The present section focuses on the analysis of the final outcome. Each section outlines: the selected collection of analysed scenarios, the graphic illustration of obtained results and the discussion.

7.8.1 Influence of Usage of Time-Dependent Traffic Information and Dynamic Adjustment of Routing and Scheduling Plan on Freight Fleet's Performance

In order to do a comparative analysis of the influence of the TD travel time information from all the alternatives presented in Tables 7.2 - 7.8 there were selected the affected ones. The summary of compared scenarios is presented in Table 7.9.

Hence, the first group of tested scenarios regards performance of the fleet when either SPI or CSR methods were used in DRSM. In each case, the number of static customers is equal to 100 and TDSP Calculator uses the travel time data recorded in time intervals of length δ equal to 1 second. The scenarios differ in the type of used information on travel times and in the fact whether the current routing plan is adjusted in accordance with new data. Depending on the case the Time-Dependent Travel Time Data Forecasting Module is launched.

N^{o} scenario	TW	N^{o} of static customers	Method	Travel time data	TDSP Calculator used	Forecaster used
1	narrow	100	SPI	perfect	once	-
3	narrow	100	SPI	AS	once	-
5	narrow	100	SPI	TD	multiple times	multiple times
2	wide	100	SPI	perfect	once	-
4	wide	100	SPI	AS	once	-
6	wide	100	SPI	TD	multiple times	multiple times
17	narrow	100	CSR	perfect	once	-
19	narrow	100	CSR	AS	once	-
21	narrow	100	CSR	TD	multiple times	multiple times
18	wide	100	CSR	perfect	once	-
20	wide	100	CSR	AS	once	-
22	wide	100	CSR	TD	multiple times	multiple times

Table 7.9 Scenarios compared to evaluate the influence of usage of TD traffic information and dynamic adjustment of routing and scheduling plan on freight fleet's performance

The initially proposed and finally created routing plans are always different. The only exceptions constitute the scenarios with perfect information. In those cases, since the routing plan was prepared using the same data that were employed in the simulation the outcome is the same.

In majority of testing scenarios (67%), when other than perfect travel time information was used, there were served less customers than initially planned. When CSR is employed the final costs of the solutions, total waiting and travel time are always higher than intended. Even the number of performed routes is higher for the majority of scenarios. In this context, the only exception constitutes the case with wide TWs and using TD traffic information.

When SPI is employed, similarly as in the previous case, there were reached lower service levels for the majority of tested scenarios (83%), when other than perfect travel time information was used. While the values of performed waiting time are higher than initially planned, the final travel times and costs of the solutions do not always exceed the intended numbers. In some cases the obtained values are lower which is due to the fact that provided service levels are low as well. The objective of the SPI method is to maintain the routing and scheduling plan the least changed possible. Thus, in each scenario the number of executed routes is the same as planned.

The above observations lead to the conclusion that the employment of the initial routing plan created on the basis of historical data without considering the possible future changes in travel times, might result in high number of lost opportunities to serve customers. At the same time the final costs of performed routing tasks might be minimised due to frequent adjustment to the current traffic conditions.

Figure 7.16 shows the final service level reached in every scenario from the first tested group, respectively. When perfect travel time information was used, there was reached 100% of service level. The worst results were provided for the cases when AS travel time data were used and there was not employed a forecasting module. The difference between this and the perfect case, when SPI is executed is of 21% and 11% for the scenarios with narrow and wide TWs, respectively. Similarly, when CSR is employed the service level is worse by 27% and 1% when narrow and wide TWs are defined. The most dynamic approach, using TD travel time values provided by the forecaster and regularly updating the current routing plan, allows reaching service levels the closest to the outcome produced by perfect scenarios. In the case with narrow TWs, the difference is of 10% and 1%, when SPI and CSR are used, accordingly. When wide TWs are defined, SPI serves 99%, while CSR fulfils 100% of all considered static customers' requests.

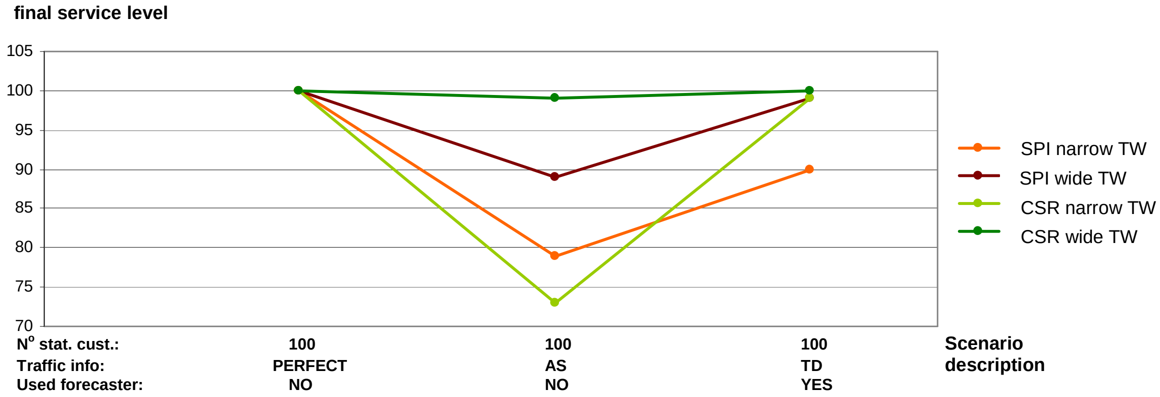


Figure 7.16 Final service level obtained in scenarios with 100 static customers when δ is equal to 1 sec

Figure 7.17 presents final costs of the solution. Naturally, the smallest values were reached when the routing and scheduling plan was prepared on the basis of perfect traffic information. The difference between these and results obtained in scenarios using AS traffic information and no forecaster is very small. When SPI is used the final schedule costs are larger by only 0,04% and 0,34% when narrow and wide TWs are defined, respectively. It is due to the fact that there were served much fewer customers than in the corresponding perfect scenarios. The recurrent update of the routing and scheduling plan and the usage of TD traffic information prove their beneficial effect on costs optimization. Here, when SPI is executed, in contrast to the case when AS data were used, the final solution costs are by 4% and 1% larger, in scenarios considering narrow and wide TWs, accordingly. The increment is due to the raise of service level in both cases. However, when CSR is used, the costs of final solutions are by 26% and 16% lower for narrow and wide TWs scenarios, respectively. This return gains importance if there is taken into consideration the fact that at the same time there are assured higher service levels.

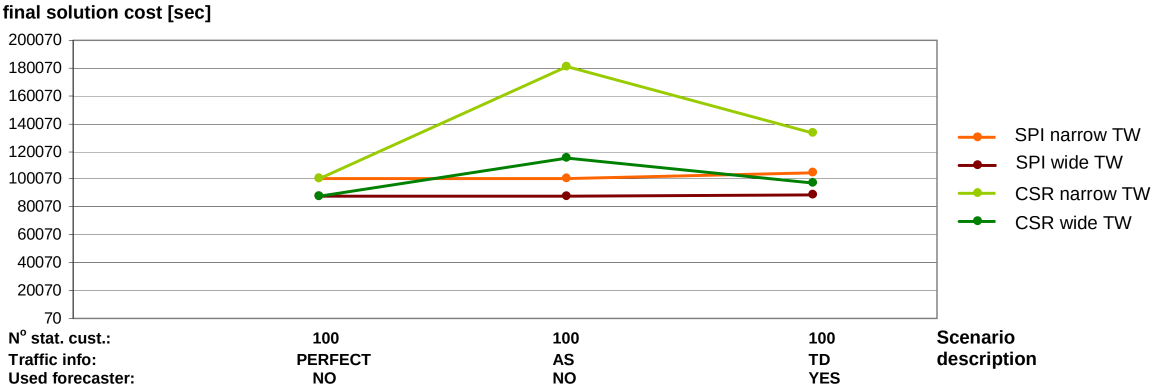


Figure 7.17 Final total solution cost obtained in scenarios with 100 static customers when δ is equal to 1 sec

Figure 7.18 shows the values of final total travel times. On its basis there can be drawn conclusions similar to previous. The best output is provided by the scenarios considering perfect traffic information. When AS traffic data and no forecasting tool are used, the produced outcome is the worst. In comparison with the perfect scenario, when SPI is applied, the final total travel time is higher by 29% and 74% for scenarios with narrow and wide TWs, respectively. In the case when CSR is employed the difference reaches 233% and 228%, accordingly. Those numbers are significantly smaller when forecaster and TD traffic data are used. In comparison with the perfect scenario, when CSR is applied, the final total travel time is higher by 93% and 66% for scenarios with narrow and wide TWs, respectively. SPI provides results by 11% and 26% higher when used to solve the scenario with wide and narrow TWs, accordingly. In the latter case, the reached value of final total travel time is larger than when AS data is used. Again, it is due to the fact that more customers are ultimately provided with the service.

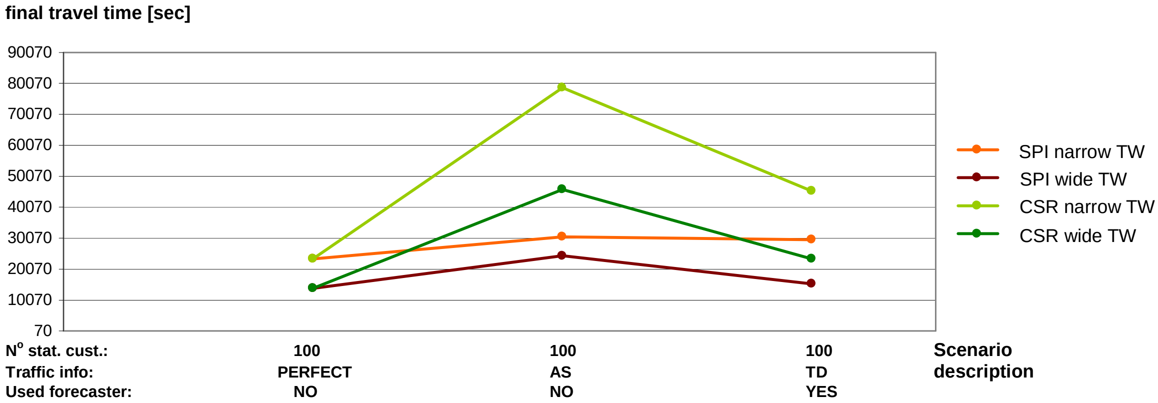


Figure 7.18 Final total travel time obtained by SPI and CSR methods in scenarios with 100 static customers when δ is equal to 1 sec

The final values of performed waiting times are shown in Figure 7.19. In the scenarios with wide TWs there were obtained very similar results when the same traffic information and methods were used. The differences are smaller than 0,3%. In the scenarios with narrow TWs, the differences in the waiting times are much more visible. In comparison with the perfect scenario, when AS data and no forecasting module are employed, the final total waiting time is longer by 33% and 237% as SPI and CSR are used, respectively. Those differences are smaller when TD information is used and reaches 20% and 63%, accordingly. In the test cases, when wide TWs are defined, in comparison with the perfect scenario, the final total waiting time is shorter by 26% and longer by 4%, when AS and TD information is used, respectively, no matter the employed solving method.

Comparison of the scenarios from the first group which differ only with the definition of TWs span shows that when wide TWs are defined in the addressed problem there are obtained lower final costs, total travel and waiting times while the fulfilled service level is elevated. It is due to the fact that a routing problem with narrow TWs is more restricted and it is more difficult to create and perform a feasible routing plan.

In the scenarios with 100% of customers known in advance it is in general more beneficial to employ CSR method. There are reached higher service levels and lower final travel and waiting costs in comparison with SPI, no matter the type of used information AS or TD. There are obtained higher solutions costs, but they are due to the fact that more customers were ultimately provided with the service.

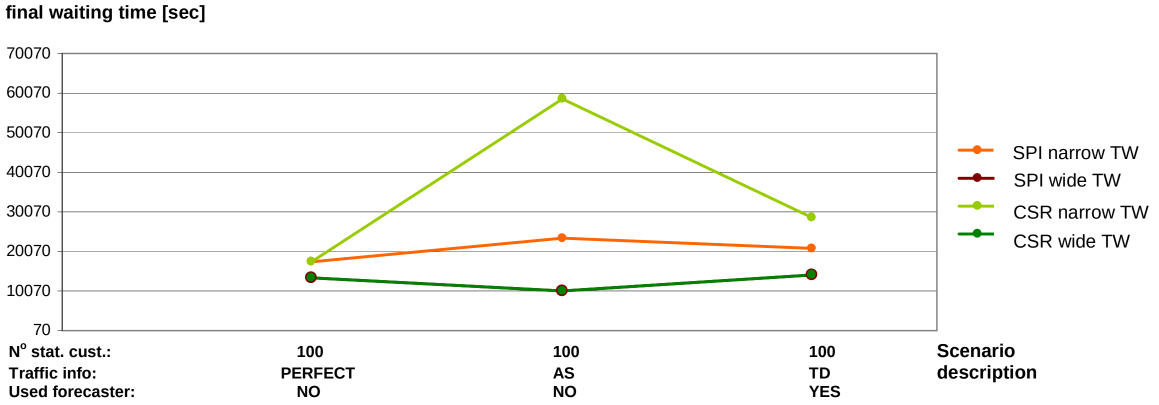


Figure 7.19 Final total waiting times in scenarios with 100 static customers when δ is equal to 1 sec

In sum, the commonly used approach based on AS values of travel times, which do not take into consideration the current traffic evolution and do not frequently update the routing and scheduling plan provide the worst final results from all tested approaches. The dynamic adjustment of routing plan can result in improvement of service level from 1% up to 36%, depending on the scenario. Similarly, the final solution cost can be shortened by 16% up to 26%. Since the service level got enhanced in some cases the final schedule cost might grow. The difference is of 1% up to 4%, in affected scenarios.

CSR is the method which allows reaching the highest service levels in combination with the lowest final solution costs. SPI gives special importance to the initial routing and scheduling plan and intends to maintain it the least changed possible. Thus, the final output strongly depends on the quality of the initial solution. For the price of maintaining it there are lost some of the opportunities to serve customers.

The reduced solution costs in connection with the high service levels justify the usage of TD travel time information instead of AS in continuation of the current thesis project.

7.8.2 Influence of the Number of Dynamic Customers on Freight Fleet’s Performance

The second group includes scenarios considering TD travel time information recorded in time intervals of length δ equal to 1 second. The test cases differ from each other in the definition of TWs, number of considered dynamic customers and applied solving method. They are compiled in Table 7.10

In the scenarios, where dynamic customers are taken into account, there is visible a significant difference between initially planned and finally performed routing plan. In the latter case, the values of both travel times and costs of the solutions are higher. Similarly, the number of performed routes and served customers is higher with respect to the initial plan. It is so, because during the course of simulation new customers’ requests appear. They are successfully introduced into the current routes and ultimately provided with the requested service. Naturally, the higher the number of dynamically appearing customers the bigger the difference between the initially planned and finally performed routing plan.

N° scenario	TW	N° of static customers	Method	Travel time data	TDSP Calculator used	Forecaster used
5	narrow	100	SPI	TD	multiple times	multiple times
7	narrow	80	SPI	TD	multiple times	multiple times
9	narrow	60	SPI	TD	multiple times	multiple times
11	narrow	50	SPI	TD	multiple times	multiple times
13	narrow	40	SPI	TD	multiple times	multiple times
15	narrow	20	SPI	TD	multiple times	multiple times
6	wide	100	SPI	TD	multiple times	multiple times
8	wide	80	SPI	TD	multiple times	multiple times
10	wide	60	SPI	TD	multiple times	multiple times
12	wide	50	SPI	TD	multiple times	multiple times
14	wide	40	SPI	TD	multiple times	multiple times
16	wide	20	SPI	TD	multiple times	multiple times
21	narrow	100	CSR	TD	multiple times	multiple times
23	narrow	80	CSR	TD	multiple times	multiple times
25	narrow	60	CSR	TD	multiple times	multiple times
27	narrow	50	CSR	TD	multiple times	multiple times
29	narrow	40	CSR	TD	multiple times	multiple times
31	narrow	20	CSR	TD	multiple times	multiple times
22	wide	100	CSR	TD	multiple times	multiple times
24	wide	80	CSR	TD	multiple times	multiple times
26	wide	60	CSR	TD	multiple times	multiple times
28	wide	50	CSR	TD	multiple times	multiple times
30	wide	40	CSR	TD	multiple times	multiple times
32	wide	20	CSR	TD	multiple times	multiple times

Table 7.10 Scenarios compared to evaluate the influence of the number of dynamic customers on freight fleet's performance

The values of final service levels obtained in each scenario considering dynamic customers and TD travel time information are presented in Figure 7.20. CSR method reaches 100% of service level in all the scenarios with wide TWs providing better performance than SPI in most of the cases. Also, when narrow TWs are defined, CSR is able to serve higher number of customers than SPI. As a consequence, from the point of view of customers' satisfaction it is of benefit to employ CSR method in the DRSM.

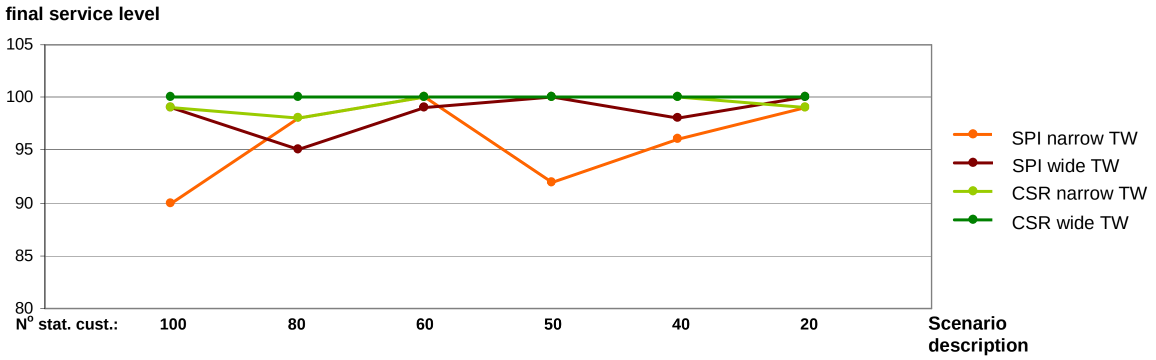


Figure 7.20 Final total service levels obtained in scenarios considering dynamic customers, when δ is equal to 1 sec and used traffic data is time-dependent

Regarding the change in performance of CSR method, when there are defined narrow TWs it is observable that the differences in service levels are of maximum 1 customer pair. In fact, in each case in which there were noted unfulfilled requests, there was missed only one customer. However, in the scenario considering 80% of static customers, the missing request was a pickup and its delivery partner was omitted by default.

In the scenario with 20% of customers' requests known in advance there was missed one customer, which is due to the fact that the tested scenario is highly dynamic. The missed requests in the scenarios with defined 100% and 80% static customers are due to the fact that the initial routing and scheduling plan is prepared on the basis of historical information of travel times. The execution of the plan entails the fact that after visiting a pickup customer the entire pair is permanently attached to the initially assigned route. Consequently, the subsequent change in traffic conditions might results in missed requests, since they cannot be feasibly relocated.

Figure 7.21 presents final values of the costs of the solutions while Figure 7.22 shows the final travel times performed in corresponding test case. In both figures there might be noted a tendency defining direct dependence between the final result and the degree of dynamism of the addressed problem. The greater the number of dynamically appearing customers' requests the higher the final total cost and travel time of performed solution. It is so, because every time a new order is received one of the existing routes gets extended due to insertion of the new customer. This change is more definite in scenarios with narrow TWs. When wide TWs are defined, it is easier to fit in a new order without having to significantly extend the time of execution of existing routes.

Comparison of scenarios with narrow TWs, which differ with the employed method but which reached the same service level, shows that SPI provides a solution with lower final cost only for one case: 80% of static customers. In majority of scenarios with wide TWs, CSR provides higher service levels in conjunction with lower final solution costs and travel times in comparison to SPI. There are however two cases where there was served the same number of customers when used SPI and CSR methods: test with defined 50% and 20% of static customers. Here, SPI provided solutions of lower final cost and total travel time. These examples show that the biggest drawback of SPI represent lost service opportunities.

The analysis of the results shows also that in the highly dynamic cases SPI behaves similar to CSR since it creates an initial routing plan considering small number of customers. While the simulation progresses the initial plan loses its importance and the objective becomes the most beneficial introduction of the new customers. Hence, it is possible for the SPI to outperform CSR.

Given that customer's satisfaction is the most important, CSR is more beneficial to use than SPI since it allows accomplishing larger number of orders in majority of tested scenarios.

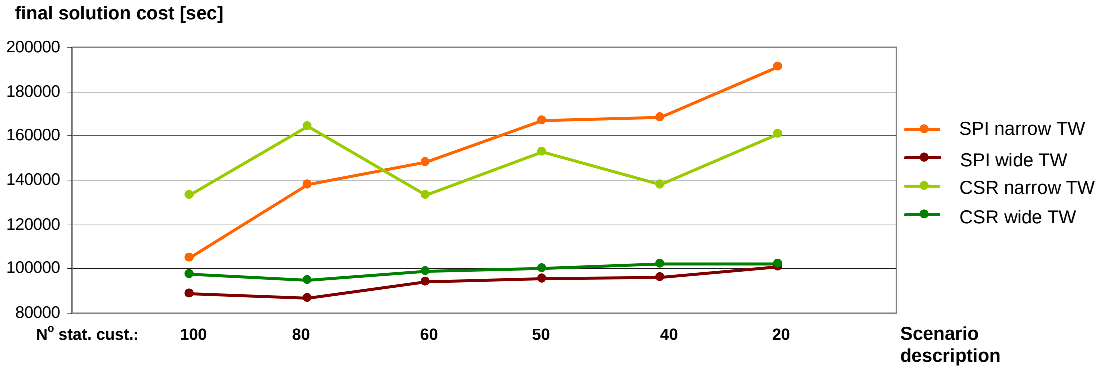


Figure 7.21 Final solution costs obtained in scenarios considering dynamic customers, when δ is equal to 1 sec and used traffic data is time-dependent

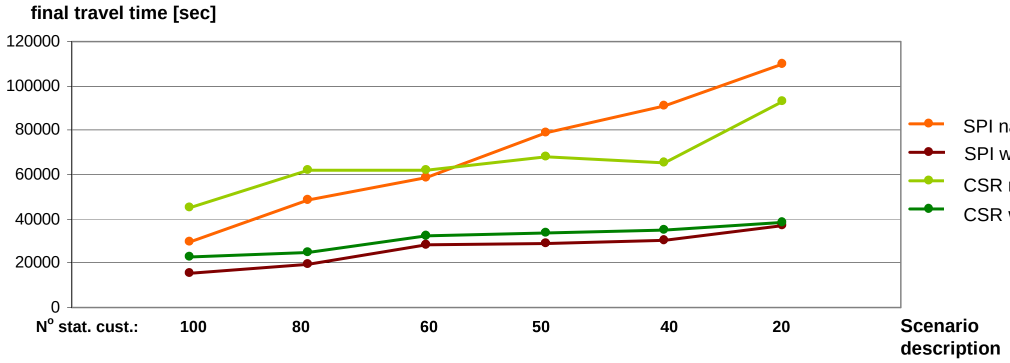


Figure 7.22 Final travel times obtained in scenarios considering dynamic customers, when δ is equal to 1 sec and used traffic data is time-dependent

Figure 7.23 shows the values of final total waiting time obtained in each tested case employing TD travel time data. There might be observed a downward trend regarding scenarios with wide TWs. The values of total waiting time diminish together with the increment of the number of dynamic requests. It is so, since when there are considered wide TWs, it is easier to introduce new pairs of customers in the existing routes and thus shorten the waiting time, no matter the method. Both SPI and CSR methods reach very similar numbers.

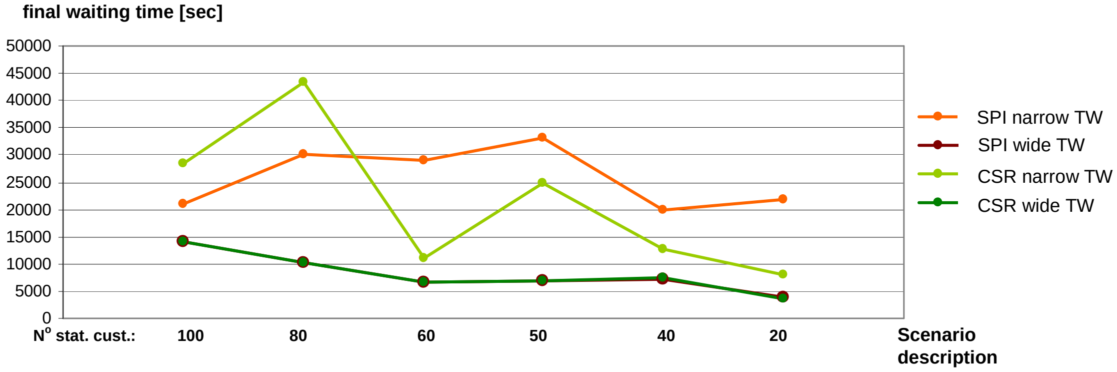


Figure 7.23 Final waiting times obtained in scenarios considering dynamic customers, when δ is equal to 1 sec and used traffic data is time-dependent

In the highly static scenarios when narrow TWs are defined, SPI provides lower values of final total waiting time. It is the opposite for the test cases with high number of dynamic customers where CSR performs better. It is due to the fact that CSR modifies more extensively the routing and scheduling plan allowing for feasible introduction of high number of new customers in the current sequences and thus to shorten the waiting times.

In sum, taking into consideration the reached values of the service level and final solution costs, if there are considered dynamic customers' calls, CSR proves to perform better than SPI. This method, due to the fact that, it first destroys and then builds from scratch a routing plan, better responds to dynamic changes. It is able to consider wider spectrum of problem affecting factors and extensively modify the current plan in order to reckon with them.

In the scenarios with wide TWs each time a new request is registered it is easier to feasibly introduce it in the existing sequences without necessity of significantly prolonging the routes or creating a new one. In the case of the scenarios with narrow TWs the insertion is more difficult.

As a consequence, the final values of waiting, travel and solution cost are higher in comparison with the scenarios with wider TWs' span.

7.8.3 Influence of Employment of 20% of Buffer Time on Freight Fleet's Performance

Scenarios with narrow TWs are difficult to solve. Too tight planning might result in high number of missed orders and force the dispatcher to increment the number of routes in order to meet the demand. Hence, it might be convenient to take into account additional amount of travel time as a reserve. Then, if new dynamic customers appear or if there is any change in traffic flow, freight vehicles might still reach their destination points on time and fulfil their tasks. In order to investigate more thoroughly this aspect, there was tested number of scenarios (Table 7.11) with 20% of buffer added to the travel time of each shortest path provided by Time-Dependent Travel Time Data Forecasting Module.

N° scenario	TW	N° of static customers	Method	Travel time data	TDSP Calculator used	Forecaster used	Buffer
5	narrow	100	SPI	TD	multiple times	multiple times	0%
7	narrow	80	SPI	TD	multiple times	multiple times	0%
9	narrow	60	SPI	TD	multiple times	multiple times	0%
11	narrow	50	SPI	TD	multiple times	multiple times	0%
13	narrow	40	SPI	TD	multiple times	multiple times	0%
15	narrow	20	SPI	TD	multiple times	multiple times	0%
33	narrow	100	SPI	TD	multiple times	multiple times	20%
35	narrow	80	SPI	TD	multiple times	multiple times	20%
37	narrow	60	SPI	TD	multiple times	multiple times	20%
39	narrow	50	SPI	TD	multiple times	multiple times	20%
41	narrow	40	SPI	TD	multiple times	multiple times	20%
43	narrow	20	SPI	TD	multiple times	multiple times	20%
21	narrow	100	CSR	TD	multiple times	multiple times	0%
23	narrow	80	CSR	TD	multiple times	multiple times	0%
25	narrow	60	CSR	TD	multiple times	multiple times	0%
27	narrow	50	CSR	TD	multiple times	multiple times	0%
29	narrow	40	CSR	TD	multiple times	multiple times	0%
31	narrow	20	CSR	TD	multiple times	multiple times	0%
45	narrow	100	CSR	TD	multiple times	multiple times	20%
47	narrow	80	CSR	TD	multiple times	multiple times	20%
49	narrow	60	CSR	TD	multiple times	multiple times	20%
51	narrow	50	CSR	TD	multiple times	multiple times	20%
53	narrow	40	CSR	TD	multiple times	multiple times	20%
55	narrow	20	CSR	TD	multiple times	multiple times	20%
6	wide	100	SPI	TD	multiple times	multiple times	0%
8	wide	80	SPI	TD	multiple times	multiple times	0%
10	wide	60	SPI	TD	multiple times	multiple times	0%
12	wide	50	SPI	TD	multiple times	multiple times	0%
14	wide	40	SPI	TD	multiple times	multiple times	0%
16	wide	20	SPI	TD	multiple times	multiple times	0%
34	wide	100	SPI	TD	multiple times	multiple times	20%
36	wide	80	SPI	TD	multiple times	multiple times	20%
38	wide	60	SPI	TD	multiple times	multiple times	20%
40	wide	50	SPI	TD	multiple times	multiple times	20%
42	wide	40	SPI	TD	multiple times	multiple times	20%
44	wide	20	SPI	TD	multiple times	multiple times	20%
22	wide	100	CSR	TD	multiple times	multiple times	0%
24	wide	80	CSR	TD	multiple times	multiple times	0%
26	wide	60	CSR	TD	multiple times	multiple times	0%
28	wide	50	CSR	TD	multiple times	multiple times	0%
30	wide	40	CSR	TD	multiple times	multiple times	0%
32	wide	20	CSR	TD	multiple times	multiple times	0%
46	wide	100	CSR	TD	multiple times	multiple times	20%
48	wide	80	CSR	TD	multiple times	multiple times	20%
50	wide	60	CSR	TD	multiple times	multiple times	20%
52	wide	50	CSR	TD	multiple times	multiple times	20%
54	wide	40	CSR	TD	multiple times	multiple times	20%
56	wide	20	CSR	TD	multiple times	multiple times	20%

Table 7.11 Scenarios compared to evaluate the influence of employment of 20% of buffer time on freight fleet's performance

Figure 7.24 depicts values of final service levels obtained by solving scenarios with narrow TWs, using SPI and CSR methods, respectively. In each case there were employed TD travel time data with or without 20% of buffer added. Following this scheme, Figure 7.25 presents values of final solution costs reached by each of the tested methods.

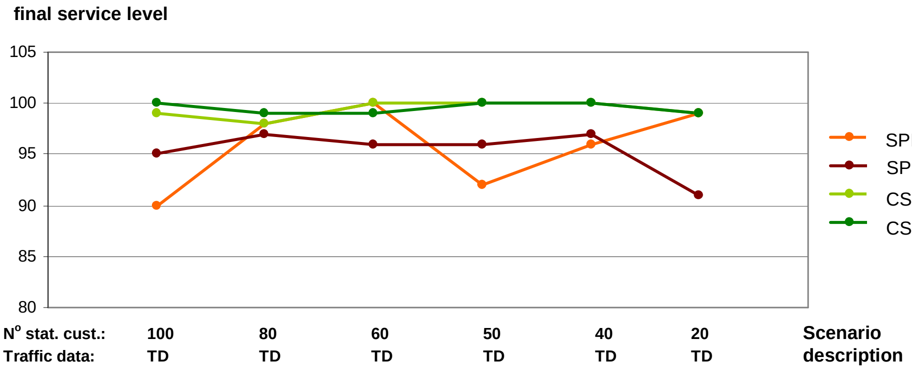


Figure 7.24 Final service levels obtained in scenarios with defined: narrow TWs, 100 static customers, δ is equal to 1 sec, TD traffic data and 20% of buffer time

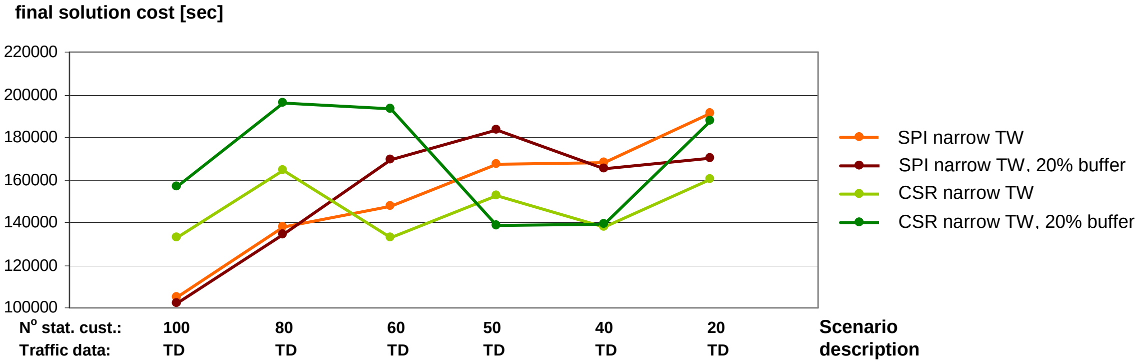


Figure 7.25 Final solution costs obtained in scenarios with defined: narrow TWs, 100 static customers, δ is equal to 1 sec, TD traffic data and 20% of buffer time

On account of comparison, it was noted that in all scenarios considering narrow TWs and buffer, when using CSR the fleet is able to serve higher number of customers than when SPI is employed. The average service level calculated for all test cases is equal to 99,4%. When SPI is used it is equal to 95,4%. In this context, the second best method is CSR without buffer (99,1%). SPI without buffer allows to serve in average 96,3% of customers.

When solving scenarios with narrow TWs using CSR, and 20% buffer is considered, the service level is increased in average by 0,3%. It is at the expense of the solution cost, travel time and waiting time which are longer by 12%, 8% and 66% respectively in average for all tested scenarios.

In three most dynamic scenarios (with: 50%, 40% and 20% of static customers) employing CSR, there were obtained the same values of service level for the case with and without buffer time added. In the last two, the lowest final solution cost was provided by the approach not considering buffer.

The values of service levels and final costs obtained using SPI and CSR methods to solve scenarios with wide TWs are presented in Figures 7.26 and 7.27, respectively. Similarly as before there were considered two cases: with and without 20% of buffer time added.

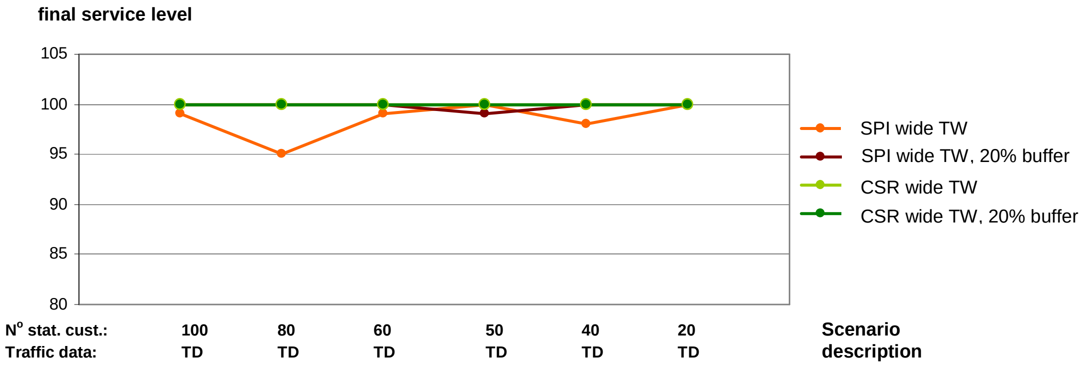


Figure 7.26 Final service levels obtained in scenarios with defined: wide TWs, 100 static customers, δ is equal to 1 sec, TD traffic data and 20% of buffer time

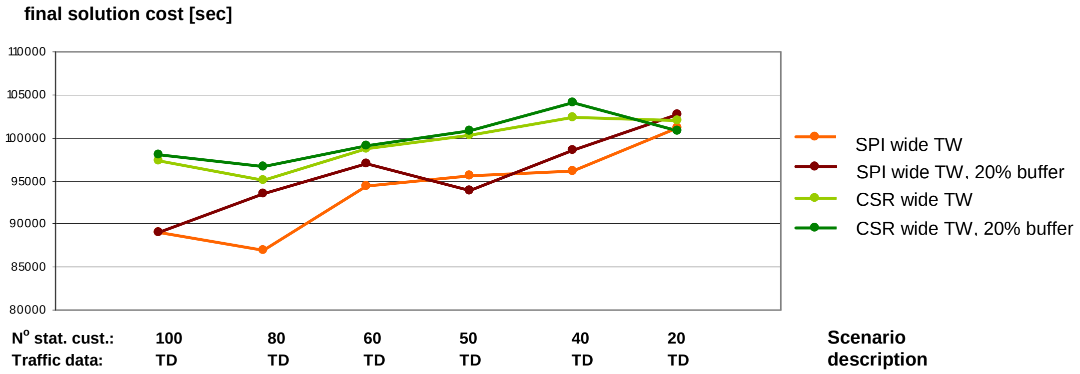


Figure 7.27 Final solution costs obtained in scenarios with defined: wide TWs, 100 static customers, δ is equal to 1 sec, TD traffic data and 20% of buffer time

The comparison of scenarios with wide TWs shows that CSR reaches 100% of service levels for all tested cases, regardless of whether buffer is used or not. The difference is more visible when SPI is employed. In this case, the usage of buffer results in higher service levels in most of the instances. Consequently, the worst performance is provided by SPI with no buffer added.

For each scenario, where there was reached 100% of service level using either CRS with or without buffer, there were compared values of final cost. As a result, in majority of the scenarios, the employment of buffer results in increment of final solution costs. It indicates that when wide TWs are defined it is not necessary.

In the scenarios with 20% of static customers SPI with and without buffer used reaches 100% of service level. Comparison of these two cases shows that the final schedule cost is the lowest when no buffer is used.

In sum, when there is used a method which does not provide good service levels, such as SPI, adding a buffer to the travel time is proficient since it allows reaching higher service levels. Nonetheless, when the employed method provides already good service levels, such as CSR, adding buffer does not significantly improve final service levels. Even more, it degrades considerably the final cost of the solutions, in main due to much higher waiting time.

7.8.4 Influence on Freight Fleet's Performance of Traffic Flow Blocked in 10% of Urban Road Network Due to an Incident

Another, group of tests concerns evaluation of performance of proposed approaches in extreme conditions, when traffic flow on 10% of underlying city road network is blocked (Table 7.12). The traffic jam starts at 10 am and lasts for one hour.

N° scenario	TW	N° of static customers	Method	Travel time data	TDSP Calculator used	Forecaster used	Traffic blocked
5	narrow	100	SPI	TD	multiple times	multiple times	0%
57	narrow	100	SPI	TD	multiple times	multiple times	0%
6	wide	100	SPI	TD	multiple times	multiple times	10%
58	wide	100	SPI	TD	multiple times	multiple times	10%
21	narrow	100	CSR	TD	multiple times	multiple times	0%
59	narrow	100	CSR	TD	multiple times	multiple times	0%
22	wide	100	CSR	TD	multiple times	multiple times	10%
60	wide	100	CSR	TD	multiple times	multiple times	10%

Table 7.12 Scenarios compared to evaluate the influence on freight fleet's performance of traffic flow blocked in 10% of urban road network due to an incident

Figure 7.28 presents reached service levels, while Figure 7.29 outlays obtained final solution costs.

Naturally, in general, the traffic jam results in deterioration of final service level. The change is more visible in the case of the scenarios with narrow TWs. It reaches 6% when SPI is employed and 15% when CSR is used. Notwithstanding, in the latter case the level of ultimately provided service is higher. In the scenarios with wide TWs the deterioration of service quality is little or none. It reaches 1% when SPI is employed. In sum, no matter the span of defined TWs, the usage of CSR method results in higher number of finally served customers.

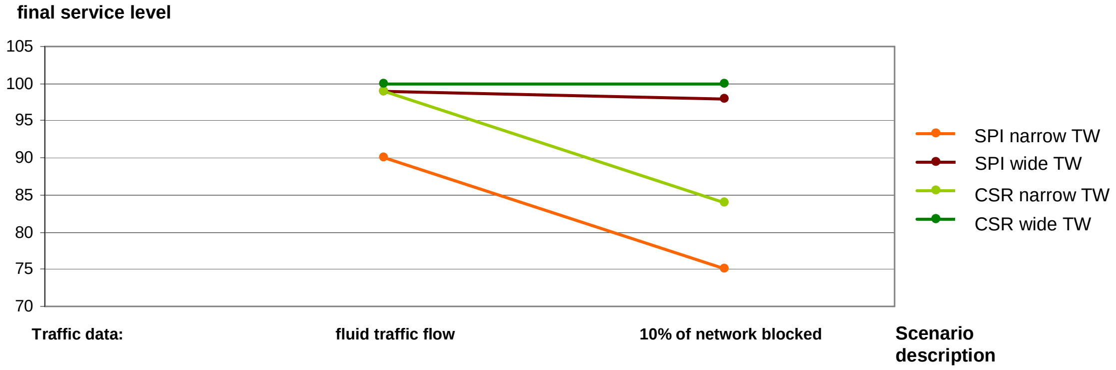


Figure 7.28 Final service level obtained by SPI and CSR methods in scenarios with 100 static customers, δ is equal to 1 sec, TD traffic data and when there is blocked 10% of underlying network

The chart in Figure 7.29 shows the increment of the final costs due to blocked traffic flow. The only exception consist the scenario with narrow TWs using SPI, where the final cost decreased by 2%. It is due to the fact that fewer customers were served, thus the finally performed routes were shorter. Traffic blocking affects the performance of the fleet more in scenarios with narrow TWs. When CSR is used the final solution cost is higher by 73%. In scenarios with wide TWs final costs grow by 6% and 7%, when SPI and CSR methods are employed, respectively.

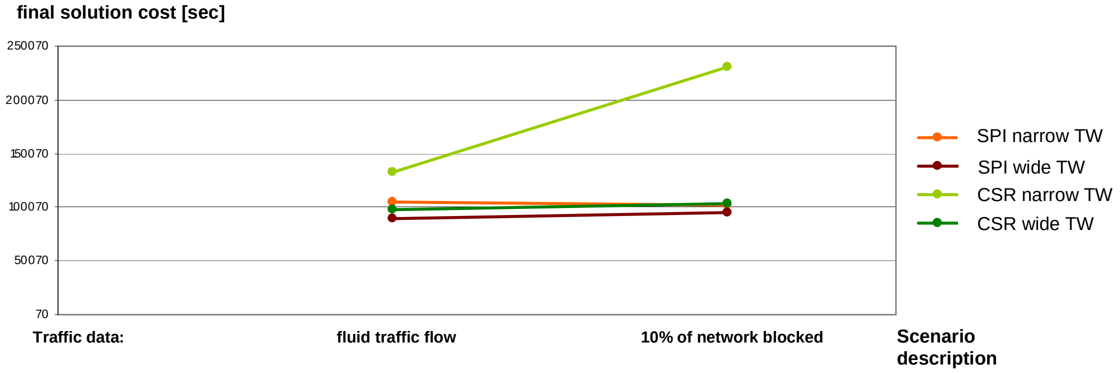


Figure 7.29 Final solution cost obtained by SPI and CSR methods in scenarios with 100 static customers, δ is equal to 1 sec, TD traffic data and when there is blocked 10% of underlying network

Consequently, in order to guarantee the highest level of customer service in situations regarding significant traffic flow blockage, it is recommended to employ CSR method in the DRSM. An extensive modification of the current routing plan, taking into account new data on traffic, allows for such adjustment, which minimizes the number of lost orders while optimizing the final cost.

7.8.5 Influence of Decrement in Travel Time Data Precision on Final Results

In the present thesis project due to the fact that the conducted experiments were performed on the basis of simulation it was possible to obtain very high precision of calculation. Microscopic simulation is time based which means that it updates the state of the system with a frequency determined by the simulation step. This requires synchronizing the TDSP algorithm with simulation to avoid discrepancies. Hence, in all the experiments there was used time factor δ = 1 sec. There were also performed additional experiments changing the δ and setting it equal to 10s, to see how it could mitigate the effects of the discrepancies. However, in the real-life applications the updates are usually longer periods depending on used technologies and applications. Consequently, if such data are employed using the proposed approach and methodology it is necessary to adjust the architecture of the data storing structures as well as the stored data. The simulator has to be synchronized with TDSP Calculator. It means that the data used by TDSP Calculator have to represent the multiplication of the magnitude defining the simulation step δ in order to avoid discrepancies in the final output.

All the scenarios presented in the current chapter were performed on a laptop Dell Latitude D830 with a dual core processor Intel core 2 duo T7700 2.40 Ghz, 4GB of RAM and running Windows 7, 64 bits operating system.

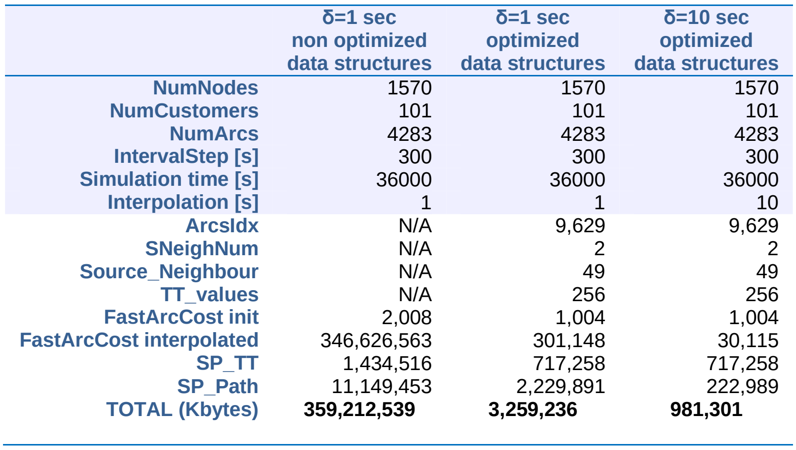
The amount of data surpasses significantly the processing capacity of any commercially available PC. On that account, it was necessary to introduce optimized data structures in order to handle the information required to conduct the designed testing scenarios.

Due to the fact that the original travel time data were stored as decimal values it was decided to round them and store them with a precision of 0.25 second. It is also assumed that travel time between two adjacent nodes in the graph cannot be superior to 4,5 hours. This allows storing travel time data on smaller blocks of memory space.

The analysis of the graph defining the structure of the underlying urban road network allowed observing that each node has no more than eight direct successor nodes. As a result it was also possible to store the index of those successor nodes on reduced blocks of memory space.

Similarly, in order to reach an optimum processing speed/memory space compromise, index tables have been used to store the data of the original and interpolated travel times and also for the SP cube. Those index tables are called *ArcsIdx* and *Source_Neighbour*, respectively.

For comparison purposes there was prepared Table 7.13 containing information of how much memory is required with and without the optimization of data structures. The table also contains the memory requirements in the case when travel time data is interpolated using 10 seconds long interval steps. The table is followed with the description of introduced simulation data structures and parameters.



	δ=1 sec non optimized data structures	δ=1 sec optimized data structures	δ=10 sec optimized data structures
NumNodes	1570	1570	1570
NumCustomers	101	101	101
NumArcs	4283	4283	4283
IntervalStep [s]	300	300	300
Simulation time [s]	36000	36000	36000
Interpolation [s]	1	1	10
ArcsIdx	N/A	9,629	9,629
SNeighNum	N/A	2	2
Source_Neighbour	N/A	49	49
TT_values	N/A	256	256
FastArcCost init	2,008	1,004	1,004
FastArcCost interpolated	346,626,563	301,148	30,115
SP_TT	1,434,516	717,258	717,258
SP_Path	11,149,453	2,229,891	222,989
TOTAL (Kbytes)	**359,212,539**	**3,259,236**	**981,301**

Table 7.13 Comparison of needed memory space for running 1 sec interpolated scenario with and without optimized data structures and when travel time data were interpolated to 10 sec long intervals

Variables and parameters defining both the graph and the performed scenarios:

- *NumNodes* – total number of nodes in the graph,
- *NumCustomers* – total number of customers in the scenario (static and dynamic),
- *NumArcs* – total number of arcs in the graph,
- *IntervalStep* – original value of time intervals δ = 300 sec during which travel time data were recorded,
- *Simulation time* – total simulation horizon,
- *Interpolation* – interval step of expanded travel time data. δ = 1 sec and δ = 10 sec.

Simulation data structures:

- *ArcIdx* – vector containing indexes of every arc of the graph,
- *SneighNum* – vector containing the number of direct predecessors for each node of the graph,
- *Source_Neighbour* - table containing the list of direct predecessors for each node of the graph,
- *TT_values* – vector containing all possible travel time values starting from 0 second up to 16383.75 seconds with an increment of 0.25 second,
- *FastArcCost init* – table containing the original travel time values recorded every 5 minutes, with a size of: *NumArcs* x *Simulation time* / *IntervalStep,*
- *FastArcCost interpolated*– table containing the travel time values after interpolation, with a size of: *NumArcs* x *Simulation time* / *Interpolation,*
- *SP_TT* – matrix containing the shortest path travel times (*Labels cube* from chapter 7.1.1), with a size of: *NumCustomers* x *NumCustomers* x *Simulation time*
- *SP_Path* – matrix containing the shortest path nodes (*SP Cube* from chapter 7.1.1), with a size of: *NumCustomers* x *NumNodes* x *Simulation time* / 10 / *Interpolation*

Performance of one testing scenario using optimized data storing structures requires 3,3 GB of memory space. So as to explore the possibility to reduce travel time data precision in order to speed up simulation time and be able to deploy the algorithms in a real-life application more easily it was decided to measure how, or if, the decrement in travel time data precision impacts the final results.

For the purpose of this study it was decided to store the travel time data for ten seconds long intervals instead of originally defined five minutes long periods. The obtained results were compared with the outcome provided when the simulation is performed on a 1 second time increment. This means that the travel time data has been interpolated for every 1 second and 10 seconds, respectively.

The proposed method to evaluate the impact on reducing simulation data precision is to compare every simulation scenario with $\delta=1$ sec to its equivalent using $\delta=10$ sec by analysing the absolute difference in final service level and solution cost.

Thus, in Figure 7.30 there are presented the values of absolute difference in reached service levels for scenarios with specified: TWs span, number of dynamic customers and applied solving method. Similarly, Figure 7.31 shows the differences in final schedule costs obtained in corresponding scenarios.

N° scenario	TW	N° of static customers	Method	Travel time data	TDSP Calculator used	Forecaster used	δ
61	narrow	100	SPI	TD	multiple times	multiple times	10
63	narrow	80	SPI	TD	multiple times	multiple times	10
65	narrow	60	SPI	TD	multiple times	multiple times	10
67	narrow	50	SPI	TD	multiple times	multiple times	10
69	narrow	40	SPI	TD	multiple times	multiple times	10
71	narrow	20	SPI	TD	multiple times	multiple times	10
5	narrow	100	SPI	TD	multiple times	multiple times	1
7	narrow	80	SPI	TD	multiple times	multiple times	1
9	narrow	60	SPI	TD	multiple times	multiple times	1
11	narrow	50	SPI	TD	multiple times	multiple times	1
13	narrow	40	SPI	TD	multiple times	multiple times	1
15	narrow	20	SPI	TD	multiple times	multiple times	1
62	wide	100	SPI	TD	multiple times	multiple times	10
64	wide	80	SPI	TD	multiple times	multiple times	10
66	wide	60	SPI	TD	multiple times	multiple times	10
68	wide	50	SPI	TD	multiple times	multiple times	10
70	wide	40	SPI	TD	multiple times	multiple times	10
72	wide	20	SPI	TD	multiple times	multiple times	10
6	wide	100	SPI	TD	multiple times	multiple times	1
8	wide	80	SPI	TD	multiple times	multiple times	1
10	wide	60	SPI	TD	multiple times	multiple times	1
12	wide	50	SPI	TD	multiple times	multiple times	1
14	wide	40	SPI	TD	multiple times	multiple times	1
16	wide	20	SPI	TD	multiple times	multiple times	1
73	narrow	100	CSR	TD	multiple times	multiple times	10
75	narrow	80	CSR	TD	multiple times	multiple times	10
77	narrow	60	CSR	TD	multiple times	multiple times	10
79	narrow	50	CSR	TD	multiple times	multiple times	10
81	narrow	40	CSR	TD	multiple times	multiple times	10
83	narrow	20	CSR	TD	multiple times	multiple times	10
21	narrow	100	CSR	TD	multiple times	multiple times	1
23	narrow	80	CSR	TD	multiple times	multiple times	1
25	narrow	60	CSR	TD	multiple times	multiple times	1
27	narrow	50	CSR	TD	multiple times	multiple times	1
29	narrow	40	CSR	TD	multiple times	multiple times	1
31	narrow	20	CSR	TD	multiple times	multiple times	1
74	wide	100	CSR	TD	multiple times	multiple times	10
76	wide	80	CSR	TD	multiple times	multiple times	10
78	wide	60	CSR	TD	multiple times	multiple times	10
80	wide	50	CSR	TD	multiple times	multiple times	10
82	wide	40	CSR	TD	multiple times	multiple times	10
84	wide	20	CSR	TD	multiple times	multiple times	10
22	wide	100	CSR	TD	multiple times	multiple times	1
24	wide	80	CSR	TD	multiple times	multiple times	1
26	wide	60	CSR	TD	multiple times	multiple times	1
28	wide	50	CSR	TD	multiple times	multiple times	1
30	wide	40	CSR	TD	multiple times	multiple times	1
32	wide	20	CSR	TD	multiple times	multiple times	1

Table 7.14 Scenarios compared to evaluate the influence of decrement in travel time data precision on final results

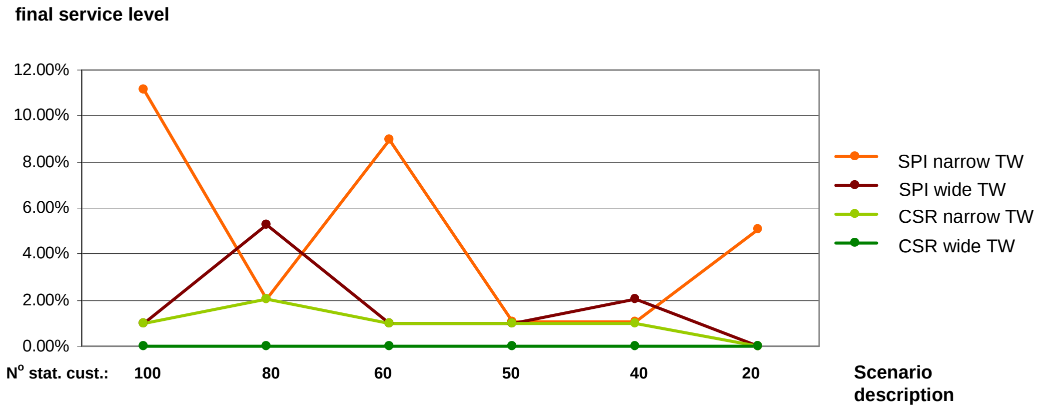


Figure 7.30 Absolute differences in reached final service levels in corresponding scenarios

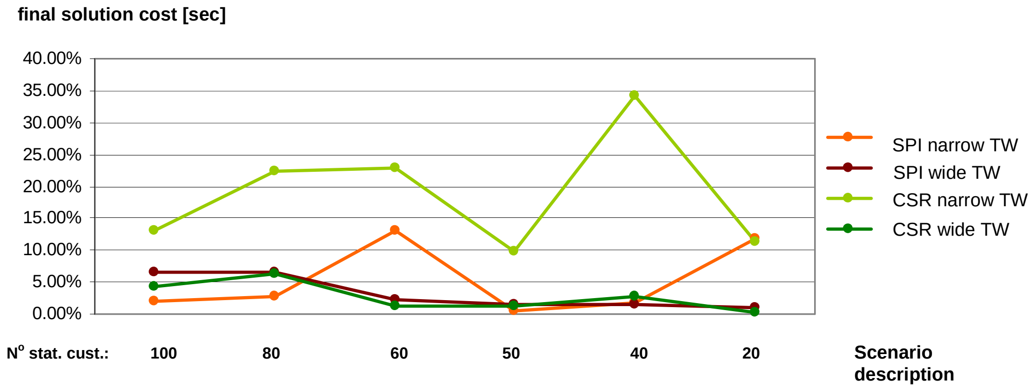


Figure 7.31 Absolute differences in reached final solution costs in corresponding scenarios

On the qualitative level, the final service level and number of performed routes are impacted accordingly by 2% and 6% in average for all tested scenarios.

More precisely, the absolute differences in service levels in the case of using SPI to solve the scenarios with narrow and wide TWs reach 5% and 2%. When CSR is employed these differences are of 1% and 0%, respectively. With exception of the scenarios with narrow TWs and using SPI, the service levels are consistent when there is employed different data precision δ=1 sec and δ=10 sec. The degraded precision in travel time input data has a limited impact on the service level.

Then, on the quantitative level, the absolute difference in final solution costs is equal to 8%, in average for all the tested scenarios. This value for the final travel and waiting time reaches 14% and 23%, respectively.

In particular, the absolute differences in final solution costs in the case of using SPI to solve the scenarios with narrow and wide TWs reach 5% and 3%. When CSR is employed these differences are of 19% and 3%, respectively. It indicates that the final solution costs resulting from solving scenarios with narrow TWs by CSR are not reliable in the case when the travel time data interpolation precision is of 10. In this case, the reason for such high discrepancy is due to the fact that the routing and scheduling plan gets modified more often than when SPI is used or when the span of defined TWs is higher. Therefore, the travel time approximation, due to the δ=10 sec interpolation, is summed up more often as well.

In sum when solving scenarios using CSR, and aiming at obtaining high service level, it is acceptable to use only a 10 sec interpolation precision as there is no significant impact on the final outcome. However, from the point of view of the final solution cost, when narrow TWs are defined, there can be noted significant differences in the quality of the result.

On the other hand, scenarios executed with SPI and 10 seconds precision have a service level considerably impacted independently from the type of defined TWs.

As a consequence, since the objective was to investigate the influence that travel time data precision has on the final outcome obtained for each scenario, it was found that in order to achieve the highest service level in combination with the lowest solution cost, it is most beneficial to use 1 sec interpolation.

Conclusions

"Once you can accept the universe as matter expanding into nothing that is something, wearing stripes with plaid comes easy."

Albert Einstein (1879-1955)

Chapter 8

In order to proficiently direct a fleet of goods' transporting vehicles in urban area it is proper to base managing decisions on information provided by professional Decision Support System, which facilitates consideration of all dynamic factors conditioning the faced distribution problem. The current thesis provides a proposal of such system and the present chapter constitutes a final summary of the whole work that was done in its framework.

The introductory part of the present chapter provides description of the main goals and actions that were taken, in order to achieve them. There are reviewed major performed steps, addressed problems and applied solving strategies. There are also presented main findings and final conclusions drawn on the basis of obtained results. Section 8.1 provides suggestions on the possible directions to undertake as a continuation in the future research.

Recapitulation

A urban network is subject to numerous random events. Therefore, an efficient freight management in city areas should reckon with changeable nature of traffic conditions and thus the variability in vehicles' travel times as well as for the other dynamic factors conditioning the freight distribution problem such as: customers' requests and service conditions (demands, TWs, etc.) and operational conditions of the employed fleet (vehicles' availability, status, positions, current occupancy of the carriage space, etc.).

The objective of the present thesis project was to propose, implement and computationally test on the basis of simulation the architecture of a DSS for real-time freight management able to account for all these dynamic determinants. The design of its architecture was based on integration of the chosen pickup and delivery vehicle routing model and dynamic traffic simulation models, for which the purpose is to carefully emulate the evolving traffic conditions. The optimal dynamic routing and scheduling of a vehicle fleet was obtained due to dynamic modifications of current routing and scheduling plan on the basis of newly revealed information.

The main objective of the thesis is practical and regards both a proposal of an approach and development of a computational tool apt to support solving the real-life problems found in the CL environment. However, its realisation was done on the basis of scientific improvements, since the addressed dynamic problem has been studied in insufficient degree.

To attain the objectives the whole work started from literature review. The collection of researched topics comprised both the models of static routing problems and the methods used for solving them. Since the PDVRPTW model was selected to represent the freight logistics operations, there was investigated its dynamic character more thoroughly and a close attention was paid to the manners of its both defining and resolving.

In the course of work there was noted the importance of clear specification of addressed routing problem. Also, there was ascertained the determinant influence on the final solution of both variability of used information and choice of employed method.

In effect, it was observed that the dynamic PDVRPTW is rarely addressed in the literature. In addition, when it is considered each time there is taken into account a different set of constraints and initial assumptions. As a consequence, it was decided to define and employ such a list that would reckon with the highest number of problem determining dynamic factors. The main motivation of this action was to increase the innovation value of the current thesis and to complement the present state of the art.

In continuation, there was proposed a DSS based on integration of the previously selected vehicle routing model with traffic simulation with the purpose of evaluation of CL applications. Used approach deals with the PDVRPTW in an emulated dynamic environment through implementation and evaluation of heuristics. It aims at recurrent optimal modification of current routing and scheduling plan on the basis of newly revealed information conditioning the addressed problem.

The ambition was to create a highly sensitive mechanism, which would allow for reaction in real-time to the dynamic changes of the factors affecting the performance of freight vehicles and by consequence the quality of final solution. The reason was also to seize the opportunity of employing the recent technological developments achieved in the field of ITS and use the data which might be provided in the real-time fashion by a system such as: ATIS, GPS, GPRS or other ICT tools.

Therefore, inspired by the proposal provided by Regan et al. (1996, 1998), there was developed a refined version of the DSS's design for efficient dynamic urban freight management. The operation of each of the modules was adapted to the addressed dynamic PDVRPTW paying special attention to the time-dependent character of the problem and employed feeding data. The original scheme was also complemented with specification of new working units, necessary to adjust the real-time information on city traffic and freight fleet performance. The date was available due to both network monitoring and vehicles' tracking, which in the real life is facilitated by modern ITS tools.

The main elements of the developed DSS are the proposed routing and scheduling modules. Hence, in the initial phase of work regarding the investigation, all the efforts were focused on the design and development of a proficient method constituting their operational core.

The conclusion drawn from the initial literature review indicated that so far there was not proposed a way to estimate the general quality of operation of PDVRPTW solving approaches. Hence, instead of choosing one from the available methods' proposals, it was decided to create and test a number of composed heuristics with the objective of selecting one apt to solve the addressed problem providing quickly an outcome of acceptable quality. The complementary purpose was to provide answers to the questions on how the individual components affect each other and what effect they have on final result.

Thus, the aim was not to design and construct such meta-heuristic, which would prove to be substantially faster and more efficient than the approaches proposed by other authors but to find a routine good enough from the point of view of the complete undertaking.

In order to investigate the impact, that the preliminary data composition has on the final solution there were tested various data pre-processing methods. They provide the information ordered and ready to be employed by the initial solution constructing method. There were reviewed strategies based on: simple pairing approach, PDP adapted Sweep Algorithm and definitions of Customers' Aggregation Areas. The latter was ultimately selected due to its proven best performance.

The initial solution was created on the ground of the Simple Insertion Procedure. Its task is to rapidly provide a collection of feasible routes.

The quality of initial solution strongly affects the final outcome. The composite approaches which obtain most advantageous initial solutions take the longest to perform the complete calculation process, but achieve most favourable results in comparison with others.

In order to optimize the initial solution there was developed and implemented the PTS optimization method. It constitutes an adapted version of UTS meta-heuristic proposed by Cordeau et al., 2001, which was originally designed and used to solve a VRPTW. Its original formula was adjusted in order to solve the addressed PDVRPTW.

The main modifications are related with the fact that in the definition of the problem there are specified pickup-delivery customers' pairs instead of individual customers. As a consequence, each variation of the current set of routes performed by a local search operator needs to be made with compulsory consideration of additional constrains of pairing and precedence. Similarly, both architecture and functioning of the adaptive memory structures of the UTS were adjusted to reckon with the fact that the customers are joined in couples with the rules of mutual dependencies.

In order to raise the efficiency of the original approach, in the routine of the PDVRPTW adapted UTS there was introduced parallelism by executing simultaneously two local search operators: NPDPSO and NPDPEO. As a result, there was developed the PTS heuristic for the PDVRPTW, where two individual processors create and search two different neighbourhoods of the same, currently best solution. Thus, the whole exploration space gets expanded and the probability of the complete process to be entrapped within local optima is reduced.

Lastly performed procedure regards post-optimization of the solution provided by PTS. There were examined two alternative methods: NPDPRO and PDP adapted 2-opt algorithm. In essence, they aim at such reordering of the sequence of customers to visit in each route, so that the new solution is feasible and with lower final cost than the original. The comparison of performance of the two methods showed that the employment of NPDPRO is more beneficial.

Different combinations of all the above described methods allowed for designing of 16 dissimilar composite approaches apt to solve the static version of the PDVRPTW. The quality of their performance was compared between them and with the chosen reference heuristic proposed by Li and Lim (2001). The regarded variables were: final schedule cost and final CPU.

The time of operation of all the 16 tested composite methods is comparable. Thus, the finally selected approach to be implemented as a core of the proposed routing and scheduling modules is the one which was able to reach the lowest values of final schedule cost with respect to the rest of tested methods. It initially organizes customers using the definitions of Customers' Aggregation Areas and post-optimizes the solution with NPDPRO.

The chosen approach was first implemented in the IRSM. Due to the fact that the ultimately considered travel times' information is time-dependent instead of static, each of the individual procedures was properly adjusted. As a result, all the consultations of costs of trips between two customers are made with mandatory consideration of the moment when they start.

In this way modified PDVRPTW solving approach was also implemented in the DRSM. However, there needed to be effectuated additional changes in order to reckon with not only the real-time traffic development but also with both changeable information on operational conditions of employed fleet and customers' requests and service specifications.

Thus, the original initial solution creating procedure was replaced with an algorithm which objective is to provide a new feasible set of routes considering recently reported service requests. There were tested two candidate methods: SPI and CSR.

SPI dynamically modifies the current routing and scheduling plan by introducing the novel pair in the most favourable locations, if feasible. Otherwise, it creates additional route containing new customers. Its general objective is to maintain the plan in a form which is the closest to the original design. CSR destroys the present plan in order to create a new one from scratch.

This initial step is not omitted even when a DRSM's triggering event does not regard the appearance of a new request. The initial set of routes is always optimised using PTS and post-optimised by NPDPRO.

Each time DRSM is triggered there is first checked both position and status of employed freight vehicles. Next, the customers which have already been provided with requested service are removed from the current plan. The novelty in the design of DRSM with respect to IRSM is the fact that the starting point of each route is no longer the depot but a node defining the current position of the vehicle, either "dummy" or real. In addition, depending on vehicle's status there are calculated variables defining the remaining time of currently performed activity, either service, travel or waiting.

To obtain information on fleet vehicles' performance there was designed and developed a VFP Simulator. At the moment of DRSM launching it provides precise data on currently carried out activity, capacity's occupancy, location and so-far-fulfilment of assigned tasks. At the same time it is used for evaluation purposes. The fact that there is not considered any random component in traffic's evolution, which would affect freight's performance, facilitates the comparison of tested scenarios and final assessment of proposed approach.

The costs of trips between customers were represented in terms of time-dependent shortest paths between them. They are provided by TDSP Calculator. It was developed on the basis of a known algorithm proposed by Ziliaskopoulos and Mahmassani, 1993. However, so as to support its M2M extended design its original composition and data storing structures were modified.

The forecasts of travel times representing development of traffic states are provided by the Time-Dependent Travel Times Forecasting Module. It does not constitute an integral part of the proposed DSS however it delivers the essential input to DSS. Its design was based on exponential smoothing - a simple technique, which can be applied to time series data in order to make forecasts.

All the developed modules were connected in a way to create a platform for evaluation of CL applications, in the case of the PDVRPTW and to test a new approach to deal with the dynamic case, through fast insertion heuristics and PTS, when new customer requirements arrive during the operational period.

A set of computational experiments was designed and conducted to evaluate the performance of a freight fleet using the simulation platform to emulate daily traffic conditions in urban areas, under different scenarios.

Thus, at the final stage of the research, there were created and tested 84 different scenarios reckoning with: two types of TWs (wide and narrow), two solving methods (SPI and CSR), two different approaches addressing travel times' data calculation precision (δ = 1 second, δ = 10 seconds), two definitions of traffic flow (fluid and 10% of network blocked for one hour) and additional aspect regarding usage of 20% of buffer time.

In sum, the main objective of the current thesis was to propose, implement and computationally test, on the basis of a simulation, the architecture of a Decision Support System for real-time freight management able of accounting for the dynamic factors affecting the addressed pickup and delivery vehicle routing problems with time windows. This task was completed successfully and the main findings and contributions were presented in the current document.

8.1 Main Findings

1. In the search of an efficient approach to employ as a key method of both IRSM and DRSM there were designed and tested 16 different composite heuristics aiming at solving the static version of the PDVRPTW. Among all of them area_rr proves to perform most effectively in terms of both execution time and final schedule cost. It works best solving instances where the customers are clustered or when long scheduling horizons are considered. In around 15% of time which requires the method used as reference (Li and Lim, 2001) it is able to provide the same or better result for almost 50% of benchmarks. The difference in time reaches in average 11 minutes per each instance, which is crucial from the point of view of complete undertaking, where the time of reaction is of special importance.
2. At the first stage of DSS results analysis all efforts were focused on finding answer to the question on validity of the frequent dynamic readjustment of routing and scheduling plan. The obtained outcome proved that in each tested scenario, there is notable difference between initially proposed and actually performed routing and scheduling plan. The dynamic factors such as new customers' calls and traffic visibly affect the performance of freight fleet. Although the initial routing plan created on the basis of historical data is feasible it may happen that not all customers will be ultimately served within their TWs due to changes in traffic conditions during the day. Thus, the cyclic readjustment of current routing and scheduling plan accounting for all dynamic changes is justified and results in significant costs optimization.
3. Another major question addressed in the present thesis regards possible benefits due to utilization of time-dependent travel times' information instead of average static values. The comparison of final results obtained for the scenarios, which differ only in the type of

used traffic information, shows clear advantage of employment of time-dependent travel times' information. When it is used there are reached lower final solution costs in connection with higher service levels.

4. In the current thesis there were proposed two methods for new dynamic customers' insertion. The comparison of final solutions provided by both methods SPI and CSR shows that the latter allows reaching higher service levels in combination with lower final solutions' costs. Since it creates new version of routing and scheduling plan from scratch taking into consideration all the newly revealed information it is able to consider wider spectrum of problem affecting factors and provide better adjusted proposal. It responds better to dynamic changes. SPI intends to maintain the original design of the routing and scheduling plan. Consequently, for the price of maintaining it there are lost some of the opportunities to serve customers. In this case the final output strongly depends on the quality of the initial solution.

5. The analysis of results provided by each tested scenario resulted in observation that in the scenarios with specified narrow TWs it is difficult to feasibly introduce new orders without significantly deteriorating the overall quality of the final solution. When wide TWs are defined the necessary extension of travel and waiting time is less noticeable. In addition, there is attained higher service level and the number of ultimately performed routes is lower.

6. Wanting to explore and identify possible strategies allowing for feasible and optimal execution of routing tasks in the cases when there are specified tight problem constraints, it was decided to address the concept of buffer and add 20% to the calculated values of travel-time on each section of the underlying road network. In most of the cases, the usage of additional backup time resulted in higher final service levels, which entail higher solutions' costs. However, when the same number of customers was served in the scenarios, which differ only in the specification whether the additional buffer is employed or not, the lower final solution costs were reached when buffer was not used. Consequently, from the point of view of the solutions' quality, expressed in the number of ultimately serviced customers, the usage of buffer is beneficial. However, when the employed method provides solutions with already high service levels the improvement of final solution's cost that the additional buffer could bring is significantly reduced. In fact, in many cases the usage of buffer results in extensively augmented final solution's cost, while the same service levels are maintained.

7. In order to investigate how the proposed DSS would perform in extreme situations there was designed a number of scenarios considering the possibility of alteration of traffic flow on 10% of underlying city road network for one hour. The analysis of obtained results allowed observing that when there are defined wide TWs the dynamic adjustment of routing and scheduling plan in accordance with newly revealed traffic data permits to maintain similar high service level in combination with relatively small increment of the final solutions' costs. In the scenarios with specified narrow time widows there is more apparent negative influence that a big traffic jam has on freight fleet performance both in the context of final service level and solution's cost. Independently from the customers' TWs characterization CSR proved to perform better than SPI.

8. So as to investigate the influence that the precision of the travel times' data has on the final outcome there were tested different alternatives regarding the length of the time

intervals in which the original data was recorded and interpolated. There were considered: ten and one second long periods. The study shows that when, for investigation purposes, accurate and coherent results are required, data interpolated with ten seconds precision, although providing lower memory consumption during execution of scenarios, can not provide sufficiently precise results. As a consequence, data interpolated with precision of one second have been used in the current thesis project, at the expense of higher memory consumption.

8.2 Future Research

One of the possible lines of further investigation regards continuation of the work presented in Chapter 6. The current research focused on designing a method which would quickly provide a feasible solution of acceptable quality. Thus, there were considered significantly smaller numbers of TS iterations than these employed to test the method which was used as a reference. Consequently, the objective of the new study would be to check whether, the approaches proposed to solve the static version of PDVRPTW, are able to reach better results in the same or shorter time as the meta-heuristic proposed by Li and Lim (2001), when similar determinants are applied.

Also, in the PTS there were used values of weighting parameters proposed by Cordeau et al. (2001) for UTS. A complementary study addressing the adjustment of these values might result in valuable contribution.

The proposed DSS was tested using data provided by a simulator and without considering random ingredients affecting: traffic development, freight vehicles' operation and customers' requests. In this context, one of the desirable follow ups of the current research would be to combine the structures of the developed DSS with an advanced commercial simulator, which would provide better emulation of the real-life conditions and consider randomness in the performance of the underlying city road network.

In this context, it would be of interest to employ the same simulator that provides feeding data for subsequent performance of updated routing and scheduling plans. This connection would permit faster execution and easier management of studied scenarios, at the same time facilitating the design and testing of new ones.

The majority of commercially available simulators have defined in the list of features formulas allowing for calculation of specific functions such as, for example: the amount of emitted exhaust gases. This gives the opportunity to expand the current research on new aspects.

A connection of the proposed DSS with a sophisticated simulator would also permit to test different backgrounds, i.e.: city areas of different characteristics. This would allow for the development of such a freight operations optimization strategy, which would be best for the addressed case.

Employment of a simulator would also facilitate the task of freight performance evaluation due to its visual representation and emulation in real-time.

Usage of advanced computation tools would permit to test the proposed approaches in the context of larger problems. In the current study the size of the underlying road network corresponds to one city district in which there were located 100 customers and one depot. The continuation of the study would be to check the performance of the designed DSS using as a background entire city area and much larger number of customers and depots.

New scenarios might differ from each other not only in the size but also in the definition of factors determining the addressed problem. Possible modifications regard e.g.: definitions of customers defining parameters such as their TWs, demands, variable service times, etc. There might be considered introduction of complementary strategies such as e.g.: pooling strategies of incoming service orders, waiting strategies affecting freight vehicles' performance, new requests acceptance policies, etc. Also, there could be considered novel DRSM triggering events, e.g.: regarding the breakage of one of the freight vehicles or its participation in a road accident.

In the current thesis project there was conducted a study regarding freight fleet performance in the situation when 10% of the underlying road network gets blocked for one hour due to traffic incident. Following the real-life situations the collection of affected streets includes adjacent sections. A possible follow up of this study would be to test other scenarios, with different definitions of percentage of blocked city area, more than one blocked areas and different timings regarding both duration and the moment of occurrence. In this way there might be defined and addressed specific scenarios in which natural disasters or other extreme events affect the traffic flow in urban area and there is a special need for dynamically updated optimal routing and scheduling plan.

The present thesis also addresses the aspect of influence of employment of 20% of buffer time added to the forecast of the time-dependent travel times. The continuation of this study might include different specifications of the amount of used buffer and policies defining their usage.

Another possibility of research continuation constitutes the employment and testing of the proposed DSS directly in the real-life environment. In this case the simulator and other additionally developed modules can be substituted by special devices. For example: VRP Simulator can be replaced with a combination of GPS and GPRS tools. The information on the traffic development can be provided in real-time by an ATIS. The regular update on new requests could be done via internet applications or call centre. In addition, the transfer of data could be done automatically easing the dispatcher. In every fright vehicle there could be installed a device which using the proposed algorithms would recalculate current routing plans on the basis of the information provided by the external sources. Functioning of such device could be independent or remaining in contact with a bigger computing and freight coordinating centre guarantying beneficial vehicle-to-infrastructure (V2I) and infrastructure-to-vehicle (I2V) fluid communication.

Appendices

"The shortest distance between two points is under construction."

Noelie Altito.

Appendix A

Data Files

The objective of this annex is to provide information on the numerical data sets and evaluation backgrounds, which were used to complete the application part of the present thesis project.

The first attachment: Appendix A1 presents the benchmark instances common with their analysis, description of their origin and the way in which they have been adapted to the addressed PDP. They were used to examine the quality of operation of sixteen reviewed methods proposed to solve the PDVRPTW.

The second supplement: Appendix A2 contains information on the testing instances used in the experiments evaluating the performance of the proposed Decision Support System. There is provided explanation of the designed testing scenarios, data characterising the two types of considered customers and the information on the network performance represented by a matrix of vehicles' travel times, which was gathered cyclically on each section of the underlying city network.

Appendix A1

Benchmark Instances for Testing Methods Solving PDVRPTW

This appendix provides description of the numerical data used during the first application step of the present thesis project regarding construction and evaluation of a heuristic solving the PDVRPTW. The general characteristics of the PDP have been presented in Chapter 2, which also includes a detailed explanation of the nature of the specific problem addressed in this work.

The selected instances were first introduced by Li and Lim (2001) [LiLi_2001] and since that time in the vast majority of cases they were used by other authors. This finding is a conclusion coming from Chapter 3.2, which includes a review of literature on the development of practical ways to solve the PDVRPTW, performed in the recent past. The resume of results obtained by testing the proposed methods on the basis of the chosen instances is presented in Chapter 6. The output was compared with the outcome achieved by the same authors that proposed the benchmarks (Li and Lim, 2001). Moreover, the same section contains description of the processes of design, construction and evaluation of the candidate approaches apt to solve the addressed PDVRPTW and outlines the final conclusions.

The Li and Lim's instances were generated on the basis of the benchmark cases, which were introduced by Solomon (1987b) for the VRPTW. The authors first solved to optimality the VRPTW applying their heuristic approach (Li et al. 2001) and then randomly paired up the customer locations within the achieved routes, obtaining a novel testing set appropriate for evaluation of algorithms solving the PDVRPTW.

The data were obtained from a web page dedicated to VRPs (http_12). However, their format got adapted to the necessities of the present thesis project. The final structure is explained on the following scheme:

Number of customers including depot
Number of vehicles
Vehicle's capacity

Id	Coordinate x	Coordinate y	Demand	Time Window Lower-bound	Time Window Upper-bound	Service Time	Pickup/Delivery Index	Pair Id
0	x_0	y_0	$d_0=0$	e_0	l_0	$s_0=0$	0	0
1	x_1	y_1	(+) d_1	e_1	1_1	s_1	0	1
2	x_2	y_2	(-) d_2	e_2	1_2	s_2	1	1
3	x_3	y_3	(+) d_3	e_3	1_3	s_3	0	2
4	x_4	y_4	(-) d_4	e_4	1_4	s_4	1	2
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Table A.1 Data format of the testing instances

Thus:

- the first row contains a sum of all the customers and one depot,
- the second row defines the number of all the vehicles in a fleet, obtained from a Solomon's instance corresponding to the Li and Lim's,
- the third row represents vehicle's capacity, also obtained from a Solomon's instance corresponding to the Li and Lim's (it is considered that in the studied cases the vehicles are homogenous),
- the following rows include data regarding customers organized in columns:
    - customer's identification,
    - coordinate x of customer's position on the plane,
    - coordinate y of customer's position on the plane,
    - demand – number of units of cargo requested by a customer, which is positive for a customer requiring service of a pickup and negative for a delivery,
    - customer's time window lower-bound,
    - customer's time window upper-bound,
    - service time – the time a vehicle must spend at the customer's in order to provide the required supply,
    - pickup/delivery index – a binary value, which depicts if a current customer reports pickup (0) or delivery (1) request,
    - pair identification – a number defining a pair, to which the current customer belongs, in the above example there are two pairs.

It is important to note, that the first multi-column row defining the customers describes the depot. In the studied problem it is considered that there is only one depot and its: identification, demand, service time, pickup/delivery index and pair identification are equal to zero, since it does not have a pair partner and does not provide/receive any cargo.

There are six collections of benchmark cases: lc_100, lc_200, lr_100, lr_200, lrc_100 and lrc_200. Each of them contains a different number of instances, which ranges from 8 up to 12. Similarly, the number of included customers varies for all datasets and does not follow any specific formula, for example the set lc_100 contains a compilation of 107 customers, except the collection lc_103, which comprises 105 customers including the depot.

The analysis of individual collections indicates an interesting feature showing that the first 100 customers from each instance, belonging to the same collection, share the same positions on the plane. Consequently, in this aspect, within the same group the files are highly compatible with one another. For example, in the collection 1c_100 having nine datasets, eight of them are correlated in 94,39%. Since the pack lc_103 includes smaller number of customers, the compatibility reaches 96,19%. In order to illustrate the present feature, there are provided two scatter diagrams showing respectively the shared and the individual locations, particular for each collection. The assignment of the figures is the following:

lc_100	Figures A1 and A2
lc_200	Figures A5 and A6
lr_100	Figures A9 and A10
lr_200	Figures A13 and A14
lrc_100	Figures A17 and A18
lrc_200	Figures A21 and A22

Data set	Avg distance between the customers' locations in a pair
lc_100	5.6437
lc_200	19.6040
lr_100	12.3529
lr_200	25.7737
lrc_100	12.6220
lrc_200	30.6281

Table A.2 Average Euclidean distance between the customers linked in a pair, calculated for each instances collection

Another feature indicating differences between the instances are the sizes of the customers' TW. The values vary both between the packages and between all the contained individual customers. It might be noted that there are three different patterns describing their distribution in each dataset:

- constant, e.g.: in the set lc_107 and lc_109 the time window's size is the same for all the customers and equal to 180 and 360 respectively,
- cumulated in one span of values, the example is provided in Table A.3:

Dataset	lc_101	lc_105	lc_106	lc_108
Min Value	37	75	29	149
Max Value	89	177	387	353
Span	52	102	358	204

Table A.3 Minimum and maximum values of the customers' TWs' sizes in the benchmarks: lc_101, lc_105, lc_106 and lc_108. The span is calculated as a difference between the highest and the lowest figure

- cumulated in two distant spans of values, the example is provided in Table A.4:

Dataset	lc_102				lc_103				lc_104			
	% of customers	Min value	Max value	Span	% of customers	Min value	Max value	Span	% of customers	Min value	Max value	Span
Low span values	74.8	43	81	38	49.5	43	81	38	24.3	43	79	36
High span values	25.2	1105	1236	131	50.5	1088	1236	148	75.7	1087	1236	149

Table A.4 Minimum and maximum values of the customers' TWs' sizes defining two spans' limits in the benchmarks: lc_102, lc_103 and lc_104. The spans are calculated as a difference between these figures. The columns: % of customers define the percentage of customers characterized by low or high TW size respectfully

In the last case the number of customers assigned to each span varies and seem to comply with another pattern, where each set contains approximately:

- set lc_102 → 25% of customers with high and 75% of customers with low value of TW,
- set lc_103 → 50% of customers with high and 50% of customers with low value of TW,
- set lc_104 → 75% of customers with high and 25% of customers with low value of TW.

Moreover, for each considered instance the sizes of the spans are similar. Their average rates are equal to 37,3 and 142,7 for the low and for the high TWs' values, accordingly.

The summary Table A.6 contains the details regarding customers' TWs in all instances. However, for the comparison purposes, there was introduced a figure showing the accumulated TWs value estimated for every dataset. Moreover, for the sake of clarity, for each benchmarks grouping, there was created a complementary collection of diagrams, which is to present graphically the overview of the TWs' sizes. They depict values contained by no more than three distinct instances. The sets have been grouped in this way to ensure the best transparency of illustration. As a consequence, it becomes easier to note the differences between the individual cases. The assignment of the figures is the following:

lc_100	Figures A3 and A4
lc_200	Figures A7 and A8
lr_100	Figures A11 and A12
lr_200	Figures A15 and A16
lrc_100	Figures A19 and A20
lrc_200	Figures A23 and A24

The values of the customers' service times are distributed in such a way that their sum in each set has the same value for all the collection, e.g.: in lc_100 it is equal to 9000 and in lr_100 it is equal to 1000. For the individual customers the service time value is also constant, e.g.: in lc_100 it is equal to 90 and in lr_100 to 10. Nevertheless, considering that in most of the cases there are more than 50 pairs per benchmark some customers will be associated with a different service time value set as zero.

The precise assignment of service time, demand, pickup/delivery index and pair identification to each customer is specific for each dataset and does not follow any particular pattern. However, the general comparison of all the instances' collections, regarding particular features, demonstrates that the data are consistent with one another although at distinctive percentage. The largest discrepancy among the datasets is characteristic for the determination of the pair identification feature. The test instances are more similar to each other regarding the service times' assignation. The summary Table A.5 contains the average number of data, which are differing in each benchmark set.

	Service Time			Demand	P-D Index	Pair Id
Dataset	Value per customer	Sum per set	Avg % of incompatibility	Avg % of incompatibility	Avg % of incompatibility	Avg % of incompatibility
lc_10	90	9000	9.368617	44.1171	29.6821	56.4861
lc_20	90	9000	2.988123	41.6006	28.8141	64.9260
lr_10	10	1000	4.596592	32.8476	20.8253	44.9451
lr_20	10	1000	3.510636	62.7183	40.9216	81.9599
lrc_10	10	1000	9.847776	61.7421	39.6252	84.4800
lrc_20	10	1000	2.988123	66.9183	42.2385	92.6616

Table A.5 Summary of values defining: service time, demand, pickup/delivery index and pair identification. For each variable and collection of instances the *Avg % of incompatibility* is the average percent of data, which are different from each other. In addition the table contains the values of the service time per customer and summarized for each benchmarks' set

		Euclidean distance between customers in pairs			TW				
Dataset	Number of customers	Min value	Max value	Avg value	Min value	Max value	Span	% of customers in a span	Avg Value
lc_101	106	0	14.14214	5.32635	37	89	52	100.00	60.5283
lc_102	106	0	11.18034	5.68401	43	81	38	74.77	320.3868
					1105	1236	131	25.23	
lc_103	104	0	38.32754	6.00731	43	81	38	49.52	588.5385
					1088	1236	148	50.48	
lc_104	106	0	38.07887	6.36639	43	79	36	24.30	858.2358
					1087	1236	149	75.70	
lc_105	106	0	12.20656	5.25709	75	177	102	100.00	121.5189
lc_106	106	0	15.81139	5.51120	29	387	358	100.00	157.5849
lc_107	106	0	12.20656	5.71890	180	180	0		180.0000
lc_108	106	0	12.20656	5.68799	149	353	204	100.00	242.4906
lc_109	106	0	12.20656	5.23388	360	360	0		360.0000
lc_201	102	0	59.90826	18.75374	160	160	0	100.00	160.0000
lc_202	102	0	61.03278	22.52213	160	160	0	74.51	952.9412
					3253	3289	36	25.49	
lc_203	102	0	61.03278	22.08919	160	160	0	50.98	1684.3333
					3242	3290	48	49.02	
lc_204	102	0	59.90826	18.53786	160	160	0	24.51	2507.7157
					3241	3291	50	75.49	
lc_205	102	0	47.43416	17.66241	320	320	0	100.00	320.0000
lc_206	102	0	64.03124	21.57108	299	707		408.00	488.8824
lc_207	102	0	53.85165	17.84681	177	1253	1076	100.00	613.5490
lc_208	102	0	53.85165	17.84910	640	640	0	100.00	640.0000
lr_101	106	0	25.29822	11.43487	10	10	0	100.00	10.0000
lr_102	110	0	26.92582	11.40240	10	10	0	74.55	58.1818
					93	208	115	25.45	
lr_103	104	0	45.17743	12.82167	10	10	0	50.00	102.8942
					180	213	33	50.00	
lr_104	104	0	33.54102	11.53614	10	10	0	24.04	150.4423
					170	215	45	75.96	
lr_105	106	0	26.00000	10.98728	30	30	0	100.00	30.0000
lr_106	104	0	26.62705	12.33152	30	30	0	75.96	70.7596
					183	208	25	24.04	
lr_107	104	0	41.76123	14.41749	6	30	24	50.00	112.8077
					180	231	51	50.00	
lr_108	100	3.6056	29.01724	13.97975	30	30	0	25.00	153.3100
					170	215	75	75.00	
lr_109	106	0	35.60899	13.54803	37	83		46.00	58.4057
lr_110	104	0	45.80393	11.63112	23	177		154.00	87.0577
lr_111	108	0	25.31798	11.32002	19	191		172.00	93.0000
lr_112	104	0	35.00000	12.82474	73	166		93.00	117.6132
lr_201	102	0	40.02499	16.75012	27	212		185.00	115.7843
lr_202	100	3.1623	63.32456	28.23341	27	211	184	75.00	328.8100
					953	978	25	25.00	
lr_203	102	0	81.84131	24.87315	27	191	164	50.98	533.5882
					950	953	3	49.02	
lr_204	100	3.1623	76.21680	31.25207	27	167	140	25.00	751.2600
					940	985	45	75.00	
lr_205	102	0	75.29276	25.40870	240	240	0	100.00	240.0000
lr_206	100	7.2111	61.71710	24.90170	240	240	0	75.00	422.3900
					953	978	25	25.00	
lr_207	102	0	58.69412	28.69476	240	240	0	50.00	602.9706
					950	983	33	50.00	

		Euclidean distance between customers in pairs			TW				
Dataset	Number of customers	Min value	Max value	Avg value	Min value	Max value	Span	% of customers in a span	Avg Value
lr_208	100	7	75.02666	30.65743	240	240	0	25.00	783.3100
					940	985	45	75.00	
lr_209	102	0	63.00794	21.19178	91	764	673	100.00	351.6569
lrc_101	106	0	46.52956	12.36964	106	106	0	100.00	30.0000
lrc_102	106	0	51.08816	13.79362	30	30	0	73.58	73.8113
					171	217	46	26.42	
lrc_103	106	0	39.69887	11.02335	30	30	0	49.06	114.0472
					171	225	54	50.94	
lrc_104	108	0	36.61967	11.68808	30	30	0	26.85	151.6481
					171	225	54	73.15	
lrc_105	108	0	43.46263	13.48867	10	120	110	100.00	53.9444
lrc_106	106	0	35.12834	13.59881	60	60	0	100.00	60.0000
lrc_107	106	0	34.20526	12.10753	41	155	114	100.00	88.1038
lrc_108	104	0	40.49691	12.90595	27	180	153	100.00	112.2885
lrc_201	102	0	69.20260	31.00995	120	120	0	100.00	120.0000
lrc_202	102	0	75.18643	30.60859	120	120	0	75.49	315.0588
					891	937	46	24.51	
lrc_203	102	0	68.46897	29.03232	120	120	0	50.98	509.7059
					891	945	54	49.02	
lrc_204	102	0	55.90170	24.74242	120	120	0	24.51	721.0882
					891	945	54	75.49	
lrc_205	102	0	95.52487	32.91791	60	480	420	100.00	221.0490
lrc_206	102	0	69.64194	33.40382	240	240	0	100.00	240.0000
lrc_207	102	0	83.63014	33.77872	91	764	673	100.00	349.7941
lrc_208	102	0	67.18631	29.53103	293	664	371	100.00	470.6765

Table A.6 Summary of values defining: TWs (minimal, maximal and average TW size, size of each span and a percentage of customers included in it) and pairs of customers (minimal, maximal and average Euclidean distance between a couple of customers). In addition the table contains the number of customers considered in each instance

In the analysis presented above the instances belonging to the benchmarks collection lc_100 were used as examples. However the described characteristics are true for all the remaining datasets.

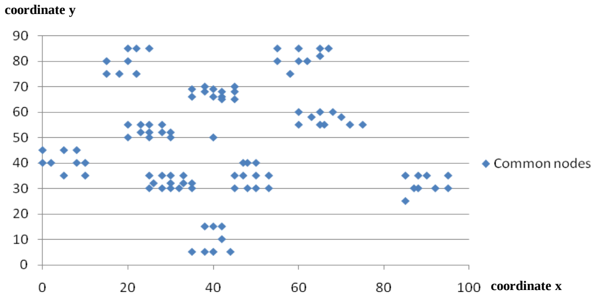


Figure A.1 Scatter diagram of the first 100 customers' locations on a plane (shared by the instances of the set lc_100)

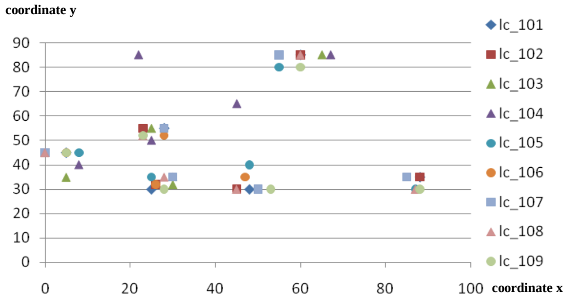


Figure A.2 Scatter diagram of customers' locations on a plane, which are not shared by the instances from the set lc_100

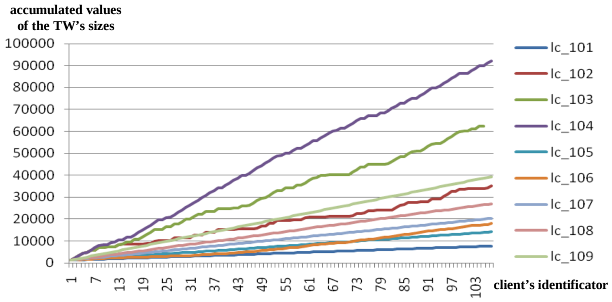


Figure A.3 Cumulative values of TW' sizes for each instance of the set lc_100

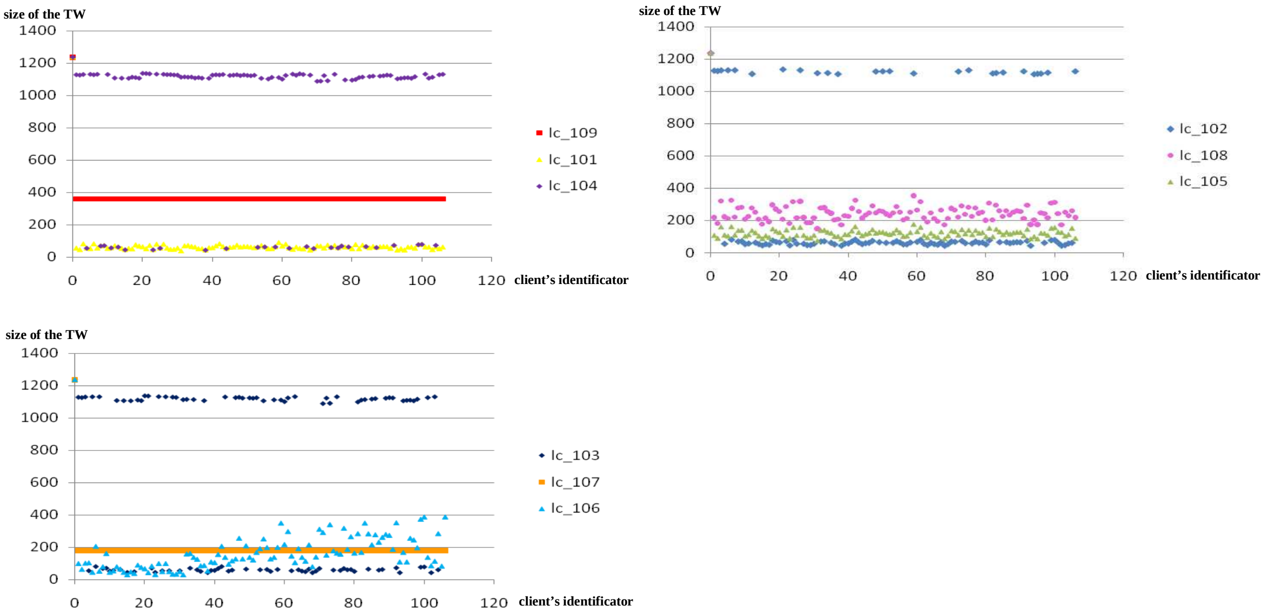


Figure A.4. TW's sizes for each customer of each instance of the set lc_100 (separated in three diagrams for improved visibility)

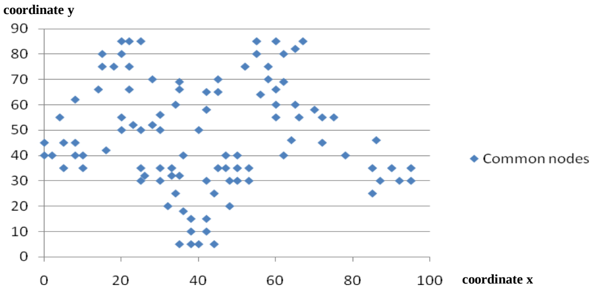


Figure A.5 Scatter diagram of the first 100 customers' locations on a plane (shared by the instances of the set lc_200)

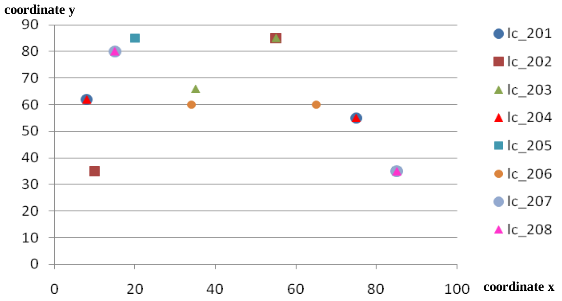


Figure A.6 Scatter diagram of customers' locations on a plane, which are not shared by the instances from the set lc_200

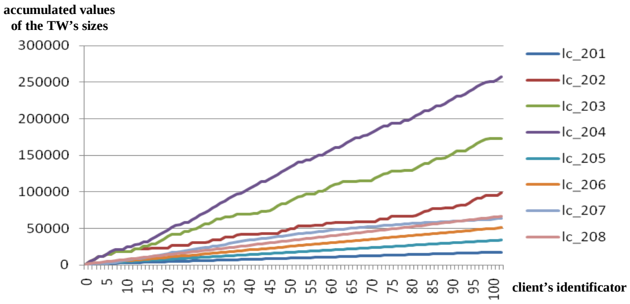


Figure A.7 Cumulative values of TW' sizes for each instance of the set lc_200

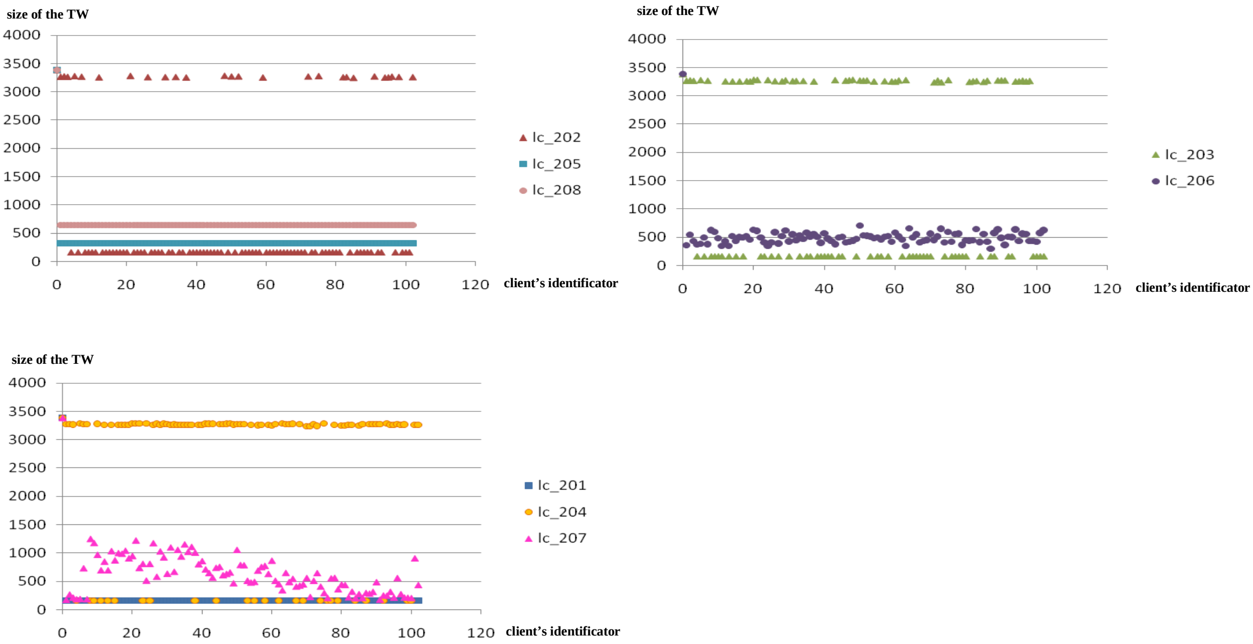


Figure A.8 TW's sizes for each customer of each instance of the set lc_200 (separated in three diagrams for improved visibility)

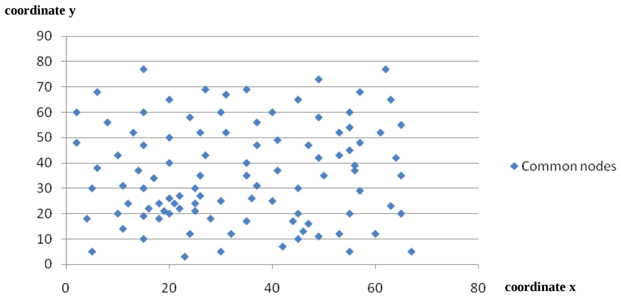


Figure A.9 Scatter diagram of the first 100 customers' locations on a plane (shared by the instances of the set lr_100)

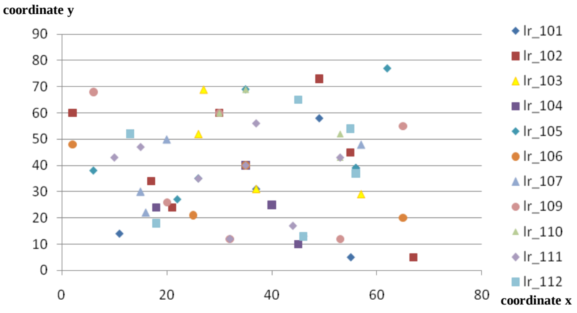


Figure A.10 Scatter diagram of customers' locations on a plane, which are not shared by the instances from the set lr_100

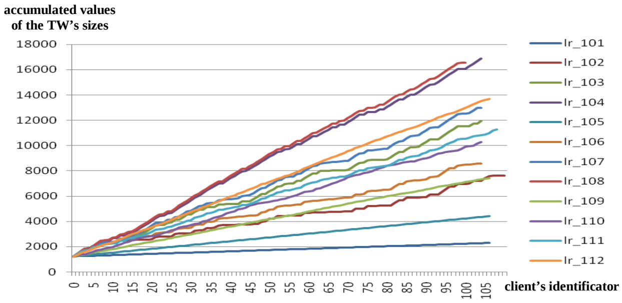


Figure A.11 Cumulative values of TW' sizes for each instance of the set lr_100

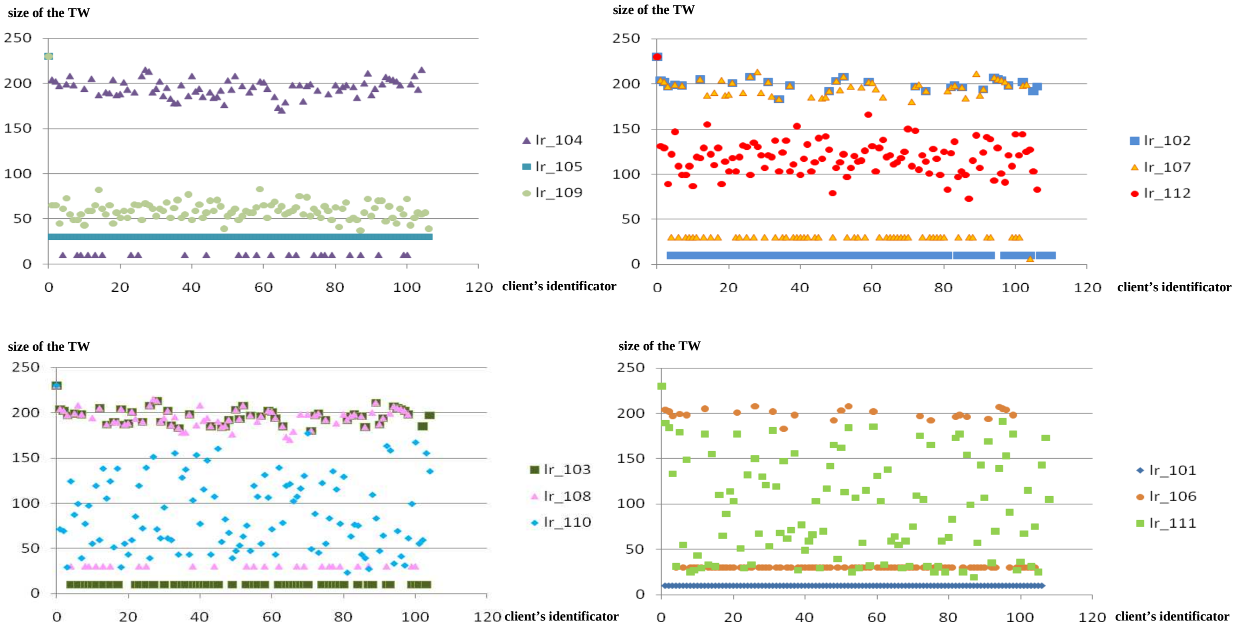


Figure A.12 TW's sizes for each customer of each instance of the set lr_100 (separated in four diagrams for improved visibility)

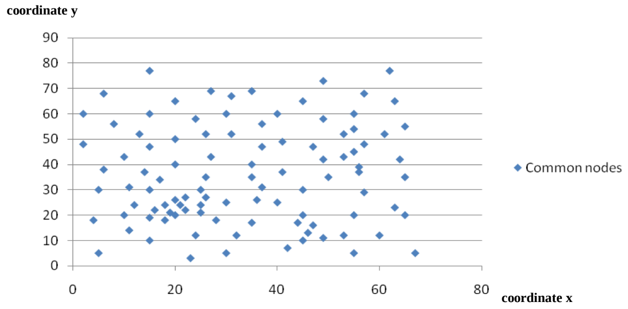


Figure A.13 Scatter diagram of the first 100 customers' locations on a plane (shared by the instances of the set lr_200)

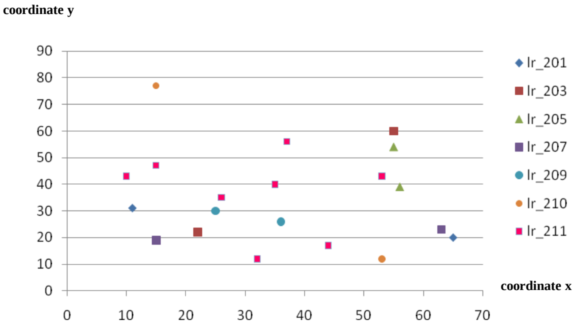


Figure A.14 Scatter diagram of customers' locations on a plane, which are not shared by the instances from the set lr_200

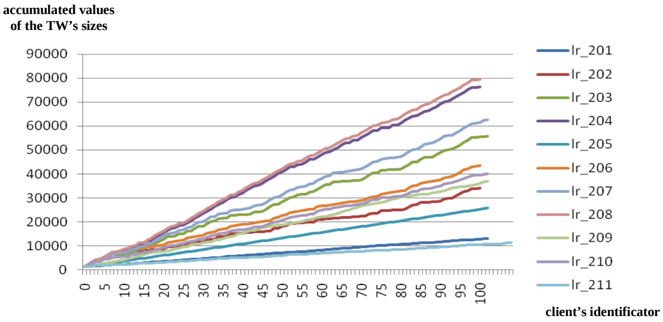


Figure A.15 Cumulative values of TW' sizes for each instance of the set lr_200

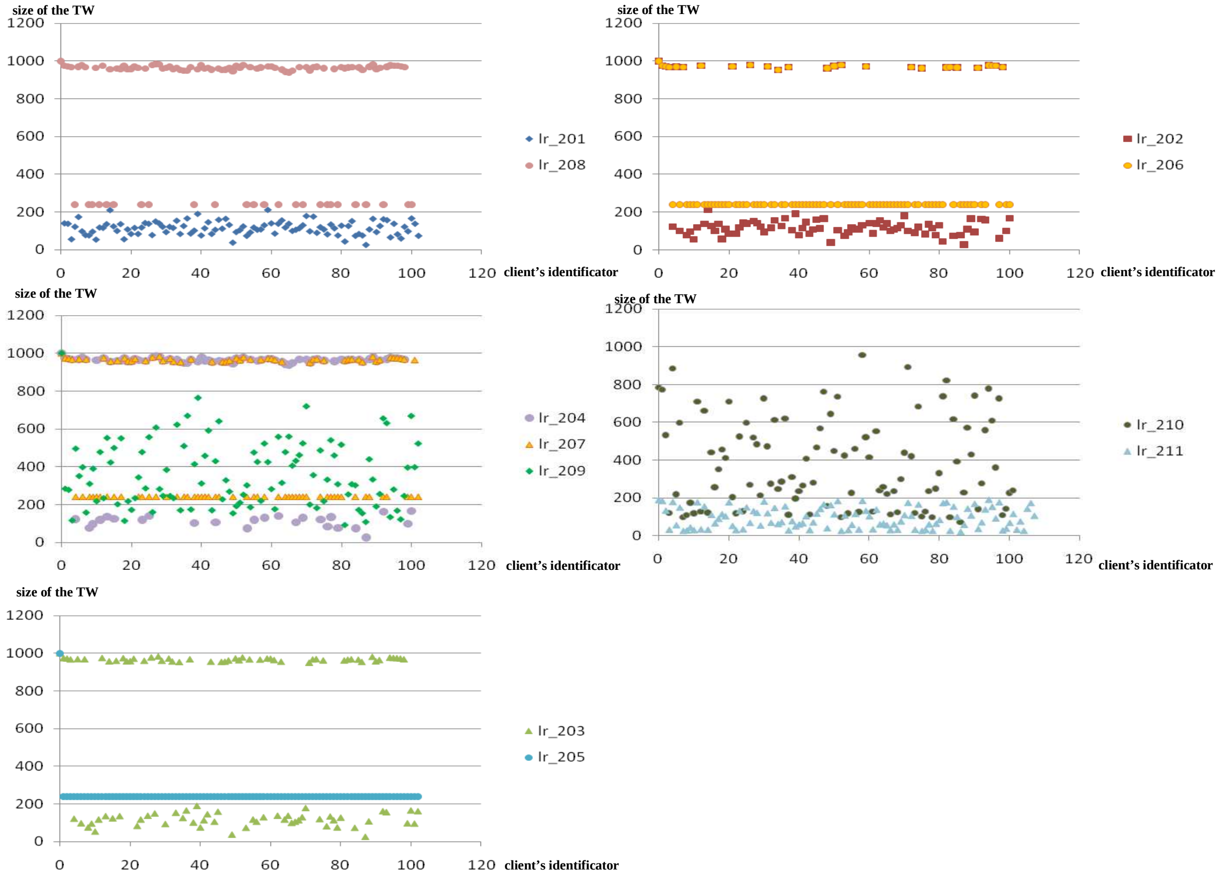


Figure A.16 TW's sizes for each customer of each instance of the set lr_200 (separated in four diagrams for improved visibility)

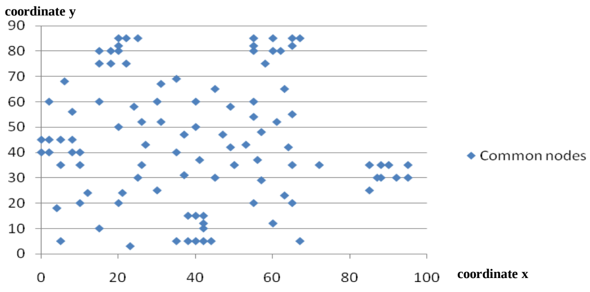


Figure A.17 Scatter diagram of the first 100 customers' locations on a plane (shared by the instances of the set lrc_100)

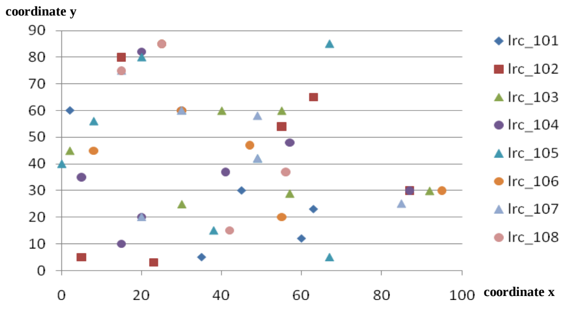


Figure A.18 Scatter diagram of customers' locations on a plane, which are not shared by the instances from the set lrc_100

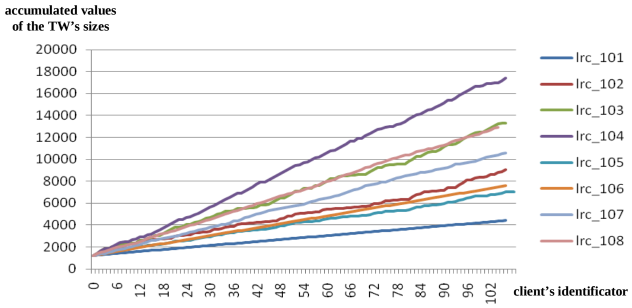


Figure A.19 Cumulative values of TW' sizes for each instance of the set lrc_100

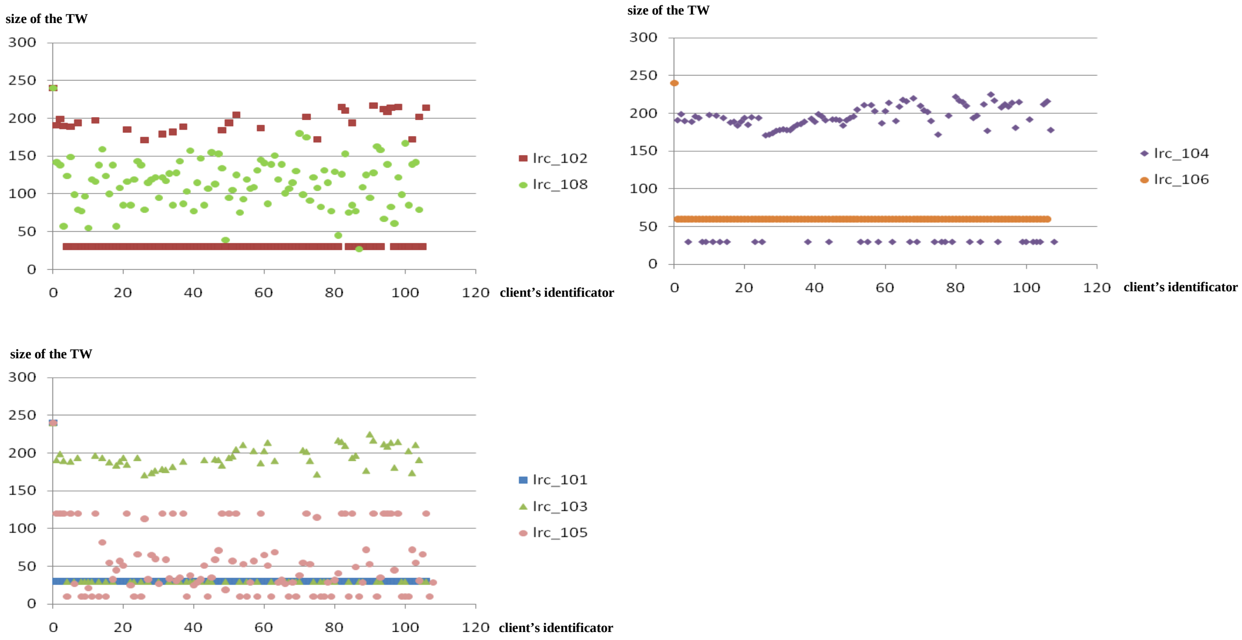
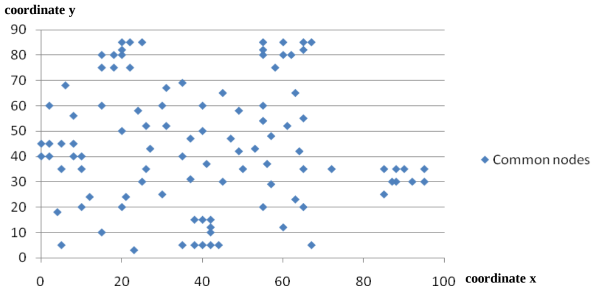


Figure A.20 TW's sizes for each customer of each instance of the set lrc_100 (separated in three diagrams for improved visibility)



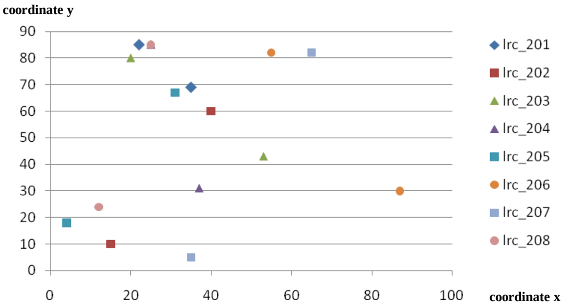


Figure A.21 Scatter diagram of the first 100 customers' locations on a plane (shared by the instances of the set lrc_200

Figure A.22 Scatter diagram of customers' locations on a plane, which are not shared by the instances from the set lrc_200

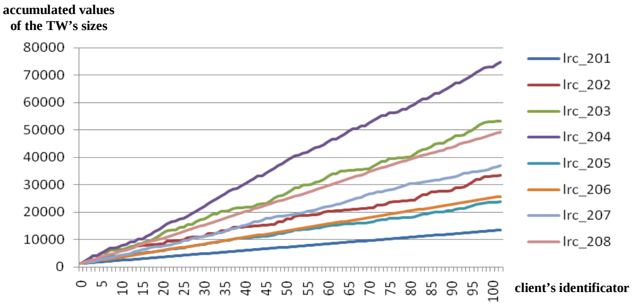
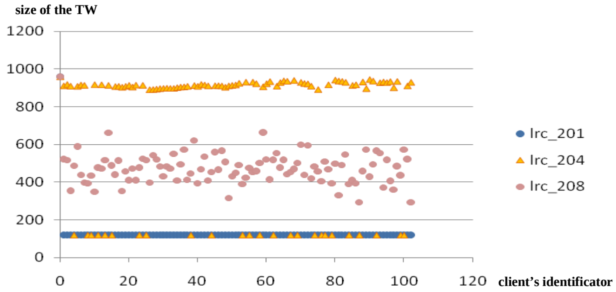
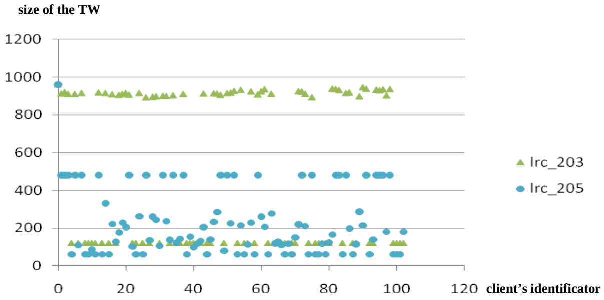


Figure A.23 Cumulative values of TW' sizes for each instance of the set lrc_200





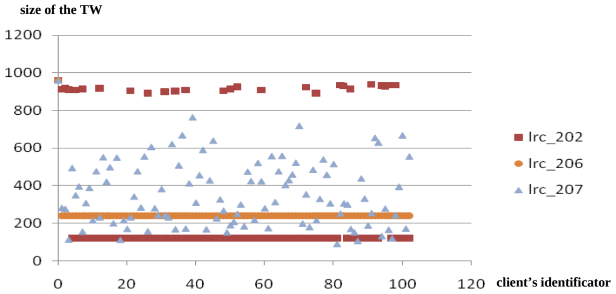


Figure A.24 TW's sizes for each customer of each instance of the set lrc_200 (separated in three diagrams for improved visibility)

Appendix A2

Benchmark Instances for Testing Decision Support System

The objective of this appendix is to explain how the testing instances used in the experiments evaluating the performance of the proposed DSS were generated. The description regards both the data characterising the customers and the information on the city roads network performance.

The customers' data were generated on the basis of the benchmark instances proposed by (http_3). In contrast to the testing scenarios presented in Appendix A1, here there are distinguished two types of customers. The *static customers* are those, about which all the information is known at the time of making the initial routing and scheduling plan. The *dynamic customers* are those who make a request for the service, when the initial tours are already being pursued. This description corresponds to the real-life situation, when at the beginning of the working day the dispatcher has no information on how many customers would turn up, when and what would be their characteristics: TWs size, demand, etc.

The testing scenarios differ between each other in terms of the proportions in the number of dynamic and static customers and the width of their TWs. They are outlined in Chapter 7.7.

In each created instance, there is defined one depot and its TW specifies the ten-hour long simulation and scheduling horizon. It starts at 7am and lasts till 5pm, which in terms of seconds corresponds to: 25200÷61200 sec. Other variables characterising the depot are the same for all testing scenarios and consistent with the original proposal.

The total number of the customers in each instance is equal to 100.

The original data regarding the customers' *Id* and the *Service Time* are not modified. The latter has a fixed value equal to 600 seconds. The customer's *Demand* was originally defined as invariable and equal to 10 units. These figures were maintained when defining the pickup customers. However, for their delivery partners, in order to highlight their different profile, the value of the demand was established as negative, thus equal to -10.

The customer's location variables: *Coordinate x* and *Coordinate y*, which were defined in the instances prepared for testing the methods solving the PDVRPTW, are substituted with the *Node*

Id. It specifies a node of a graph representing the underlying city network, to which the particular customer is assigned to. The original value of each Node Id also stays unchanged.

In order to designate the *Pair Id* and the *Pickup/Delivery Index* to each customer, there was used a collection of routes obtained using the algorithm solving a DVRPTW (Barcelo and Orozco, 2010b) The set consists of 5 routes each containing 20 customers, which facilities the task. The customers forming a couple are chosen randomly but within one route. The assignation of the Pickup/Delivery Index is also random, but respecting both the precedence and the pairing constraint.

On the same basis there was made the specification of the customers as either static or dynamic. For example: in the scenario containing 20% of static and 80% of dynamic customers, the first group consists of the 20 customers included in the first route, while the rest is determined as dynamic. The same rule was applied to create all the testing scenarios.

The dynamic customers report the service demand during the working day. They may respond the order call in the interval between 8am and 4pm (28800÷57600 sec.), which corresponds to the usual working hours of a real-life reception office. The collection of the requests arrivals was calculated using exponential random variables:

$$x = -m \cdot \ln \mu \qquad\qquad \mu \in U(0,1) \tag{A2.1}$$

where:

x : exponential random variable,
m : mean interval,
μ : uniform random number between 0 and 1.

The value of m is different depending on if the width of the TWs in the addressed scenario was specified as wide or narrow. In the first case there are considered the intervals of 60 seconds and 240 seconds in the latter. This differentiation and final figures were determined this way due to the pre-defined limits of permitted time horizon for accepting the request calls. Because of the fact, that the dynamic customers can order a service the earliest at 8am, the accumulated values of x for the consecutive customers are summarised 28800 seconds of the new request arrivals acceptance horizon lower-bound. The result constitutes the definition of the exact moment of each new dynamic customer's call arrival – denominated as: *New Call*.

The new requests' arrivals were specified for each individual customer. However, in the problem addressed in the present thesis project, there are considered customer pairs. Hence, in order to adjust the data, there was chosen the smaller value of the previously calculated arrival moments of the two customers forming the same couple. This number was established as valid for both of them.

When specifying the depot and the static customers, their New Call variable is set equal to zero.

In general sense, the sizes of the customers' TWs stay unchanged. It means that:

- in the scenario considering narrow TWs their possible widths are: 1800 and 3600 seconds,

- in the scenario considering wide TWs, their possible widths are: 14400, 16200, 18000, 19800 and 21600 seconds.

However, in some cases in order to meet the precedence constraint it was necessary to exchange the TW's interval values between the two dynamic customers of the same couple. Moreover, the moment of the dynamic customers' TWs' opening needed to be delayed in time with respect to the instant the request call is performed. Hence, in the case of the scenarios specifying the TWs as narrow the required delay was calculated as a random value between half an hour and two hours (1800÷7200 sec.). When defining the delay for the scenarios containing wide TWs, there was considered a smaller interval between zero and half an hour (0÷1800 sec.).

Summarizing, all the TWs intervals must fall within the allowed scheduling horizon. The delivery customer's TW cannot be opened before his pickup pair partner's window opens. Similarly, the latest moment, when the pickup customer can close his TW is when his delivery pair partner closes his. Consequently, the delivery customer always closes the TW at the same time or later than its corresponding pickup and the pickup opens at the same time or before the delivery.

The values of the static customers' TWs are the same as originally defined.

The final structure of the data defining the static and dynamic customers is explained on the following examples accordingly:

Number of static customers including depot
Number of vehicles
Vehicle's capacity

Id	Node Id	Demand	Time Window Lower-bound	Time Window Upper-bound	Service Time	Pickup/Delivery Index	Pair Id	New Call
0	n_1	$d_0=0$	e_0	l_0	$s_0=0$	0	0	0
1	n_2	(+) $d_1=10$	e_1	l_1	$s_1=600$	0	1	$a_1=0$
2	n_3	(-) $d_2=-10$	e_2	l_2	$s_2=600$	1	1	$a_2=0$
3	n_4	(+) $d_3=10$	e_3	l_3	$s_3=600$	0	2	$a_3=0$
4	n_5	(-) $d_4=-10$	e_4	l_4	$s_4=600$	1	2	$a_4=0$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Table A.7 Data format of the testing instances - static customers

Number of dynamic customers

Id	Node Id	Demand	Time Window Lower-bound	Time Window Upper-bound	Service Time	Pickup/Delivery Index	Pair Id	New Call
11	n_{11}	(+) $d_{11}=10$	e_{11}	l_{11}	$s_{11}=600$	0	1	a_{11}
12	n_{12}	(-) $d_{12}=-10$	e_{12}	l_{12}	$s_{12}=600$	1	1	a_{12}
13	n_{13}	(+) $d_{13}=10$	e_{13}	l_{13}	$s_{13}=600$	0	2	a_{13}
14	n_{14}	(-) $d_{14}=-10$	e_{14}	l_{14}	$s_{14}=600$	1	2	a_{14}
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Table A.8 Data format of the testing instances - dynamic customers

Thus:

- in the case of the table containing the information about the static customers, the first three rows characterize the specific scenario defining:
    - number of static customers plus depot,
    - total number of vehicles in the considered fleet,
    - vehicles' uniform capacity.

- in the case of the table containing the information about the dynamic customers the first row provides their number,
- the following rows in both cases include data regarding contained customers organized in columns:
  - customer's identification,
  - identification of a network node the specific customer is assigned to,
  - demand – number of units of cargo requested by a customer, which is positive for a customer requiring service of a pickup and negative for a delivery,
  - customer's time window lower-bound (seconds),
  - customer's time window upper-bound (seconds),
  - service time – the time a vehicle must spend at the customer's in order to provide the required supply (seconds),
  - pickup/delivery index – a binary value, which depicts if a current customer reports pickup (0) or delivery (1) request,
  - pair identification – a number defining a pair, to which the current customer belongs, in the above example there are two pairs,
  - new call - the time instant, when the dynamic customer reports the service demand (seconds).

In order to evaluate the performance of the proposed DSS there had to be emulated the functioning of a real-time ATIS. More exactly, there were required data which such system would provide in real life. On that account, as a valid substitute there was used traffic information provided by a microscopic simulator. The data were accumulated during one simulation replication lasting as long as the pre-established ten hours long scheduling horizon. The travel times values were collected on every section of the selected area of the underlying city network every five minutes. Originally recorded in milliseconds, they were rounded to seconds. This procedure was repeated for five simulation replications. One, randomly selected replication was chosen to represent the current state of the network, the information about which is revealed to the decision maker as the time passes. On the basis of other replications there was prepared a travel times' matrix containing the average values. These data represent the historical state known to the decision maker in the instant of designing the initial routing plan.

Both matrices, as well as the data regarding the customers are available at the (http_3, http_8).

Appendix B

Results

This appendix contains numerical results of all the experiments performed in the present thesis project.

The first part: Appendix B1, presents the outputs obtained from testing the performance of sixteen composed meta-heuristics proposed for solving the addressed PDVRPTW. The outlined results are very detailed. Hence, in order to facilitate their comparison there were also prepared summary tables.

Appendix B2 provides the numerical results describing the performance of the proposed Decision Support System. Similarly as in the previous case, this annex contains detailed output data, which got recapitulated in summary tables.

Appendix B1

Performance of Methods Proposed for Solving PDVRPTW

This appendix contains numerical results of the experiments conducted during the first application step of the present thesis project. The collection of reviewed meta-heuristics was defined in details in Chapter 6. They were proposed for solving the PDVRPTW addressed in the current undertaking, which was specified in Chapter 2.

The first part of this annex, presents all the obtained results compiled in form of tables. Each one of them has a header describing the name of the method, which provided the output. The whole listing of sixteen reviewed approaches includes:

- pair_rr,
- pair_2opt,
- area_rr,
- area_2opt,
- angle_r_nCust_rr,
- angle_r_nCust_2opt,
- angle_r_nVeh_rr,
- angle_r_nVeh_2opt,
- angle_r_1_rr,
- angle_r_1_2opt,
- angle_s_nCust_rr,
- angle_s_nCust_2opt,
- angle_s_nVeh_rr,
- angle_s_nVeh_2opt,
- angle_s_1_rr,
- angle_s_1_2opt.

The tested procedures involve three different routines for the initial arrangement of customers: by area, by pair and by angle. The last one considers additional sorting step dividing the customers in as many sub-lists as: considered customers, available vehicles and one. This process might begin from a fixed or randomly chosen starting point. In the utter case, the execution of the complete procedures was carried out 100 times. In order to represent their performance, there were prepared two separated collections of tables presenting the best and the average values obtained during the multiple executions.

The way in which the selected variables are organized was designed to facilitate the analysis of both the complete strategy and its individual steps. Hence, the data were saved after performing each of the corresponding stages:

- initial solution creating method:
    - number of obtained routes,
    - complete schedule cost,
    - aggregated waiting time,
    - CPU [sec].
- Parallel Tabu Search:
    - number of obtained routes,
    - complete schedule cost,
    - aggregated waiting time,
    - CPU [sec],
    - number of PTS iterations κ performed till the best solution was found.
- post-optimization method:
    - number of obtained routes,
    - complete schedule cost,
    - aggregated waiting time,
    - travel cost,
    - actual cpu [sec] - corresponds to the sum of the time till the best solution was found in the PTS and the duration of the post-optimization stage,
    - total cpu [sec] - corresponds to the duration time of the complete procedure.

The outputs are compared with the results obtained by Li nad Lim (2001). Hence, although the duration of the reviewed methods' executions was originally calculated in milliseconds, they were rounded to seconds, since Li nad Lim (2001) report their findings in this unit.

The values of interest are highlighted by distinctive colour:

- red – marks the result of better value than the one obtained by Li nad Lim (2001),
- green – marks the result of the same value as the one obtained by Li nad Lim (2001).

Moreover, each listing is summarised and contains information on aggregated and average values regarding: final schedule cost, waiting time, travel cost, best and total cpu [sec].

SUMMARY OF RESULTS

area_2opt

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	actual cpu[sec]	total cpu[sec]
1_lc_10	14	12593,87	0,00	0	10	9828,94	0,00	3	106	10	**9828,94**	0,00	828,937	**3**	**23**
2_lc_10	16	13040,75	0,00	0	11	10244,82	0,00	16	490	11	10242,02	0,00	1242,02	**16**	**17**
3_lc_10	17	12623,02	47,36	0	11	10055,23	0,00	17	476	11	**10016,68**	0,00	1016,68	**17**	**18**
4_lc_10	17	11317,09	0,00	0	10	9952,77	0,00	1	56	10	**9925,59**	0,00	925,594	**1**	**20**
5_lc_10	16	13366,61	0,00	0	10	9848,93	0,00	3	82	10	9848,93	0,00	848,929	**3**	**21**
6_lc_10	18	13999,28	0,00	0	10	9828,94	0,00	2	71	10	**9828,94**	0,00	828,938	**2**	**20**
7_lc_10	17	13523,15	0,00	0	10	9828,94	0,00	7	227	10	**9828,94**	0,00	828,937	**7**	**20**
8_lc_10	15	12818,83	0,00	0	10	9834,15	0,00	4	126	10	9828,04	0,00	828,039	**4**	**20**
9_lc_10	14	10828,29	0,00	0	10	9828,94	0,00	1	41	10	**9828,94**	0,00	828,937	**1**	**20**
1_lc_20	5	15773,64	12,14	0	3	9591,56	0,00	132	403	3	**9591,56**	0,00	591,557	132	178
2_lc_20	5	13566,47	8,33	0	3	9815,87	23,47	167	463	3	9777,18	5,28	771,896	167	183
3_lc_20	5	13344,71	30,60	0	4	10180,78	35,92	72	247	4	10062,28	35,92	1026,36	**72**	176
4_lc_20	4	13067,58	0,53	0	4	10037,35	0,00	139	401	4	9940,44	0,00	940,443	**139**	**187**
5_lc_20	5	12830,17	84,84	0	3	9626,34	0,00	20	66	3	**9588,88**	0,00	588,876	**20**	246
6_lc_20	4	12485,90	151,96	0	3	9783,08	2,32	61	193	3	9707,72	0,00	707,721	**61**	229
7_lc_20	4	12390,00	13,68	0	3	9589,95	0,00	93	286	3	**9588,32**	0,00	588,324	**93**	194
8_lc_20	5	12844,43	43,27	0	3	9607,80	0,00	68	203	3	**9595,99**	0,00	595,989	**68**	204
1_lr_10	24	4270,24	90,53	0	19	3559,97	6,77	0	41	19	**3559,97**	6,77	2553,20	**0**	**9**
2_lr_10	19	3592,03	15,53	0	19	3592,03	15,53	0	0	19	3592,03	15,53	2576,49	**0**	**13**
3_lr_10	18	3662,51	90,53	0	13	2672,36	12,47	1	61	13	**2672,36**	12,47	1659,89	**1**	**15**
4_lr_10	15	3216,17	0,00	0	11	2168,17	4,06	7	277	11	2168,17	4,06	1164,11	**7**	**16**
5_lr_10	19	3307,87	4,18	0	18	3200,14	4,18	0	1	18	3197,78	4,18	2193,59	**0**	**13**
6_lr_10	17	3209,83	7,22	0	14	2619,74	7,22	1	31	14	2611,45	7,22	1604,23	**1**	**16**
7_lr_10	16	3190,01	0,00	0	13	2417,24	2,24	2	120	13	2414,93	2,24	1412,69	**2**	**17**
8_lr_10	15	3212,18	0,00	0	12	2221,56	0,00	1	67	12	2204,50	0,00	1204,50	**1**	**19**
9_lr_10	16	3151,24	14,69	0	14	2584,90	14,69	1	31	14	2576,03	14,69	1561,35	**1**	**17**
10_lr_10	16	3217,18	0,00	0	13	2379,27	13,69	3	166	13	2371,50	13,69	1357,82	**3**	**14**
11_lr_10	14	2956,15	0,00	0	11	2258,35	0,88	10	316	11	2250,70	0,88	1249,82	**10**	**18**
12_lr_10	15	3028,16	0,00	0	11	2124,59	0,00	16	458	11	2114,29	0,00	1114,29	**16**	**17**
1_lr_20	6	4811,66	0,00	0	4	3110,31	125,00	93	369	4	**3105,46**	125,00	1980,46	**93**	**134**
2_lr_20	5	4274,08	5,36	0	4	2949,17	2,94	77	289	4	2939,60	2,94	1936,66	**77**	**174**
3_lr_20	5	4170,46	0,00	0	3	2419,07	1,71	170	352	3	**2403,06**	1,71	1401,35	**170**	**261**
4_lr_20	4	3784,26	0,00	0	3	2250,79	0,00	194	407	3	2243,99	0,57	1243,42	**194**	**244**
5_lr_20	5	3802,82	0,00	0	3	2485,83	0,86	148	358	3	**2480,29**	0,86	1479,43	**148**	**221**
6_lr_20	6	4272,78	0,00	0	3	2424,57	5,22	194	472	3	**2423,41**	5,22	1418,19	**194**	**207**
7_lr_20	4	3591,27	0,00	0	3	2110,79	0,00	311	485	3	2061,83	6,01	1055,82	**311**	**326**
8_lr_20	4	3315,28	0,00	0	3	2033,56	0,00	198	368	3	2030,12	0,00	1030,12	**198**	**280**
9_lr_20	5	3691,78	0,00	0	3	2368,63	2,47	220	496	3	**2368,02**	2,47	1365,55	**220**	**223**
10_lr_20	5	3753,85	0,08	0	3	2450,28	6,11	145	324	3	**2450,28**	6,11	1444,17	**145**	**249**
11_lr_20	4	3.104,66	0,00	0	3	2.067,74	0,00	232	490	3	2.055,47	0,00	1.055,47	**232**	**238**
1_lrc_10	18	3612,94	6,29	0	16	3256,61	6,29	0	5	16	3245,99	6,29	2239,71	**0**	**13**
2_lrc_10	16	3481,43	0,00	0	13	2773,33	0,00	1	35	13	2771,63	0,00	1771,63	**1**	**19**
3_lrc_10	16	3342,29	0,00	0	11	2428,07	0,00	5	213	11	**2422,22**	0,00	1422,22	**5**	**15**
4_lrc_10	15	3348,96	0,00	0	13	2579,46	0,00	1	31	13	2578,47	0,00	1578,47	**1**	**21**
5_lrc_10	17	3470,64	0,00	0	17	3470,64	0,00	0	0	17	3467,77	0,00	2467,77	**0**	**15**
6_lrc_10	16	3355,62	0,00	0	13	2653,79	0,00	2	86	13	2651,84	0,00	1651,84	**2**	**17**
7_lrc_10	17	3557,00	0,00	0	14	2604,63	0,00	1	72	14	2602,85	0,00	1602,85	**1**	**17**
8_lrc_10	16	3373,55	0,00	0	10	2272,14	0,00	3	121	10	**2226,82**	0,00	1226,82	**3**	**21**
1_lrc_20	6	4702,49	3,92	0	5	3613,21	79,38	76	419	5	3611,74	79,38	2532,36	**76**	**98**
2_lrc_20	6	4673,44	0,35	0	4	3040,75	12,44	21	95	4	2993,31	12,44	1980,87	**21**	**161**
3_lrc_20	5	4368,04	1,61	0	4	2615,22	0,14	120	357	4	**2594,98**	4,61	1590,37	**120**	**178**
4_lrc_20	5	3698,70	0,00	0	3	2366,63	0,00	149	369	3	**2358,25**	0,00	1358,25	**149**	**221**
5_lrc_20	6	4783,24	28,38	0	4	3270,04	33,56	18	114	4	**3259,95**	33,56	2226,39	**18**	**122**
6_lrc_20	5	3804,83	17,96	0	4	2803,66	21,41	139	466	4	2784,99	21,41	1763,58	**139**	**152**
7_lrc_20	5	3764,76	0,00	0	3	2418,07	0,00	157	399	3	**2372,90**	7,77	1365,14	**157**	**207**
8_lrc_20	5	3314,54	0,00	0	3	2165,81	2,74	196	451	3	**2151,28**	2,74	1148,54	**196**	**224**
										sum	**269419,62**	**442,02**	**76977,60**	**3719,00**	**6018,00**
										avg	**4811,06**	**7,89**	**1374,60**	**66,41**	**107,46**

area_rr

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	actual cpu[sec]	total cpu[sec]
1_lc_10	14	12593,87	0,00	0	10	9828,94	0,00	3	106	10	**9828,94**	0,00	828,937	**3**	**23**
2_lc_10	16	13040,75	0,00	0	11	10244,82	0,00	17	490	11	10242,02	0,00	1242,02	**17**	**17**
3_lc_10	17	12623,02	47,36	0	11	10055,23	0,00	17	476	11	**10045,75**	0,00	1045,75	**17**	**18**
4_lc_10	17	11317,09	0,00	0	10	9952,77	0,00	2	56	10	**9946,90**	0,00	946,898	**2**	**20**
5_lc_10	16	13366,61	0,00	0	10	9848,93	0,00	3	82	10	**9828,94**	0,00	828,937	**3**	**21**
6_lc_10	18	13999,28	0,00	0	10	9828,94	0,00	2	71	10	**9828,94**	0,00	828,938	**2**	**20**
7_lc_10	17	13523,15	0,00	0	10	9828,94	0,00	7	227	10	**9828,94**	0,00	828,937	**7**	**20**
8_lc_10	15	12818,83	0,00	0	10	9834,15	0,00	4	126	10	**9826,44**	0,00	826,439	**4**	**20**
9_lc_10	14	10828,29	0,00	0	10	9828,94	0,00	1	41	10	**9828,94**	0,00	828,937	**1**	**20**
1_lc_20	5	15773,64	12,14	0	3	9591,56	0,00	131	403	3	**9591,56**	0,00	591,557	132	177
2_lc_20	5	13566,47	8,33	0	3	9815,87	23,47	166	463	3	9814,43	5,15	809,284	166	182
3_lc_20	5	13344,71	30,60	0	4	10180,78	35,92	72	247	4	10062,28	35,92	1026,36	**72**	175
4_lc_20	4	13067,58	0,53	0	4	10037,35	0,00	140	401	4	9802,07	0,00	802,067	**140**	**188**
5_lc_20	5	12830,17	84,84	0	3	9626,34	0,00	20	66	3	**9588,88**	0,00	588,876	**20**	246
6_lc_20	4	12485,90	151,96	0	3	9783,08	2,32	61	193	3	9707,72	0,00	707,721	**61**	229
7_lc_20	4	12390,00	13,68	0	3	9589,95	0,00	92	286	3	**9588,32**	0,00	588,324	**92**	193
8_lc_20	5	12844,43	43,27	0	3	9607,80	0,00	69	203	3	**9601,45**	0,00	601,45	**69**	205
1_lr_10	24	4270,24	90,53	0	19	3559,97	6,77	0	41	19	**3559,97**	6,77	2553,20	**0**	**9**
2_lr_10	19	3592,03	15,53	0	19	3592,03	15,53	0	0	19	3592,03	15,53	2576,49	**0**	**13**
3_lr_10	18	3662,51	90,53	0	13	2672,36	12,47	1	61	13	**2672,36**	12,47	1659,89	**1**	**15**
4_lr_10	15	3216,17	0,00	0	11	2168,17	4,06	7	277	11	2168,17	4,06	1164,11	**7**	**16**
5_lr_10	19	3307,87	4,18	0	18	3200,14	4,18	0	1	18	3197,78	4,18	2193,59	**0**	**14**
6_lr_10	17	3209,83	7,22	0	14	2619,74	7,22	1	31	14	2611,45	7,22	1604,23	**1**	**16**
7_lr_10	16	3190,01	0,00	0	13	2417,24	2,24	2	120	13	2414,93	2,24	1412,69	**2**	**17**
8_lr_10	15	3212,18	0,00	0	12	2221,56	0,00	1	67	12	2204,50	0,00	1204,50	**1**	**19**
9_lr_10	16	3151,24	14,69	0	14	2584,90	14,69	1	31	14	2558,76	14,69	1544,07	**1**	**17**
10_lr_10	16	3217,18	0,00	0	13	2379,27	13,69	3	166	13	2371,50	13,69	1357,82	**3**	**14**
11_lr_10	14	2956,15	0,00	0	11	2258,35	0,88	10	316	11	2250,32	0,88	1249,44	**10**	**18**
12_lr_10	15	3028,16	0,00	0	11	2124,59	0,00	16	458	11	2111,45	0,00	1111,45	**16**	**17**
1_lr_20	6	4811,66	0,00	0	4	3110,31	125,00	93	369	4	**3110,11**	125,00	1985,11	**93**	**134**
2_lr_20	5	4274,08	5,36	0	4	2949,17	2,94	77	289	4	2939,60	2,94	1936,66	**77**	**174**
3_lr_20	5	4170,46	0,00	0	3	2419,07	1,71	171	352	3	**2402,78**	1,71	1401,07	**171**	**262**
4_lr_20	4	3784,26	0,00	0	3	2250,79	0,00	192	407	3	2247,25	0,57	1246,68	**192**	**242**
5_lr_20	5	3802,82	0,00	0	3	2485,83	0,86	148	358	3	**2480,29**	0,86	1479,43	**148**	**220**
6_lr_20	6	4272,78	0,00	0	3	2424,57	5,22	193	472	3	**2419,42**	0,00	1419,42	**193**	**206**
7_lr_20	4	3591,27	0,00	0	3	2110,79	0,00	310	485	3	2011,78	0,00	1011,78	**310**	**324**
8_lr_20	4	3315,28	0,00	0	3	2033,56	0,00	197	368	3	2028,68	0,00	1028,68	**197**	**279**
9_lr_20	5	3691,78	0,00	0	3	2368,63	2,47	220	496	3	**2368,02**	2,47	1365,55	**220**	**222**
10_lr_20	5	3753,85	0,08	0	3	2450,28	6,11	144	324	3	**2438,96**	6,11	1432,85	**144**	**247**
11_lr_20	4	3.104,66	0,00	0	3	2.067,74	0,00	231	490	3	2.055,47	0,00	1.055,47	**231**	**238**
1_lrc_10	18	3612,94	6,29	0	16	3256,61	6,29	0	5	16	3249,95	6,29	2243,66	**0**	**13**
2_lrc_10	16	3481,43	0,00	0	13	2773,33	0,00	1	35	13	2770,91	0,00	1770,91	**1**	**19**
3_lrc_10	16	3342,29	0,00	0	11	2428,07	0,00	5	213	11	**2421,57**	0,00	1421,57	**5**	**15**
4_lrc_10	15	3348,96	0,00	0	13	2579,46	0,00	1	31	13	2575,36	0,00	1575,36	**1**	**21**
5_lrc_10	17	3470,64	0,00	0	17	3470,64	0,00	0	0	17	3465,32	0,00	2465,32	**0**	**15**
6_lrc_10	16	3355,62	0,00	0	13	2653,79	0,00	2	86	13	2651,84	0,00	1651,84	**2**	**17**
7_lrc_10	17	3557,00	0,00	0	14	2604,63	0,00	1	72	14	2596,62	0,00	1596,62	**1**	**17**
8_lrc_10	16	3373,55	0,00	0	10	2272,14	0,00	3	121	10	**2238,27**	0,00	1238,27	**3**	**21**
1_lrc_20	6	4702,49	3,92	0	5	3613,21	79,38	76	419	5	3609,55	79,38	2530,17	**76**	**98**
2_lrc_20	6	4673,44	0,35	0	4	3040,75	12,44	21	95	4	2993,31	12,44	1980,87	**21**	**160**
3_lrc_20	5	4368,04	1,61	0	4	2615,22	0,14	120	357	4	**2587,87**	0,14	1587,73	**120**	**179**
4_lrc_20	5	3698,70	0,00	0	3	2366,63	0,00	150	369	3	**2350,42**	0,00	1350,42	**150**	**222**
5_lrc_20	6	4783,24	28,38	0	4	3270,04	33,56	18	114	4	**3259,95**	33,56	2226,39	**18**	**123**
6_lrc_20	5	3804,83	17,96	0	4	2803,66	21,41	139	466	4	2784,56	21,41	1763,15	**139**	**152**
7_lrc_20	5	3764,76	0,00	0	3	2418,07	0,00	156	399	3	**2365,90**	7,77	1358,14	**156**	**207**
8_lrc_20	5	3314,54	0,00	0	3	2165,81	2,74	198	451	3	**2140,17**	2,74	1137,43	**198**	**225**
										sum	**269239,67**	**426,19**	**76813,46**	**3717,00**	**6011,00**
										avg	**4807,85**	**7,61**	**1371,67**	**66,38**	**107,34**

pair_2opt

		tabu serch								final solution					
instance	service time	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	actual cpu[sec]	total cpu[sec]
1_lc_10	9000	35333,95	792,30	0	10	9828,94	0,00	2	103	10	**9828,94**	0,00	828,937	**2**	**24**
2_lc_10	9000	31668,84	19,40	0	11	10147,04	0,00	9	314	11	10147,04	0,00	1147,04	**9**	**17**
3_lc_10	9000	27696,83	491,40	0	10	10059,58	0,00	15	414	10	**10048,50**	0,00	1048,5	**15**	**19**
4_lc_10	9000	19829,90	178,17	0	10	9980,30	0,00	8	263	10	**9961,90**	0,00	961,901	**8**	**20**
5_lc_10	9000	34640,63	866,32	0	10	9828,94	0,00	1	50	10	**9828,94**	0,00	828,937	**1**	**20**
6_lc_10	9000	34935,92	775,90	0	12	10701,42	35,79	3	130	12	10700,61	35,79	1664,82	**3**	**21**
7_lc_10	9000	33581,41	831,32	0	10	9830,17	0,00	1	47	10	**9828,94**	0,00	828,937	**1**	**20**
8_lc_10	9000	32795,59	720,62	0	10	9828,04	0,00	5	204	10	**9826,44**	0,00	826,438	**5**	**19**
9_lc_10	9000	27567,60	741,32	0	10	9830,94	0,00	6	195	10	**9828,94**	0,00	828,937	**6**	**19**
1_lc_20	9000	102505,62	2335,36	0	17	22812,42	654,06	1	34	17	22812,42	654,06	13158,4	**1**	241
2_lc_20	9000	91317,33	1593,86	0	4	10027,54	9,49	100	322	4	10005,95	9,49	996,456	100	178
3_lc_20	9000	73231,71	415,77	0	4	9962,16	0,00	156	453	4	9881,75	0,00	881,754	156	176
4_lc_20	9000	47718,36	1098,00	0	4	9961,69	0,00	121	414	4	9917,73	0,00	917,73	**121**	**154**
5_lc_20	9000	94266,58	293,83	0	3	9588,88	0,00	62	232	3	**9588,88**	0,00	588,876	**62**	**190**
6_lc_20	9000	95753,52	1666,58	0	4	9758,27	0,00	17	88	4	9630,21	0,00	630,213	**17**	230
7_lc_20	9000	85804,12	348,83	0	4	11097,16	42,38	6	62	4	11081,87	42,38	2039,48	**6**	124
8_lc_20	9000	85839,43	596,49	0	4	10457,44	42,02	55	247	4	10438,95	42,02	1396,93	**55**	**135**
1_lr_10	1000	8381,80	86,50	0	23	4131,85	54,76	0	37	23	4131,85	54,76	3077,08	**0**	**8**
2_lr_10	1000	7647,44	0,00	0	20	3335,82	37,11	0	38	20	3335,82	37,11	2298,71	**0**	**14**
3_lr_10	1000	7019,41	45,50	0	18	3202,36	30,06	0	40	18	3202,36	30,06	2172,30	**0**	**12**
4_lr_10	1000	5691,53	55,74	0	10	2099,75	7,20	16	456	10	2093,70	7,20	1086,50	**16**	**18**
5_lr_10	1000	7687,61	103,87	0	17	3003,74	22,00	1	82	17	3001,98	22,00	1979,98	**1**	**12**
6_lr_10	1000	7250,26	35,50	0	14	2565,77	4,62	1	79	14	2563,26	4,62	1558,63	**1**	**16**
7_lr_10	1000	6716,31	22,00	0	12	2362,81	0,00	4	213	12	2360,80	0,00	1360,80	**4**	**16**
8_lr_10	1000	5486,53	27,14	0	11	2107,47	0,00	3	170	11	2105,01	0,00	1105,01	**3**	**18**
9_lr_10	1000	6988,82	38,07	0	12	2385,37	14,69	6	261	12	2378,77	14,69	1364,08	**6**	**14**
10_lr_10	1000	6302,48	83,46	0	12	2298,51	0,00	3	146	12	2298,51	0,00	1298,51	**3**	**14**
11_lr_10	1000	6683,68	16,90	0	10	2190,56	9,88	11	325	10	**2186,63**	9,88	1176,76	**11**	**20**
12_lr_10	1000	5502,13	0,00	0	11	2130,61	0,00	18	493	11	2127,94	0,00	1127,94	**18**	**18**
1_lr_20	1000	26796,13	648,88	0	4	3110,58	59,07	108	479	4	**3104,09**	59,07	2045,03	**108**	**115**
2_lr_20	1000	24929,34	551,50	0	4	2946,78	4,77	74	311	4	2946,78	4,77	1942,01	**74**	**136**
3_lr_20	1000	20256,08	364,93	0	3	2406,57	1,54	223	469	3	**2403,77**	1,54	1402,22	**223**	**243**
4_lr_20	1000	13629,57	201,11	0	3	2253,09	0,84	191	431	3	2253,09	0,84	1252,25	**191**	**229**
5_lr_20	1000	23474,88	566,08	0	3	2496,12	1,77	166	407	3	**2490,58**	1,77	1488,81	**166**	**214**
6_lr_20	1000	22360,12	560,42	0	3	2396,60	2,87	39	140	3	**2385,79**	2,87	1382,92	**39**	**204**
7_lr_20	1000	17494,60	326,04	0	3	2214,27	0,00	230	495	3	2208,56	0,00	1208,56	**230**	**233**
8_lr_20	1000	11707,01	395,49	0	3	2017,98	0,00	223	497	3	2004,46	0,00	1004,46	**223**	**225**
9_lr_20	1000	21525,22	620,77	0	4	2623,02	2,44	104	392	4	2611,94	2,44	1609,51	**104**	**146**
10_lr_20	1000	22951,93	634,71	0	3	2426,78	0,00	108	317	3	**2422,19**	3,72	1418,47	**108**	**218**
11_lr_20	1000	16.734,23	380,21	0	6	3.315,03	6,52	1	49	6	3.315,03	6,52	2.308,50	**1**	**55**
1_lrc_10	1000	8439,52	106,92	0	15	3107,77	0,00	2	129	15	3103,81	0,00	2103,81	**2**	**12**
2_lrc_10	1000	8008,14	0,00	0	13	2761,35	15,00	4	220	13	**2760,90**	15,00	1745,90	**4**	**15**
3_lrc_10	1000	7100,61	0,00	0	13	2602,68	7,81	2	94	13	2602,68	7,81	1594,86	**2**	**19**
4_lrc_10	1000	6539,00	0,00	0	10	2237,21	0,15	5	189	10	**2236,67**	0,15	1236,52	**5**	**23**
5_lrc_10	1000	8239,12	132,95	0	17	3297,41	9,82	1	79	17	3297,41	9,82	2287,59	**1**	**13**
6_lrc_10	1000	7664,31	91,92	0	14	2728,56	4,19	2	94	14	2726,65	4,19	1722,46	**2**	**16**
7_lrc_10	1000	6920,66	86,92	0	14	2638,65	0,00	1	54	14	2616,30	0,00	1616,30	**1**	**18**
8_lrc_10	1000	6253,26	10,92	0	10	2235,59	0,00	4	200	10	**2223,39**	0,00	1223,39	**4**	**19**
1_lrc_20	1000	26309,96	582,92	0	5	3503,24	79,38	35	231	5	3492,28	79,38	2412,90	**35**	**101**
2_lrc_20	1000	24393,34	224,56	0	4	3160,26	9,24	29	192	4	3149,70	2,35	2147,35	**29**	**125**
3_lrc_20	1000	18430,53	566,92	0	4	2749,38	1,98	57	256	4	2736,44	1,98	1734,46	**57**	**141**
4_lrc_20	1000	14292,10	293,62	0	3	2262,44	6,59	179	433	3	**2260,70**	6,59	1254,11	**179**	**217**
5_lrc_20	1000	24876,00	370,77	0	5	3447,50	34,14	95	473	5	**3447,38**	34,14	2413,24	**95**	**102**
6_lrc_20	1000	22861,43	537,71	0	4	2668,65	16,84	147	461	4	2662,16	16,84	1645,32	**147**	**167**
7_lrc_20	1000	21000,16	445,37	0	4	2710,30	4,55	19	124	4	2690,63	4,55	1686,08	**19**	**144**
8_lrc_20	1000	18216,25	349,92	0	7	3569,67	39,52	3	88	7	3569,67	39,52	2530,16	**3**	**43**
										sum	**288867,69**	**1269,92**	**95597,74**	**2683,00**	**4980,00**
										avg	**5158,35**	**22,68**	**1707,10**	**47,91**	**88,93**

pair_rr

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	actual cpu[sec]	total cpu[sec]
1_lc_10	53	35333,95	792,30	0	10	9828,94	0,00	2	103	10	**9828,94**	0,00	828,937	**2**	**24**
2_lc_10	53	31668,84	19,40	0	11	10147,04	0,00	9	314	11	10147,04	0,00	1147,04	**9**	**17**
3_lc_10	52	27696,83	491,40	0	10	10059,58	0,00	15	414	10	**10048,50**	0,00	1048,5	**15**	**19**
4_lc_10	53	19829,90	178,17	0	10	9980,30	0,00	8	263	10	**9961,90**	0,00	961,901	**8**	**20**
5_lc_10	53	34640,63	866,32	0	10	9828,94	0,00	1	50	10	**9828,94**	0,00	828,937	**1**	**20**
6_lc_10	53	34935,92	775,90	0	12	10701,42	35,79	3	130	12	10700,61	35,79	1664,82	**3**	**21**
7_lc_10	53	33581,41	831,32	0	10	9830,17	0,00	1	47	10	**9828,94**	0,00	828,937	**1**	**20**
8_lc_10	53	32795,59	720,62	0	10	9828,04	0,00	5	204	10	**9826,44**	0,00	826,438	**5**	**19**
9_lc_10	53	27567,60	741,32	0	10	9830,94	0,00	6	195	10	**9828,94**	0,00	828,937	**6**	**19**
1_lc_20	51	102505,62	2335,36	0	17	22812,42	654,06	1	34	17	22812,42	654,06	13158,4	**1**	237
2_lc_20	51	91317,33	1593,86	0	4	10027,54	9,49	97	322	4	9935,85	9,49	926,354	97	173
3_lc_20	51	73231,71	415,77	0	4	9962,16	0,00	153	453	4	9954,72	0,00	954,724	153	173
4_lc_20	51	47718,36	1098,00	0	4	9961,69	0,00	120	414	4	9917,72	0,00	917,718	**120**	**154**
5_lc_20	51	94266,58	293,83	0	3	9588,88	0,00	62	232	3	**9588,88**	0,00	588,876	**62**	**188**
6_lc_20	51	95753,52	1666,58	0	4	9758,27	0,00	17	88	4	9626,27	0,00	626,27	**17**	228
7_lc_20	51	85804,12	348,83	0	4	11097,16	42,38	6	62	4	11081,87	42,38	2039,48	**6**	123
8_lc_20	51	85839,43	596,49	0	4	10457,44	42,02	54	247	4	10438,95	42,02	1396,93	**54**	**134**
1_lr_10	53	8381,80	86,50	0	23	4131,85	54,76	0	37	23	4131,85	54,76	3077,08	**0**	**8**
2_lr_10	55	7647,44	0,00	0	20	3335,82	37,11	0	38	20	3335,82	37,11	2298,71	**0**	**14**
3_lr_10	52	7019,41	45,50	0	18	3202,36	30,06	0	40	18	3202,36	30,06	2172,30	**0**	**11**
4_lr_10	52	5691,53	55,74	0	10	2099,75	7,20	16	456	10	2099,75	7,20	1092,55	**16**	**18**
5_lr_10	53	7687,61	103,87	0	17	3003,74	22,00	1	82	17	3001,98	22,00	1979,98	**1**	**12**
6_lr_10	52	7250,26	35,50	0	14	2565,77	4,62	1	79	14	2563,26	4,62	1558,63	**1**	**15**
7_lr_10	52	6716,31	22,00	0	12	2362,81	0,00	4	213	12	2352,47	0,00	1352,47	**4**	**15**
8_lr_10	50	5486,53	27,14	0	11	2107,47	0,00	3	170	11	2104,64	0,00	1104,64	**3**	**18**
9_lr_10	53	6988,82	38,07	0	13	2466,56	22,36	5	253	13	2442,95	22,36	1420,59	**5**	**13**
10_lr_10	52	6302,48	83,46	0	14	2444,88	0,90	1	75	14	2440,98	0,90	1440,08	**1**	**14**
11_lr_10	54	6683,68	16,90	0	11	2237,02	13,72	17	489	11	2233,65	13,72	1219,93	**17**	**17**
12_lr_10	53	5502,13	0,00	0	15	2406,63	0,00	1	42	15	2397,57	0,00	1397,57	**1**	**24**
1_lr_20	51	26796,13	648,88	0	4	3110,58	59,07	107	479	4	**3079,36**	59,07	2020,29	**107**	**115**
2_lr_20	50	24929,34	551,50	0	4	2946,78	4,77	74	311	4	2946,78	4,77	1942,01	**74**	**135**
3_lr_20	51	20256,08	364,93	0	3	2406,57	1,54	224	469	3	**2398,36**	1,54	1396,81	**224**	**244**
4_lr_20	50	13629,57	201,11	0	3	2253,09	0,84	191	431	3	2244,82	0,84	1243,98	**191**	**230**
5_lr_20	51	23474,88	566,08	0	3	2496,12	1,77	165	407	3	**2490,58**	1,77	1488,81	**165**	**214**
6_lr_20	50	22360,12	560,42	0	3	2396,60	2,87	38	140	3	**2390,53**	2,87	1387,65	**38**	**203**
7_lr_20	51	17494,60	326,04	0	3	2214,27	0,00	230	495	3	2204,02	0,84	1203,18	**230**	**233**
8_lr_20	50	11707,01	395,49	0	3	2017,98	0,00	223	497	3	2004,39	0,00	1004,39	**223**	**225**
9_lr_20	51	21525,22	620,77	0	4	2623,02	2,44	105	392	4	2617,86	2,44	1615,42	**105**	**148**
10_lr_20	51	22951,93	634,71	0	3	2426,78	0,00	109	317	3	**2419,82**	2,78	1417,04	**109**	**221**
11_lr_20	50	16.734,23	380,21	0	6	3.315,03	7	1	50	6	3.315,03	6,52	2.308,50	**1**	**52**
1_lrc_10	53	8439,52	106,92	0	20	3663,21	0,00	0	36	20	3658,80	0,00	2658,80	**0**	**12**
2_lrc_10	53	8008,14	0,00	0	13	2761,35	15,00	4	220	13	**2760,90**	15,00	1745,90	**4**	**15**
3_lrc_10	53	7100,61	0,00	0	13	2602,68	7,81	2	94	13	2602,68	7,81	1594,86	**2**	**19**
4_lrc_10	54	6539,00	0,00	0	10	2237,21	0,15	6	189	10	**2233,38**	0,15	1233,23	**6**	**23**
5_lrc_10	54	8239,12	132,95	0	17	3297,41	9,82	1	79	17	3297,31	9,82	2287,49	**1**	**14**
6_lrc_10	53	7664,31	91,92	0	14	2728,96	4,19	1	61	14	2718,71	4,19	1714,52	**1**	**20**
7_lrc_10	53	6920,66	86,92	0	14	2638,65	0,00	1	54	14	2611,07	0,00	1611,07	**1**	**18**
8_lrc_10	52	6253,26	10,92	0	10	2235,59	0,00	4	200	10	**2222,21**	0,00	1222,21	**4**	**20**
1_lrc_20	51	26309,96	582,92	0	5	3503,24	79,38	36	231	5	3491,75	79,38	2412,36	**36**	**103**
2_lrc_20	51	24393,34	224,56	0	4	3160,26	9,24	29	192	4	3146,85	2,35	2144,50	**29**	**125**
3_lrc_20	51	18430,53	566,92	0	4	2749,38	1,98	60	256	4	2722,74	1,98	1720,77	**60**	**144**
4_lrc_20	51	14292,10	293,62	0	3	2262,44	6,59	179	433	3	**2253,71**	7,84	1245,87	**179**	**217**
5_lrc_20	51	24876,00	370,77	0	5	3447,50	34,14	95	473	5	**3444,89**	34,14	2410,75	**95**	**101**
6_lrc_20	51	22861,43	537,71	0	4	2668,65	16,84	148	459	4	2662,16	16,84	1645,32	**148**	**169**
7_lrc_20	51	21000,16	445,37	0	4	2710,30	4,55	20	124	4	2680,38	4,55	1675,83	**20**	**145**
8_lrc_20	51	18216,25	349,92	0	7	3569,67	39,52	3	88	7	3569,05	39,52	2529,54	**3**	**44**
										sum	**289852,35**	**1283,48**	**96568,79**	**2665,00**	**4977,00**
										avg	**5175,93**	**22,92**	**1724,44**	**47,59**	**88,88**

angle_s_nCust_2opt

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	actual cpu[sec]	total cpu[sec]
1_lc_10	43	29243,75	343,85	0	10	9828,94	0,00	2	80	10	**9828,94**	0,00	828,937	**2**	**25**
2_lc_10	42	26539,27	242,46	0	10	9831,73	0,00	4	159	10	**9828,94**	0,00	828,937	**4**	**19**
3_lc_10	41	23792,09	435,32	0	11	10195,51	0,00	12	431	11	10169,99	0,00	1169,99	**13**	**15**
4_lc_10	44	18249,83	0,00	0	10	9997,39	0,00	20	493	10	**9976,45**	0,00	976,449	**20**	**20**
5_lc_10	43	28885,61	312,99	0	10	9828,94	0,00	9	272	10	**9828,94**	0,00	828,937	**9**	**20**
6_lc_10	41	29234,04	339,28	0	10	9828,94	0,00	1	66	10	**9828,94**	0,00	828,937	**1**	**20**
7_lc_10	44	28887,17	279,47	0	10	9838,59	0,00	3	99	10	9838,59	0,00	838,59	**3**	**20**
8_lc_10	41	26444,51	282,38	0	10	9830,57	0,00	8	245	10	9830,57	0,00	830,57	**8**	**20**
9_lc_10	44	23920,07	185,85	0	10	9830,94	0,00	5	170	10	**9828,94**	0,00	828,94	**5**	**20**
1_lc_20	41	83006,41	747,46	0	3	9591,56	0,00	19	134	3	**9591,56**	0,00	591,56	**19**	210
2_lc_20	36	65995,73	378,00	0	4	10047,48	0,00	113	423	4	9961,39	0,00	961,39	113	144
3_lc_20	37	59033,73	899,02	0	3	10023,88	0,00	114	374	3	9952,47	0,00	952,47	**114**	170
4_lc_20	41	43587,16	641,21	0	4	9971,59	0,00	138	423	4	9928,60	0,00	928,60	**139**	**171**
5_lc_20	39	76846,75	856,73	0	3	9605,96	0,00	50	224	3	9601,66	0,00	601,66	**50**	**169**
6_lc_20	39	75613,48	814,73	0	4	9902,11	0,00	44	195	4	9819,85	0,00	819,85	**44**	173
7_lc_20	39	70255,91	602,61	0	4	11126,32	30,67	10	97	4	11112,88	30,67	2082,21	**10**	111
8_lc_20	39	69386,34	696,73	0	4	11280,01	44,15	13	118	4	11280,01	44,15	2235,86	**13**	**107**
1_lr_10	47	7635,11	115,52	0	20	3673,84	9,29	1	77	20	3673,84	9,29	2664,55	**1**	**9**
2_lr_10	43	6584,22	143,97	0	18	3264,86	2,85	1	42	18	3264,86	2,85	2262,02	**1**	**13**
3_lr_10	48	6634,10	62,03	0	13	2647,57	21,39	3	172	13	**2645,44**	21,39	1624,05	**3**	**13**
4_lr_10	40	4838,73	0,00	0	11	2156,33	0,00	5	196	11	2156,33	0,00	1156,33	**5**	**17**
5_lr_10	43	6466,35	116,59	0	14	2614,50	1,61	6	293	14	**2614,50**	1,61	1612,89	**6**	**11**
6_lr_10	41	6196,63	116,91	0	12	2393,73	11,01	3	179	12	**2393,30**	11,01	1382,29	**3**	**15**
7_lr_10	39	5496,87	0,00	0	10	2197,87	0,00	7	277	10	**2193,93**	0,00	1193,93	**7**	**17**
8_lr_10	40	4800,31	0,00	0	19	2759,23	2,37	0	22	19	2759,23	2,37	1756,86	**0**	**13**
9_lr_10	42	5858,35	101,48	0	15	2655,14	0,00	1	53	15	2652,96	0,13	1652,84	**1**	**16**
10_lr_10	44	5586,58	76,94	0	12	2305,16	0,00	2	120	12	2305,16	0,00	1305,16	**2**	**13**
11_lr_10	41	5550,66	93,59	0	12	2344,07	0,00	13	458	12	2331,38	0,00	1331,38	**13**	**15**
12_lr_10	40	4607,39	19,14	0	10	2108,72	0,00	4	152	10	2107,72	0,00	1107,72	**4**	**20**
1_lr_20	37	20906,73	745,20	0	4	3181,33	22,66	116	494	4	**3173,94**	22,66	2151,28	**116**	**118**
2_lr_20	34	19895,42	684,01	0	4	2941,39	36,79	121	482	4	2941,39	36,79	1904,60	**121**	**127**
3_lr_20	36	16276,38	298,21	0	3	2533,80	3,51	166	476	3	**2531,16**	3,51	1527,66	**166**	**180**
4_lr_20	35	11757,21	259,57	0	3	2226,75	2,98	176	401	3	2226,75	2,98	1223,77	**176**	**233**
5_lr_20	36	18006,80	653,97	0	3	2468,86	10,52	105	311	3	**2460,30**	10,52	1449,78	**105**	**204**
6_lr_20	36	18141,83	653,97	0	3	2396,38	10,07	87	280	3	**2383,21**	2,66	1380,55	**87**	**190**
7_lr_20	35	14554,30	418,55	0	3	2180,84	0,00	238	494	3	2171,92	0,00	1171,92	**238**	**243**
8_lr_20	35	9588,99	114,19	0	3	1967,54	0,00	240	443	3	1954,57	0,00	954,57	**240**	**280**
9_lr_20	36	16589,16	604,32	0	3	2355,45	33,57	134	403	3	**2343,71**	33,57	1310,14	**134**	**186**
10_lr_20	38	18423,90	444,80	0	3	2410,86	0,00	190	479	3	**2405,42**	0,00	1405,42	**190**	**202**
11_lr_20	39	13.908,13	404,50	0	6	3.315,03	9,48	2	58	6	3.315,03	9,48	2.305,55	**2**	**54**
1_lrc_10	39	6589,07	60,03	0	17	3345,09	31,78	1	59	17	3345,09	31,78	2313,31	**1**	**12**
2_lrc_10	39	6176,91	6,67	0	14	2914,94	0,00	1	61	14	2909,79	0,00	1909,79	**1**	**17**
3_lrc_10	41	5855,56	52,35	0	14	2670,57	0,00	1	67	14	2666,79	0,00	1666,79	**1**	**16**
4_lrc_10	39	5236,08	0,00	0	10	2211,28	3,07	8	251	10	**2208,38**	3,07	1205,31	**8**	**21**
5_lrc_10	41	6633,65	25,27	0	22	3844,80	0,00	0	20	22	3842,94	0,00	2842,94	**0**	**12**
6_lrc_10	37	5543,24	2,27	0	13	2684,57	0,00	1	83	13	2676,13	0,00	1676,13	**1**	**18**
7_lrc_10	37	5127,65	0,64	0	13	2490,16	4,34	12	451	13	2479,11	4,34	1474,77	**12**	**14**
8_lrc_10	38	4841,61	0,00	0	12	2380,48	0,00	1	60	12	2378,13	0,00	1378,13	**1**	**19**
1_lrc_20	33	18539,37	169,54	0	5	3691,11	26,25	33	250	5	3684,76	26,25	2658,51	**33**	**95**
2_lrc_20	38	20164,18	132,00	0	4	3001,28	48,54	98	406	4	2985,45	48,54	1936,91	**98**	**133**
3_lrc_20	35	14396,08	507,11	0	3	2436,65	2,08	203	495	3	**2416,27**	2,08	1414,19	**203**	**206**
4_lrc_20	37	12278,14	442,09	0	3	2289,33	8,07	229	484	3	**2270,60**	8,07	1262,53	**229**	**238**
5_lrc_20	39	20531,19	80,99	0	4	3333,19	0,03	94	464	4	**3322,11**	0,03	2322,08	**94**	**104**
6_lrc_20	35	17153,24	198,94	0	4	2774,96	1,74	64	267	4	2749,74	1,74	1748,00	**64**	**157**
7_lrc_20	36	16223,79	169,91	0	3	2370,78	4,55	145	473	3	**2351,95**	4,55	1347,41	**145**	**158**
8_lrc_20	38	14623,34	113,94	0	9	4380,42	10,52	1	47	9	4380,42	10,52	3369,90	**1**	**25**
										sum	**275882,43**	**386,61**	**83495,84**	**3080,00**	**4868,00**
										avg	**4926,47**	**6,90**	**1491,00**	**55,00**	**86,93**

angle_s_nCust_rr

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	actual cpu[sec]	total cpu[sec]
1_lc_10	43	29243,75	343,85	0	10	9828,94	0,00	2	80	10	**9828,94**	0,00	828,937	**2**	**25**
2_lc_10	42	26539,27	242,46	0	10	9831,73	0,00	4	159	10	**9828,94**	0,00	828,937	**4**	**19**
3_lc_10	41	23792,09	435,32	0	11	10195,51	0,00	12	431	11	10182,95	0,00	1182,95	**12**	**15**
4_lc_10	44	18249,83	0,00	0	10	9997,39	0,00	20	493	10	**9997,39**	0,00	997,394	**20**	**20**
5_lc_10	43	28885,61	312,99	0	10	9828,94	0,00	8	272	10	**9828,94**	0,00	828,937	**8**	**19**
6_lc_10	41	29234,04	339,28	0	10	9828,94	0,00	1	66	10	**9828,94**	0,00	828,937	**1**	**20**
7_lc_10	44	28887,17	279,47	0	10	9838,59	0,00	3	99	10	**9828,94**	0,00	828,937	**3**	**20**
8_lc_10	41	26444,51	282,38	0	10	9830,57	0,00	8	245	10	**9826,44**	0,00	826,438	**8**	**20**
9_lc_10	44	23920,07	185,85	0	10	9830,94	0,00	5	170	10	**9828,94**	0,00	828,937	**5**	**20**
1_lc_20	41	83006,41	747,46	0	3	9591,56	0,00	19	134	3	**9591,56**	0,00	591,557	**19**	209
2_lc_20	36	65995,73	378,00	0	4	10047,48	0,00	112	423	4	9961,39	0,00	961,391	112	143
3_lc_20	37	59033,73	899,02	0	3	10023,88	0,00	113	374	3	9927,73	9,83	917,892	**113**	168
4_lc_20	41	43587,16	641,21	0	4	9971,59	0,00	136	423	4	9916,43	0,00	916,433	**136**	**167**
5_lc_20	39	76846,75	856,73	0	3	9605,96	0,00	49	224	3	**9588,88**	0,00	588,876	**49**	**167**
6_lc_20	39	75613,48	814,73	0	4	9902,11	0,00	43	195	4	9787,99	0,00	787,985	**43**	171
7_lc_20	39	70255,91	602,61	0	4	11126,32	30,67	10	97	4	11112,88	30,67	2082,21	**10**	110
8_lc_20	39	69386,34	696,73	0	4	11280,01	44,15	13	118	4	11280,01	44,15	2235,86	**13**	**106**
1_lr_10	47	7635,11	115,52	0	20	3691,67	24,13	2	142	20	3691,67	24,13	2667,53	**2**	**8**
2_lr_10	43	6584,22	143,97	0	18	3264,86	2,85	1	42	18	3264,86	2,85	2262,02	**1**	**13**
3_lr_10	48	6634,10	62,03	0	13	2647,57	21,39	3	172	13	**2647,57**	21,39	1626,18	**3**	**12**
4_lr_10	40	4838,73	0,00	0	11	2156,33	0,00	5	196	11	2156,33	0,00	1156,33	**5**	**17**
5_lr_10	43	6466,35	116,59	0	14	2614,50	1,61	6	293	14	**2614,50**	1,61	1612,89	**6**	**11**
6_lr_10	41	6196,63	116,91	0	12	2393,73	11,01	3	179	12	**2393,30**	11,01	1382,29	**3**	**15**
7_lr_10	39	5496,87	0,00	0	10	2197,87	0,00	7	277	10	**2193,93**	0,00	1193,93	**7**	**17**
8_lr_10	40	4800,31	0,00	0	19	2759,23	2,37	0	22	19	2758,44	2,37	1756,07	**0**	**13**
9_lr_10	42	5858,35	101,48	0	15	2655,14	0,00	1	53	15	2652,96	0,13	1652,84	**1**	**16**
10_lr_10	44	5586,58	76,94	0	12	2305,16	0,00	2	120	12	2305,16	0,00	1305,16	**2**	**14**
11_lr_10	41	5550,66	93,59	0	12	2344,07	0,00	13	458	12	2328,17	0,00	1328,17	**13**	**15**
12_lr_10	40	4607,39	19,14	0	10	2108,72	0,00	4	152	10	2105,34	0,00	1105,34	**4**	**20**
1_lr_20	37	20906,73	745,20	0	4	3181,33	22,66	116	494	4	**3168,02**	22,66	2145,36	**116**	**118**
2_lr_20	34	19895,42	684,01	0	4	2941,39	36,79	121	482	4	2930,97	36,79	1894,18	**121**	**127**
3_lr_20	36	16276,38	298,21	0	3	2533,80	3,51	165	476	3	**2494,50**	3,51	1490,99	**165**	**179**
4_lr_20	35	11757,21	259,57	0	3	2226,75	2,98	175	401	3	2226,75	2,98	1223,77	**175**	**231**
5_lr_20	36	18006,80	653,97	0	3	2468,86	10,52	105	311	3	**2454,94**	10,52	1444,42	**105**	**203**
6_lr_20	36	18141,83	653,97	0	3	2396,38	10,07	87	280	3	**2383,21**	4,46	1378,75	**87**	**189**
7_lr_20	35	14554,30	418,55	0	3	2180,84	0,00	237	494	3	2150,59	0,00	1150,59	**237**	**242**
8_lr_20	35	9588,99	114,19	0	3	1967,54	0,00	238	443	3	1954,31	0,00	954,31	**238**	**277**
9_lr_20	36	16589,16	604,32	0	3	2355,45	33,57	132	403	3	**2321,04**	14,94	1306,10	**132**	**183**
10_lr_20	38	18423,90	444,80	0	3	2410,86	0,00	188	479	3	**2395,88**	0,00	1395,88	**188**	**200**
11_lr_20	39	13.908,13	404,50	0	6	3.315,03	9,48	2	58	6	3.315,03	9,48	2.305,55	**2**	**55**
1_lrc_10	39	6589,07	60,03	0	17	3345,09	31,78	1	59	17	3343,25	31,78	2311,47	**1**	**12**
2_lrc_10	39	6176,91	6,67	0	14	2914,94	0,00	1	61	14	2909,79	0,00	1909,79	**1**	**16**
3_lrc_10	41	5855,56	52,35	0	14	2670,57	0,00	1	67	14	2663,39	0,00	1663,39	**1**	**16**
4_lrc_10	39	5236,08	0,00	0	10	2211,28	3,07	8	251	10	**2207,45**	3,07	1204,39	**8**	**21**
5_lrc_10	41	6633,65	25,27	0	22	3844,80	0,00	0	20	22	3842,70	0,00	2842,70	**0**	**12**
6_lrc_10	37	5543,24	2,27	0	13	2684,57	0,00	1	83	13	2671,99	0,00	1671,99	**1**	**17**
7_lrc_10	37	5127,65	0,64	0	13	2490,16	4,34	12	451	13	2484,52	4,34	1480,17	**12**	**13**
8_lrc_10	38	4841,61	0,00	0	12	2380,48	0,00	1	60	12	2379,20	0,00	1379,20	**1**	**19**
1_lrc_20	33	18539,37	169,54	0	5	3691,11	26,25	33	250	5	3681,87	26,25	2655,63	**33**	**94**
2_lrc_20	38	20164,18	132,00	0	4	3001,28	48,54	97	406	4	2975,04	48,54	1926,50	**97**	**131**
3_lrc_20	35	14396,08	507,11	0	3	2436,65	2,08	199	495	3	**2386,23**	2,08	1384,15	**199**	**202**
4_lrc_20	37	12278,14	442,09	0	3	2289,33	8,07	224	484	3	**2255,74**	0,00	1255,74	**224**	**233**
5_lrc_20	39	20531,19	80,99	0	4	3333,19	0,03	91	464	4	**3322,11**	0,03	2322,08	**91**	**101**
6_lrc_20	35	17153,24	198,94	0	4	2774,96	1,74	62	267	4	2749,74	1,74	1748,00	**62**	**154**
7_lrc_20	36	16223,79	169,91	0	3	2370,78	4,55	142	473	3	**2350,54**	4,55	1346,00	**142**	**156**
8_lrc_20	38	14623,34	113,94	0	9	4380,42	10,52	1	47	9	4380,42	10,52	3369,90	**1**	**25**
										sum	**275658,74**	**386,38**	**83272,35**	**3045,00**	**4816,00**
										avg	**4922,48**	**6,90**	**1487,01**	**54,38**	**86,00**

angle_s_nVeh_2opt

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	actual cpu[sec]	total cpu[sec]
1_lc_10	20	16069,54	343,85	0	10	9828,94	0,00	4	146	10	**9828,94**	0,00	828,937	**4**	**22**
2_lc_10	20	15294,44	242,46	0	10	9833,34	0,00	4	170	10	9830,17	0,00	830,165	**4**	**18**
3_lc_10	20	15099,46	254,02	0	10	9960,49	0,00	4	142	10	**9929,31**	0,00	929,313	**4**	**19**
4_lc_10	21	12600,33	0,00	0	10	9952,31	0,00	20	493	10	**9922,25**	0,00	922,254	**20**	**20**
5_lc_10	19	14793,38	115,00	0	10	9848,93	18,47	2	89	10	9848,93	18,47	830,455	**2**	**20**
6_lc_10	19	14913,94	339,28	0	10	9828,94	0,00	6	224	10	**9828,94**	0,00	828,938	**6**	**19**
7_lc_10	18	13759,25	279,47	0	10	9830,17	0,00	3	94	10	9830,17	0,00	830,165	**3**	**24**
8_lc_10	20	14783,78	282,38	0	10	9828,10	0,00	8	273	10	**9826,44**	0,00	826,438	**8**	**19**
9_lc_10	20	13301,27	185,85	0	10	9828,94	0,00	14	387	10	**9828,94**	0,00	828,937	**14**	**20**
1_lc_20	19	40843,78	747,46	0	3	9591,56	0,00	19	118	3	**9591,56**	0,00	591,557	**19**	217
2_lc_20	17	34460,70	930,64	0	4	9953,20	0,00	113	395	4	9887,58	0,00	887,584	113	159
3_lc_20	19	33805,68	929,94	0	3	9955,55	0,00	130	433	3	9860,00	0,00	860,004	**130**	162
4_lc_20	19	30517,00	621,35	0	4	9899,57	0,00	153	464	4	9847,47	0,00	847,475	**153**	**168**
5_lc_20	19	37394,45	760,30	0	3	9594,40	0,00	43	208	3	**9588,88**	0,00	588,876	**43**	**184**
6_lc_20	19	38949,20	261,54	0	4	9834,69	0,00	38	191	4	9794,85	0,00	794,854	**38**	201
7_lc_20	19	34832,84	516,30	0	4	11313,78	22,67	9	83	4	11313,78	22,67	2291,1	**9**	111
8_lc_20	19	34538,81	600,30	0	4	9719,68	0,00	129	456	4	**9691,86**	0,00	691,86	**129**	**149**
1_lr_10	33	5808,36	106,82	0	20	3740,15	26,78	0	20	20	3740,15	26,78	2713,37	**0**	**9**
2_lr_10	25	4471,09	90,31	0	17	3091,81	19,54	1	42	17	**3091,81**	19,54	2072,27	**1**	**11**
3_lr_10	31	4774,75	24,42	0	13	2655,14	21,39	4	203	13	**2647,44**	21,39	1626,05	**4**	**12**
4_lr_10	25	3619,68	0,00	0	12	2271,54	4,42	3	123	12	2271,54	4,42	1267,12	**3**	**20**
5_lr_10	26	4316,63	23,20	0	15	2719,67	16,97	1	52	15	2719,67	16,97	1702,70	**1**	**14**
6_lr_10	24	4047,22	40,46	0	14	2579,38	0,00	1	54	14	2577,66	3,66	1574,00	**1**	**16**
7_lr_10	25	3934,15	14,81	0	11	2259,68	0,00	12	403	11	2254,29	0,00	1254,29	**12**	**16**
8_lr_10	24	3530,37	0,00	0	14	2439,34	0,00	0	21	14	2429,21	0,00	1429,21	**0**	**16**
9_lr_10	23	3800,08	46,26	0	16	2755,73	5,68	0	28	16	2755,73	5,68	1750,05	**0**	**12**
10_lr_10	27	3908,61	20,59	0	14	2438,65	0,00	1	74	14	2420,47	0,00	1420,47	**1**	**15**
11_lr_10	24	3755,73	13,64	0	12	2359,18	0,00	3	143	12	2351,23	0,00	1351,23	**3**	**18**
12_lr_10	23	3281,09	0,00	0	12	2254,93	0,00	1	62	12	2250,58	0,00	1250,58	**1**	**18**
1_lr_20	22	13211,88	340,36	0	4	3135,61	8,95	107	439	4	**3115,61**	8,95	2106,66	**107**	**127**
2_lr_20	19	12554,75	341,85	0	4	2952,26	2,42	90	375	4	2952,26	2,42	1949,84	**90**	**130**
3_lr_20	21	12609,70	278,35	0	3	2440,35	1,06	161	393	3	**2408,60**	0,00	1408,60	**161**	**226**
4_lr_20	18	8232,37	141,51	0	3	2232,37	1,00	154	375	3	2228,94	1,00	1227,94	**154**	**222**
5_lr_20	21	11716,09	247,97	0	4	2657,91	3,67	26	134	4	2640,15	3,67	1636,47	**26**	**240**
6_lr_20	20	10820,22	329,67	0	3	2381,58	0,00	167	449	3	**2370,54**	3,94	1366,60	**167**	**190**
7_lr_20	20	10627,66	139,95	0	3	2204,62	0,95	179	403	3	2188,88	0,95	1187,93	**179**	**246**
8_lr_20	18	7252,71	55,59	0	3	2020,32	0,00	247	477	3	1984,53	0,00	984,53	**247**	**263**
9_lr_20	19	10382,65	134,69	0	3	2350,00	4,76	199	487	3	**2340,36**	4,76	1335,60	**199**	**206**
10_lr_20	24	13337,41	359,54	0	3	2473,84	8,65	188	475	3	**2468,78**	8,65	1460,14	**188**	**202**
11_lr_20	21	8.689,63	230,24	0	5	2.874,38	0,09	8	96	5	2.872,05	0,09	1.871,96	**8**	**83**
1_lrc_10	27	4856,48	27,24	0	15	3117,78	27,24	1	41	15	3106,84	27,24	2079,61	**1**	**13**
2_lrc_10	25	4483,37	0,00	0	13	2744,60	0,00	2	91	13	**2744,58**	0,00	1744,58	**2**	**18**
3_lrc_10	24	4030,32	0,00	0	11	2398,47	0,00	12	434	11	**2398,47**	0,00	1398,47	**12**	**15**
4_lrc_10	23	3756,69	0,00	0	10	2205,98	8,30	3	113	10	**2203,75**	8,30	1195,45	**3**	**21**
5_lrc_10	25	4527,11	7,79	0	14	2906,42	9,82	6	263	14	2906,42	9,82	1896,60	**6**	**13**
6_lrc_10	23	3872,26	0,00	0	13	2645,72	0,34	3	137	13	2642,76	0,34	1642,42	**3**	**17**
7_lrc_10	23	3780,92	0,64	0	14	2593,46	0,00	1	69	14	2587,82	0,47	1587,35	**1**	**19**
8_lrc_10	23	3496,67	0,00	0	11	2343,30	0,00	3	120	11	2323,31	0,00	1323,31	**3**	**17**
1_lrc_20	19	12218,12	119,93	0	5	3533,05	50,44	23	182	5	3527,32	50,44	2476,88	**23**	**111**
2_lrc_20	20	12209,59	66,67	0	4	2950,34	2,53	114	416	4	2942,24	2,53	1939,71	**114**	**147**
3_lrc_20	22	10037,14	468,12	0	4	2718,50	3,35	131	454	4	2706,70	3,35	1703,35	**131**	**149**
4_lrc_20	18	7907,00	490,18	0	4	2477,59	0,00	127	449	4	**2455,96**	0,90	1455,06	**127**	**146**
5_lrc_20	17	11801,15	80,99	0	4	3238,53	3,15	100	477	4	**3237,68**	3,15	2234,53	**100**	**107**
6_lrc_20	17	10729,55	142,54	0	4	2816,17	0,24	143	491	4	2806,56	0,24	1806,33	**143**	**146**
7_lrc_20	19	8784,59	172,77	0	7	3722,76	8,07	2	46	7	3666,03	8,07	2657,95	**3**	**235**
8_lrc_20	19	8621,20	52,77	0	3	2185,17	5,48	169	486	3	**2157,82**	5,48	1152,34	**169**	**177**
										sum	**271744,81**	**294,34**	**79450,46**	**3093,00**	**5195,00**
										avg	**4852,59**	**5,26**	**1418,76**	**55,23**	**92,77**

angle_s_nVeh_rr

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	actual cpu[sec]	total cpu[sec]
1_lc_10	20	16069,54	343,85	0	10	9828,94	0,00	4	146	10	**9828,94**	0,00	828,94	**4**	**22**
2_lc_10	20	15294,44	242,46	0	10	9833,34	0,00	4	170	10	**9828,94**	0,00	828,94	**4**	**18**
3_lc_10	20	15099,46	254,02	0	10	9960,49	0,00	4	142	10	**9960,49**	0,00	960,49	**4**	**19**
4_lc_10	21	12600,33	0,00	0	10	9952,31	0,00	19	493	10	**9935,11**	0,00	935,11	**19**	**20**
5_lc_10	19	14793,38	115,00	0	10	9848,93	18,47	2	89	10	**9828,94**	0,00	828,94	**2**	**20**
6_lc_10	19	14913,94	339,28	0	10	9828,94	0,00	6	224	10	**9828,94**	0,00	828,94	**6**	**19**
7_lc_10	18	13759,25	279,47	0	10	9830,17	0,00	3	94	10	**9828,94**	0,00	828,94	**3**	**24**
8_lc_10	20	14783,78	282,38	0	10	9828,10	0,00	8	273	10	**9826,44**	0,00	826,44	**8**	**19**
9_lc_10	20	13301,27	185,85	0	10	9828,94	0,00	14	387	10	**9828,94**	0,00	828,94	**14**	**19**
1_lc_20	19	40843,78	747,46	0	3	9591,56	0,00	19	118	3	**9591,56**	0,00	591,56	**19**	217
2_lc_20	17	34460,70	930,64	0	4	9953,20	0,00	112	395	4	9916,44	0,00	916,44	112	158
3_lc_20	19	33805,68	929,94	0	3	9955,55	0,00	129	433	3	9878,11	0,34	877,77	**129**	160
4_lc_20	19	30517,00	621,35	0	4	9899,57	0,00	152	464	4	9827,58	0,00	827,58	**152**	**167**
5_lc_20	19	37394,45	760,30	0	3	9594,40	0,00	43	208	3	**9588,88**	0,00	588,88	**43**	**183**
6_lc_20	19	38949,20	261,54	0	4	9834,69	0,00	38	191	4	9794,47	0,00	794,47	**38**	200
7_lc_20	19	34832,84	516,30	0	4	11313,78	22,67	9	83	4	11313,78	22,67	2291,10	**9**	111
8_lc_20	19	34538,81	600,30	0	4	9719,68	0,00	129	456	4	**9689,37**	0,00	689,37	**129**	**149**
1_lr_10	33	5808,36	106,82	0	20	3740,15	26,78	0	20	20	3740,15	26,78	2713,37	**0**	**9**
2_lr_10	25	4471,09	90,31	0	17	3091,81	19,54	1	42	17	**3091,81**	19,54	2072,27	**1**	**11**
3_lr_10	31	4774,75	24,42	0	13	2655,14	21,39	4	203	13	**2655,14**	21,39	1633,75	**4**	**12**
4_lr_10	25	3619,68	0,00	0	12	2271,54	4,42	3	123	12	2271,54	4,42	1267,12	**3**	**20**
5_lr_10	26	4316,63	23,20	0	15	2719,67	16,97	1	52	15	2719,67	16,97	1702,70	**1**	**14**
6_lr_10	24	4047,22	40,46	0	14	2579,38	0,00	1	54	14	2576,90	3,66	1573,23	**1**	**16**
7_lr_10	25	3934,15	14,81	0	11	2259,68	0,00	12	403	11	2254,29	0,00	1254,29	**12**	**16**
8_lr_10	24	3530,37	0,00	0	14	2439,34	0,00	0	21	14	2429,21	0,00	1429,21	**0**	**16**
9_lr_10	23	3800,08	46,26	0	16	2755,73	5,68	0	28	16	2754,15	5,68	1748,47	**0**	**12**
10_lr_10	27	3908,61	20,59	0	14	2438,65	0,00	1	74	14	2420,47	0,00	1420,47	**1**	**15**
11_lr_10	24	3755,73	13,64	0	12	2359,18	0,00	3	143	12	2350,85	0,00	1350,85	**3**	**18**
12_lr_10	23	3281,09	0,00	0	12	2254,93	0,00	1	62	12	2243,91	0,00	1243,91	**1**	**18**
1_lr_20	22	13211,88	340,36	0	4	3135,61	8,95	106	439	4	**3115,61**	8,95	2106,66	**106**	**126**
2_lr_20	19	12554,75	341,85	0	4	2952,26	2,42	90	375	4	2950,60	2,42	1948,18	**90**	**129**
3_lr_20	21	12609,70	278,35	0	3	2440,35	1,06	160	393	3	**2407,52**	4,26	1403,25	**160**	**224**
4_lr_20	18	8232,37	141,51	0	3	2232,37	1,00	153	375	3	2232,37	1,00	1231,37	**153**	**221**
5_lr_20	21	11716,09	247,97	0	4	2657,91	3,67	26	134	4	2638,44	3,67	1634,77	**26**	**240**
6_lr_20	20	10820,22	329,67	0	3	2381,58	0,00	165	449	3	**2362,91**	4,26	1358,65	**165**	**189**
7_lr_20	20	10627,66	139,95	0	3	2204,62	0,95	177	403	3	2181,63	0,95	1180,68	**177**	**245**
8_lr_20	18	7252,71	55,59	0	3	2020,32	0,00	245	477	3	1984,53	0,00	984,53	**245**	**262**
9_lr_20	19	10382,65	134,69	0	3	2350,00	4,76	198	487	3	**2337,19**	12,24	1324,95	**198**	**205**
10_lr_20	24	13337,41	359,54	0	3	2473,84	8,65	187	475	3	**2459,95**	8,65	1451,30	**187**	**201**
11_lr_20	21	8.689,63	230,24	0	5	2.874,38	0,09	8	96	5	2.872,05	0,09	1.871,96	**8**	**82**
1_lrc_10	27	4856,48	27,24	0	15	3117,78	27,24	1	41	15	3106,04	27,24	2078,81	**1**	**13**
2_lrc_10	25	4483,37	0,00	0	13	2744,60	0,00	2	91	13	**2744,60**	0,00	1744,60	**2**	**18**
3_lrc_10	24	4030,32	0,00	0	11	2398,47	0,00	12	434	11	**2397,82**	0,00	1397,82	**12**	**15**
4_lrc_10	23	3756,69	0,00	0	10	2205,98	8,30	3	113	10	**2203,88**	8,30	1195,58	**3**	**20**
5_lrc_10	25	4527,11	7,79	0	14	2906,42	9,82	5	263	14	2906,42	9,82	1896,60	**5**	**12**
6_lrc_10	23	3872,26	0,00	0	13	2645,72	0,34	3	137	13	2638,62	0,34	1638,27	**3**	**17**
7_lrc_10	23	3780,92	0,64	0	14	2593,46	0,00	1	69	14	2581,91	0,47	1581,43	**1**	**19**
8_lrc_10	23	3496,67	0,00	0	11	2343,30	0,00	3	120	11	2313,66	0,00	1313,66	**3**	**17**
1_lrc_20	19	12218,12	119,93	0	5	3533,05	50,44	23	182	5	3526,91	50,44	2476,46	**23**	**111**
2_lrc_20	20	12209,59	66,67	0	4	2950,34	2,53	113	416	4	2915,12	2,53	1912,58	**113**	**146**
3_lrc_20	22	10037,14	468,12	0	4	2718,50	3,35	131	454	4	2701,41	3,35	1698,06	**131**	**148**
4_lrc_20	18	7907,00	490,18	0	4	2477,59	0,00	127	449	4	**2451,62**	15,10	1436,52	**127**	**145**
5_lrc_20	17	11801,15	80,99	0	4	3238,53	3,15	99	477	4	**3237,68**	3,15	2234,53	**99**	**106**
6_lrc_20	17	10729,55	142,54	0	4	2816,17	0,24	142	491	4	2806,29	0,24	1806,05	**142**	**145**
7_lrc_20	19	8784,59	172,77	0	7	3722,76	8,07	2	46	7	3672,89	8,07	2664,82	**2**	**234**
8_lrc_20	19	8621,20	52,77	0	3	2185,17	5,48	168	486	3	**2160,43**	0,40	1160,03	**168**	**176**
										sum	**271712,06**	**297,39**	**79414,61**	**3072,00**	**5168,00**
										avg	**4852,00**	**5,31**	**1418,12**	**54,86**	**92,29**

angle_s_1_2opt

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	actual cpu[sec]	total cpu[sec]
1_lc_10	12	10907,10	57,31	0	10	9828,94	0,00	6	218	10	**9828,94**	0,00	828,94	**6**	**20**
2_lc_10	12	11866,28	0,00	0	10	9831,73	0,00	13	389	10	**9828,94**	0,00	828,94	**13**	**18**
3_lc_10	12	12594,14	57,49	0	10	9938,60	0,00	16	450	10	**9915,99**	0,00	915,99	**16**	**18**
4_lc_10	11	11675,74	0,00	0	10	9973,53	0,00	20	482	10	**9960,59**	0,00	960,59	**20**	**21**
5_lc_10	12	11211,20	0,00	0	10	9828,94	0,00	1	46	10	**9828,94**	0,00	828,94	**2**	**21**
6_lc_10	12	11699,28	33,71	0	10	9838,93	0,00	5	165	10	9838,93	0,00	838,93	**5**	**20**
7_lc_10	13	11843,05	0,00	0	10	9828,94	0,00	4	155	10	**9828,94**	0,00	828,94	**4**	**20**
8_lc_10	12	11598,55	0,00	0	10	9826,44	0,00	12	321	10	**9826,44**	0,00	826,44	**12**	**20**
9_lc_10	11	10913,00	0,00	0	10	9828,94	0,00	15	390	10	**9828,94**	0,00	828,94	**15**	**20**
1_lc_20	5	15773,64	12,14	0	3	9591,56	0,00	132	403	3	**9591,56**	0,00	591,56	132	178
2_lc_20	5	13566,47	8,33	0	3	9815,87	23,47	167	463	3	9777,18	5,28	771,90	167	183
3_lc_20	5	13382,10	33,69	0	3	9892,12	11,49	155	454	3	9812,19	11,49	800,70	155	176
4_lc_20	4	12980,43	0,53	0	3	9974,49	1,64	170	460	3	9941,58	0,00	941,58	**170**	**190**
5_lc_20	5	12851,59	39,86	0	4	9891,94	114,73	12	44	4	9756,94	22,10	734,85	**12**	250
6_lc_20	4	12528,29	47,03	0	4	9713,99	63,34	120	341	4	9626,65	3,78	622,87	120	197
7_lc_20	5	12637,82	9,99	0	4	9735,71	0,00	95	265	4	9722,02	0,00	722,02	**95**	202
8_lc_20	4	12684,60	43,27	0	4	11345,05	43,27	3	15	4	11291,24	43,27	2247,97	**3**	**125**
1_lr_10	23	4170,77	34,36	0	23	4170,77	34,36	0	0	23	4170,77	34,36	3136,41	**0**	**9**
2_lr_10	21	3963,05	0,00	0	17	3117,71	4,72	1	37	17	**3117,71**	4,72	2112,99	**1**	**15**
3_lr_10	17	3553,03	1,07	0	13	2615,06	12,47	10	423	13	**2615,06**	12,47	1602,59	**10**	**12**
4_lr_10	15	3288,42	0,00	0	11	2202,71	0,00	1	70	11	2202,71	0,00	1202,71	**1**	**24**
5_lr_10	18	3267,86	0,00	0	14	2614,21	22,54	9	413	14	**2614,21**	22,54	1591,68	**9**	**11**
6_lr_10	16	3032,42	0,00	0	12	2409,48	0,10	4	219	12	**2409,04**	0,10	1408,94	**4**	**14**
7_lr_10	16	3366,13	0,00	0	10	2196,62	1,87	3	133	10	**2195,91**	1,87	1194,05	**3**	**20**
8_lr_10	15	3107,29	11,32	0	13	2358,11	0,00	0	29	13	2339,48	0,00	1339,48	**0**	**15**
9_lr_10	16	3067,70	0,00	0	15	2639,09	13,49	0	27	15	2623,21	13,49	1609,72	**0**	**16**
10_lr_10	16	3198,13	0,00	0	13	2374,19	6,54	11	469	13	2369,21	6,54	1362,68	**11**	**12**
11_lr_10	13	2619,59	0,00	0	11	2279,07	0,00	2	84	11	2268,92	0,00	1268,92	**2**	**18**
12_lr_10	15	3089,72	0,00	0	11	2144,65	1,24	12	368	11	2133,38	1,24	1132,14	**12**	**17**
1_lr_20	6	4913,75	25,79	0	5	3430,39	27,46	19	112	5	**3421,48**	27,46	2394,02	**19**	**156**
2_lr_20	5	4112,50	0,00	0	3	2588,29	6,58	124	396	3	**2588,29**	6,58	1581,71	**125**	**172**
3_lr_20	4	3832,93	0,00	0	3	2593,86	0,00	114	279	3	**2575,77**	21,71	1554,06	**114**	**228**
4_lr_20	4	3810,71	0,00	0	3	2238,59	0,00	140	292	3	2236,12	0,00	1236,12	**140**	**261**
5_lr_20	5	3756,04	55,00	0	3	2473,57	6,43	150	355	3	**2467,45**	6,43	1461,01	**150**	**224**
6_lr_20	5	3910,50	16,93	0	3	2389,16	0,00	173	423	3	**2385,53**	0,00	1385,53	**173**	**209**
7_lr_20	4	3248,68	0,00	0	3	2197,98	0,00	223	450	3	2182,55	0,00	1182,55	**223**	**258**
8_lr_20	4	3232,44	0,00	0	2	1816,45	3,33	379	490	2	**1807,82**	3,33	804,49	**379**	**389**
9_lr_20	5	3966,18	4,34	0	3	2328,92	0,83	164	388	3	**2323,92**	0,83	1323,09	**164**	**222**
10_lr_20	5	3999,99	0,00	0	3	2446,06	27,53	121	284	3	**2438,67**	27,53	1411,14	**121**	**243**
11_lr_20	4	3.063,12	0,00	0	3	2.061,38	0,00	212	479	3	2041,17	0,00	1041,17	**212**	**224**
1_lrc_10	18	3612,94	6,29	0	16	3256,61	6,29	0	5	16	3245,99	6,29	2239,71	**0**	**13**
2_lrc_10	16	3481,43	0,00	0	13	2745,31	0,00	1	68	13	**2745,31**	0,00	1745,31	**1**	**18**
3_lrc_10	16	3342,29	0,00	0	11	2428,07	0,00	5	213	11	**2422,22**	0,00	1422,22	**5**	**15**
4_lrc_10	14	3104,73	0,00	0	10	2235,44	0,00	4	150	10	**2233,91**	0,00	1233,91	**4**	**22**
5_lrc_10	17	3501,83	0,00	0	17	3501,83	0,00	0	0	17	3498,97	0,00	2498,97	**0**	**15**
6_lrc_10	16	3355,62	0,00	0	13	2653,79	0,00	2	86	13	2651,84	0,00	1651,84	**2**	**17**
7_lrc_10	16	3395,53	0,00	0	12	2397,83	0,00	6	260	12	2393,76	0,00	1393,76	**6**	**15**
8_lrc_10	16	3373,55	0,00	0	10	2272,14	0,00	3	121	10	**2226,82**	0,00	1226,82	**3**	**21**
1_lrc_20	6	4520,34	3,92	0	4	3276,14	26,41	50	248	4	**3259,44**	10,82	2248,62	**50**	**122**
2_lrc_20	6	4673,44	0,35	0	4	3040,75	12,44	21	95	4	2993,31	12,44	1980,87	**21**	**161**
3_lrc_20	5	4413,24	1,61	0	4	2861,16	3,71	73	267	4	2861,16	3,71	1857,45	**73**	**159**
4_lrc_20	4	3485,79	0,00	0	3	2387,34	0,00	206	500	3	**2372,88**	0,96	1371,91	**206**	**206**
5_lrc_20	6	4783,24	28,38	0	4	3270,04	33,56	18	114	4	**3259,95**	33,56	2226,39	**18**	**122**
6_lrc_20	5	3739,36	17,96	0	4	2677,25	25,00	108	377	4	2657,33	25,00	1632,33	**108**	**156**
7_lrc_20	5	3766,46	0,00	0,03	3	2469,89	7,86	36,9	138	3	**2426,65**	7,86	1418,79	**37**	**202**
8_lrc_20	5	3482,21	0,00	0,02	3	2132,47	9,26	155	388	3	**2114,31**	9,26	1105,04	**155**	**216**
										sum	**269098,24**	**387,02**	**76711,24**	**3509,00**	**5928,00**
										avg	**4805,33**	**6,91**	**1369,84**	**62,66**	**105,86**

angle_s_1_rr

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	actual cpu[sec]	total cpu[sec]
1_lc_10	12	10907,10	57,31	0	10	9828,94	0,00	6	218	10	**9828,94**	0,00	828,94	**6**	**20**
2_lc_10	12	11866,28	0,00	0	10	9831,73	0,00	13	389	10	**9828,94**	0,00	828,94	**13**	**18**
3_lc_10	12	12594,14	57,49	0	10	9938,60	0,00	16	450	10	**9937,38**	0,00	937,38	**16**	**18**
4_lc_10	11	11675,74	0,00	0	10	9973,53	0,00	20	482	10	**9964,51**	0,00	964,51	**20**	**21**
5_lc_10	12	11211,20	0,00	0	10	9828,94	0,00	1	46	10	**9828,94**	0,00	828,94	**2**	**21**
6_lc_10	12	11699,28	33,71	0	10	9838,93	0,00	5	165	10	**9828,94**	0,00	828,94	**5**	**19**
7_lc_10	13	11843,05	0,00	0	10	9828,94	0,00	4	155	10	**9828,94**	0,00	828,94	**4**	**19**
8_lc_10	12	11598,55	0,00	0	10	9826,44	0,00	11	321	10	**9826,44**	0,00	826,44	**11**	**20**
9_lc_10	11	10913,00	0,00	0	10	9828,94	0,00	15	390	10	**9828,94**	0,00	828,94	**15**	**20**
1_lc_20	5	15773,64	12,14	0	3	9591,56	0,00	131	403	3	**9591,56**	0,00	591,56	131	177
2_lc_20	5	13566,47	8,33	0	3	9815,87	23,47	166	463	3	9814,43	5,15	809,28	166	182
3_lc_20	5	13382,10	33,69	0	3	9892,12	11,49	154	454	3	9827,56	11,49	816,07	154	175
4_lc_20	4	12980,43	0,53	0	3	9974,49	1,64	169	460	3	9871,28	0,00	871,28	**169**	**189**
5_lc_20	5	12851,59	39,86	0	4	9891,94	114,73	12	44	4	9756,94	22,10	734,85	**12**	250
6_lc_20	4	12528,29	47,03	0	4	9713,99	63,34	121	341	4	9626,27	3,78	622,49	121	198
7_lc_20	5	12637,82	9,99	0	4	9735,71	0,00	94	265	4	9710,70	0,00	710,70	**94**	201
8_lc_20	4	12684,60	43,27	0	4	11345,05	43,27	3	15	4	11289,15	43,27	2245,88	**3**	**124**
1_lr_10	23	4170,77	34,36	0	23	4170,77	34,36	0	0	23	4170,77	34,36	3136,41	**0**	**9**
2_lr_10	21	3963,05	0,00	0	17	3117,71	4,72	1	37	17	**3117,71**	4,72	2112,99	**1**	**15**
3_lr_10	17	3553,03	1,07	0	13	2615,06	12,47	10	423	13	**2615,06**	12,47	1602,59	**10**	**12**
4_lr_10	15	3288,42	0,00	0	11	2202,71	0,00	1	70	11	2202,71	0,00	1202,71	**1**	**24**
5_lr_10	18	3267,86	0,00	0	14	2614,21	22,54	9	413	14	**2614,21**	22,54	1591,68	**9**	**11**
6_lr_10	16	3032,42	0,00	0	12	2409,48	0,10	4	219	12	**2406,94**	0,10	1406,84	**4**	**14**
7_lr_10	16	3366,13	0,00	0	10	2196,62	1,87	3	133	10	**2195,91**	1,87	1194,05	**3**	**20**
8_lr_10	15	3107,29	11,32	0	13	2358,11	0,00	0	29	13	2338,12	0,00	1338,12	**0**	**15**
9_lr_10	16	3067,70	0,00	0	15	2639,09	13,49	0	27	15	2620,56	13,49	1607,06	**0**	**16**
10_lr_10	16	3198,13	0,00	0	13	2374,19	6,54	11	469	13	2369,21	6,54	1362,68	**11**	**12**
11_lr_10	13	2619,59	0,00	0	11	2279,07	0,00	2	84	11	2255,73	0,00	1255,73	**2**	**18**
12_lr_10	15	3089,72	0,00	0	11	2144,65	1,24	12	368	11	2128,31	1,24	1127,07	**12**	**17**
1_lr_20	6	4913,75	25,79	0	5	3430,39	27,46	19	112	5	**3423,60**	27,46	2396,14	**19**	**156**
2_lr_20	5	4112,50	0,00	0	3	2588,29	6,58	124	396	3	**2588,29**	6,58	1581,71	**124**	**171**
3_lr_20	4	3832,93	0,00	0	3	2593,86	0,00	113	279	3	**2549,47**	20,24	1529,23	**113**	**227**
4_lr_20	4	3810,71	0,00	0	3	2238,59	0,00	140	292	3	2236,12	0,00	1236,12	**140**	**261**
5_lr_20	5	3756,04	55,00	0	3	2473,57	6,43	149	355	3	**2467,45**	6,43	1461,01	**149**	**222**
6_lr_20	5	3910,50	16,93	0	3	2389,16	0,00	172	423	3	**2384,31**	11,27	1373,04	**172**	**208**
7_lr_20	4	3248,68	0,00	0	3	2197,98	0,00	221	450	3	2158,82	0,00	1158,82	**221**	**256**
8_lr_20	4	3232,44	0,00	0	2	1816,45	3,33	375	490	2	**1789,68**	2,81	786,87	**375**	**385**
9_lr_20	5	3966,18	4,34	0	3	2328,92	0,83	163	388	3	**2323,92**	0,83	1323,09	**163**	**221**
10_lr_20	5	3999,99	0,00	0	3	2446,06	27,53	120	284	3	**2438,04**	0,00	1438,04	**120**	**241**
11_lr_20	4	3.063,12	0,00	0	3	2.061,38	0,00	211	479	3	2.039,60	0,00	1.039,60	**211**	**223**
1_lrc_10	18	3612,94	6,29	0	16	3256,61	6,29	0	5	16	3249,95	6,29	2243,66	**0**	**13**
2_lrc_10	16	3481,43	0,00	0	13	2745,31	0,00	1	68	13	**2744,60**	0,00	1744,60	**1**	**18**
3_lrc_10	16	3342,29	0,00	0	11	2428,07	0,00	5	213	11	**2421,57**	0,00	1421,57	**5**	**15**
4_lrc_10	14	3104,73	0,00	0	10	2235,44	0,00	4	150	10	**2234,45**	0,00	1234,45	**4**	**22**
5_lrc_10	17	3501,83	0,00	0	17	3501,83	0,00	0	0	17	3496,51	0,00	2496,51	**0**	**15**
6_lrc_10	16	3355,62	0,00	0	13	2653,79	0,00	2	86	13	2651,84	0,00	1651,84	**2**	**17**
7_lrc_10	16	3395,53	0,00	0	12	2397,83	0,00	6	260	12	2395,55	0,00	1395,55	**6**	**15**
8_lrc_10	16	3373,55	0,00	0	10	2272,14	0,00	3	121	10	**2238,27**	0,00	1238,27	**3**	**21**
1_lrc_20	6	4520,34	3,92	0	4	3276,14	26,41	50	248	4	**3276,14**	26,41	2249,73	**50**	**121**
2_lrc_20	6	4673,44	0,35	0	4	3040,75	12,44	21	95	4	2993,31	12,44	1980,87	**21**	**160**
3_lrc_20	5	4413,24	1,61	0	4	2861,16	3,71	73	267	4	2860,75	3,71	1857,04	**73**	**157**
4_lrc_20	4	3485,79	0,00	0	3	2387,34	0,00	205	500	3	**2357,76**	0,00	1357,76	**206**	**206**
5_lrc_20	6	4783,24	28,38	0	4	3270,04	33,56	18	114	4	**3259,95**	33,56	2226,39	**18**	**121**
6_lrc_20	5	3739,36	17,96	0	4	2677,25	25,00	107	377	4	2654,28	25,00	1629,28	**107**	**154**
7_lrc_20	5	3766,46	0,00	0	3	2469,89	7,86	36,9	138	3	**2358,99**	32,83	1326,16	**37**	**201**
8_lrc_20	5	3482,21	0,00	0	3	2132,47	9,26	154	388	3	**2103,89**	9,26	1094,62	**154**	**215**
										sum	**268922,21**	**408,25**	**76513,98**	**3489,11**	**5897,58**
										avg	**4802,18**	**7,29**	**1366,32**	**62,31**	**105,31**

SUMMARY OF AVERAGE VALUES OF RESULTS OBTAINED FROM MULTIPLE EXECUTIONS OF THE METHODS INITIALLY ORDERING CUSTOMERS USING THE SWEEP ALGORITHM WITH RANDOMLY CHOSEN STARTING POINT

angle_r_nCust_2opt

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	actual cpu[sec]	total cpu[sec]
1_lc_10	41,84	29030,65	414,12	0	10,74	10202,02	13,79	3	114	10,74	10202,02	13,79	1188,23	**3**	**23**
2_lc_10	40,57	26083,30	334,47	0	10,29	9952,72	2,68	11	335	10,29	9951,15	2,68	948,46	**11**	**19**
3_lc_10	40,05	23087,64	306,94	0	10,24	10032,93	1,44	11	337	10,24	**10006,74**	1,41	1005,33	**11**	**18**
4_lc_10	40,91	16860,35	208,52	0	10,00	9984,22	0,58	13	344	10,00	**9950,33**	0,58	949,75	**13**	**20**
5_lc_10	42,26	28570,46	414,54	0	10,14	9893,27	2,22	4	145	10,14	9893,27	2,22	891,05	**4**	**21**
6_lc_10	39,62	28038,34	425,90	0	10,05	9859,55	0,00	7	210	10,05	9856,02	0,00	856,02	**7**	**20**
7_lc_10	42,12	28186,44	336,50	0	10,13	9859,71	0,83	4	137	10,13	9859,71	0,83	858,87	**4**	**23**
8_lc_10	41,22	27012,46	388,59	0	10,06	9841,44	0,03	10	294	10,06	9838,79	0,00	838,79	**10**	**20**
9_lc_10	42,05	23656,18	289,01	0	10,00	9833,09	0,00	8	232	10,00	**9831,06**	0,00	831,06	**8**	**20**
1_lc_20	38,49	80145,52	1772,60	0	3,13	9891,31	9,18	22	148	3,13	9891,32	9,18	882,14	**22**	183
2_lc_20	38,52	72374,25	1348,63	0	3,84	10130,70	6,64	90	331	3,84	10099,44	6,69	1092,76	**90**	153
3_lc_20	38,79	61570,74	1248,36	0	3,61	10028,67	3,67	127	411	3,61	9957,14	3,43	953,70	**127**	166
4_lc_20	38,34	42902,75	1617,61	0	3,68	9969,77	0,42	121	406	3,68	9924,85	0,54	924,31	**121**	**159**
5_lc_20	40,15	77582,09	1634,96	0	3,69	10480,81	40,14	49	210	3,69	10427,31	36,33	1390,97	**49**	**165**
6_lc_20	39,32	75304,23	1592,61	0	3,94	10395,80	23,52	59	236	3,94	10337,25	21,16	1316,09	**59**	156
7_lc_20	39,66	69321,55	1431,68	0	3,49	10114,78	12,46	896	264	3,49	10073,32	11,56	1061,76	896	988
8_lc_20	39,89	70070,02	1471,81	0	3,76	10781,19	29,55	55	241	3,76	10764,94	29,47	1735,47	**55**	**126**
1_lr_10	45,30	7411,89	64,43	0	20,20	3713,23	25,14	1	80	20,20	3713,23	25,14	2688,09	**1**	**9**
2_lr_10	43,98	6717,22	54,86	0	17,50	3158,06	15,45	1	84	17,50	**3158,06**	15,45	2142,62	**1**	**12**
3_lr_10	44,89	6378,04	42,81	0	14,96	2826,31	9,89	2	132	14,96	2824,85	9,74	1815,12	**2**	**12**
4_lr_10	39,49	4872,54	11,48	0	11,02	2208,07	1,66	5	187	11,02	2204,61	1,78	1202,83	**5**	**19**
5_lr_10	43,31	6550,73	49,30	0	16,09	2869,98	10,70	2	137	16,09	2868,65	10,70	1857,95	**2**	**12**
6_lr_10	41,90	6291,74	48,08	0	12,95	2497,56	8,74	3	143	12,95	2495,00	8,74	1486,27	**3**	**14**
7_lr_10	39,58	5578,12	36,11	0	11,60	2332,43	3,49	6	247	11,60	2329,64	3,59	1326,05	**6**	**16**
8_lr_10	39,66	4787,75	19,85	0	12,71	2314,66	0,73	1	52	12,71	2309,79	1,08	1308,71	**1**	**17**
9_lr_10	42,55	5910,85	33,85	0	13,54	2522,96	8,38	2	104	13,54	2516,38	8,85	1507,53	**2**	**16**
10_lr_10	41,47	5318,85	37,56	0	12,59	2349,61	4,56	6	280	12,59	2346,45	4,56	1341,90	**6**	**13**
11_lr_10	41,65	5612,21	25,26	0	11,35	2291,77	5,21	8	291	11,35	2287,58	5,20	1282,38	**8**	**17**
12_lr_10	40,80	4625,78	12,22	0	10,63	2124,06	0,54	7	246	10,63	2119,54	0,61	1118,93	**7**	**20**
1_lr_20	38,10	21976,79	396,70	0	4,22	3253,29	33,92	58	300	4,22	**3247,05**	33,69	2213,36	**58**	**119**
2_lr_20	36,31	20604,97	461,16	0	3,92	2896,05	12,80	89	363	3,92	2890,09	13,19	1876,89	**89**	**139**
3_lr_20	37,80	16758,25	371,53	0	3,26	2511,35	3,88	138	363	3,26	**2502,16**	3,76	1498,39	**138**	**215**
4_lr_20	35,95	11754,08	209,49	0	3,00	2223,41	1,02	185	407	3,00	2215,63	1,69	1213,94	**185**	**241**
5_lr_20	35,68	18242,95	362,18	0	3,07	2500,80	10,18	124	357	3,07	**2493,13**	9,92	1483,21	**124**	**197**
6_lr_20	36,42	17942,40	367,37	0	3,00	2397,55	2,97	121	360	3,00	**2388,45**	3,04	1385,41	**121**	**188**
7_lr_20	36,96	14966,54	316,52	0	3,04	2231,32	1,91	178	390	3,04	2221,23	2,28	1218,95	**178**	**253**
8_lr_20	34,47	9697,42	159,81	0	2,62	1984,17	0,64	210	388	2,62	1972,99	0,93	972,06	**210**	**302**
9_lr_20	38,06	17890,44	340,29	0	3,09	2387,46	8,00	121	365	3,09	**2373,12**	8,54	1364,57	**121**	**186**
10_lr_20	38,77	18928,45	331,69	0	3,19	2506,77	5,17	154	403	3,19	**2496,90**	5,66	1491,25	**154**	**205**
11_lr_20	38,78	13967,38	232,44	0	5,12	2928,20	8,44	24	164	5,12	2927,50	8,67	1918,83	**24**	**86**
1_lrc_10	42,28	7001,39	66,06	0	18,37	3514,13	17,70	1	77	18,37	3510,58	17,63	2492,95	**1**	**11**
2_lrc_10	40,59	6434,03	57,99	0	14,25	2932,79	6,15	2	98	14,25	2931,95	6,20	1925,75	**2**	**15**
3_lrc_10	41,03	5883,15	54,24	0	12,29	2529,70	5,35	4	195	12,29	2522,09	5,36	1516,73	**4**	**15**
4_lrc_10	40,55	5417,63	20,75	0	10,22	2229,67	2,96	7	210	10,22	**2227,58**	3,05	1224,53	**7**	**21**
5_lrc_10	42,09	6715,36	56,98	0	16,77	3253,56	18,43	3	144	16,77	3252,43	18,43	2234,00	**3**	**13**
6_lrc_10	39,82	6018,29	53,76	0	14,34	2818,02	7,44	2	83	14,34	2814,10	7,44	1806,65	**2**	**16**
7_lrc_10	37,54	5221,30	23,28	0	13,21	2550,75	2,97	3	139	13,21	2540,20	3,08	1537,13	**3**	**17**
8_lrc_10	36,47	4713,73	26,67	0	12,96	2462,36	3,57	3	126	12,96	2452,04	3,72	1448,31	**3**	**18**
1_lrc_20	35,58	19782,41	348,35	0	4,47	3434,41	32,64	50	306	4,47	3425,30	32,64	2392,66	**50**	**102**
2_lrc_20	37,68	19883,85	394,84	0	4,01	3056,36	15,84	90	380	4,01	3041,91	16,48	2025,43	**90**	**131**
3_lrc_20	35,84	14360,53	371,62	0	3,71	2659,76	4,96	116	373	3,71	**2642,53**	4,29	1638,24	**116**	**172**
4_lrc_20	36,99	12373,54	316,87	0	3,27	2339,47	2,37	144	377	3,27	**2326,35**	2,45	1323,90	**144**	**210**
5_lrc_20	37,92	20461,01	444,96	0	4,24	3284,50	19,56	68	357	4,24	**3272,31**	19,46	2252,85	**68**	**109**
6_lrc_20	37,48	17991,51	313,00	0	4,00	2771,17	15,62	93	358	4,00	2759,43	15,58	1743,85	**93**	**145**
7_lrc_20	37,81	16627,36	254,81	0	3,62	2598,01	10,81	110	416	3,62	2578,49	11,51	1566,98	**110**	**142**
8_lrc_20	40,10	15129,26	241,81	0	6,09	3231,07	13,79	36	259	6,09	3222,85	14,41	2208,44	**36**	**66**
										sum	**275286,83**	**508,41**	**82778,40**	**3668,00**	**5791,00**
										avg	**4915,84**	**9,08**	**1478,19**	**65,50**	**103,41**

angle_r_nCust_rr

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	actual cpu[sec]	total cpu[sec]
1_lc_10	42,07	29079,14	439,56	0	10,54	10088,64	12,67	3	113	10,54	10088,65	12,67	1075,98	**3**	**23**
2_lc_10	40,85	26349,96	325,18	0	10,30	9968,74	3,71	10	318	10,30	9956,04	1,70	954,34	**10**	**19**
3_lc_10	40,40	23246,19	307,14	0	10,19	10019,70	1,99	11	344	10,19	**10008,31**	1,58	1006,73	**11**	**18**
4_lc_10	40,86	17025,16	183,15	0	10,00	9986,40	0,06	12	329	10,00	**9972,73**	0,06	972,67	**12**	**20**
5_lc_10	42,16	28532,07	401,64	0	10,19	9903,27	5,16	4	139	10,19	9890,04	3,32	886,72	**4**	**21**
6_lc_10	39,39	27933,39	378,56	0	10,05	9858,33	0,44	6	203	10,05	9854,39	0,44	853,95	**6**	**21**
7_lc_10	42,46	28258,88	386,99	0	10,17	9877,95	2,66	4	125	10,17	9874,79	2,65	872,13	**4**	**23**
8_lc_10	41,44	27169,94	362,94	0	10,08	9844,73	0,00	10	296	10,08	9839,81	0,00	839,81	**10**	**20**
9_lc_10	41,86	23575,24	280,65	0	10,00	9833,18	0,00	8	234	10,00	**9829,14**	0,00	829,14	**8**	**20**
1_lc_20	38,07	79496,45	1844,03	0	3,12	9822,85	13,51	27	164	3,12	9821,40	13,10	808,30	**27**	186
2_lc_20	38,55	72152,98	1413,51	0	3,73	10025,94	5,69	96	347	3,73	9967,85	4,73	963,12	96	158
3_lc_20	39,19	61568,31	1406,63	0	3,49	10026,56	4,04	126	405	3,49	9932,86	4,57	928,29	**126**	168
4_lc_20	38,34	42821,64	1697,43	0	3,74	9962,50	1,03	129	416	3,74	9903,18	0,98	902,20	**129**	**163**
5_lc_20	40,13	77411,30	1488,66	0	3,57	10395,78	36,16	58	228	3,57	10348,71	35,71	1313,00	**58**	**162**
6_lc_20	39,45	75304,21	1700,88	0	3,89	10379,78	25,05	69	267	3,89	10304,83	16,53	1288,30	**70**	160
7_lc_20	39,57	69080,84	1308,12	0	3,54	10162,76	10,51	70	268	3,54	10114,09	9,51	1104,58	**70**	160
8_lc_20	39,95	69762,17	1319,45	0	3,80	10836,36	30,89	60	250	3,80	10814,27	30,43	1783,84	**60**	**127**
1_lr_10	45,61	7451,45	73,33	0	20,00	3686,59	29,62	1	86	20,00	3686,59	29,62	2656,97	**1**	**9**
2_lr_10	44,06	6730,30	54,47	0	17,39	3147,88	14,52	1	67	17,39	**3147,88**	14,52	2133,36	**1**	**13**
3_lr_10	45,01	6398,49	41,41	0	14,74	2813,29	8,06	3	144	14,74	2811,73	7,78	1803,95	**3**	**12**
4_lr_10	39,46	4865,04	9,54	0	11,03	2222,11	1,32	4	157	11,03	2219,22	1,36	1217,86	**4**	**20**
5_lr_10	43,10	6533,91	56,16	0	16,08	2866,12	11,07	2	123	16,08	2864,42	11,08	1853,34	**2**	**12**
6_lr_10	42,09	6315,02	45,03	0	12,87	2489,39	6,86	3	141	12,87	2485,44	6,79	1478,65	**3**	**15**
7_lr_10	39,70	5600,17	26,24	0	11,41	2309,05	4,02	6	234	11,41	2305,18	3,70	1301,48	**6**	**16**
8_lr_10	39,48	4769,19	21,10	0	12,75	2315,94	0,24	1	52	12,75	2309,82	0,33	1309,49	**1**	**17**
9_lr_10	41,95	5847,08	33,68	0	13,38	2506,69	8,38	2	115	13,38	2491,12	8,43	1482,69	**2**	**16**
10_lr_10	41,46	5324,39	33,99	0	12,55	2341,45	5,88	6	264	12,55	2338,66	5,86	1332,79	**6**	**14**
11_lr_10	41,87	5635,30	28,76	0	11,06	2272,77	5,11	8	282	11,06	2267,21	5,13	1262,08	**8**	**18**
12_lr_10	40,68	4616,35	13,64	0	10,83	2137,20	0,49	6	220	10,83	2129,82	0,54	1129,29	**6**	**20**
1_lr_20	38,08	21968,96	400,59	0	4,16	3226,74	33,02	62	313	4,16	**3217,75**	32,97	2184,78	**62**	**121**
2_lr_20	36,22	20571,09	425,55	0	3,90	2883,52	11,59	98	391	3,90	2877,41	11,69	1865,72	**98**	**139**
3_lr_20	38,06	16883,89	343,01	0	3,24	2510,88	2,86	143	373	3,24	**2491,18**	2,71	1488,47	**143**	**215**
4_lr_20	35,87	11723,06	212,92	0	3,01	2229,66	1,15	177	392	3,01	2220,50	2,11	1218,40	**177**	**242**
5_lr_20	35,94	18297,75	337,16	0	3,09	2509,19	9,81	105	316	3,09	**2497,59**	9,11	1488,49	**105**	**201**
6_lr_20	36,23	17963,60	365,89	0	3,01	2401,39	4,50	128	374	3,01	**2389,70**	3,39	1386,30	**128**	**188**
7_lr_20	37,33	15024,70	294,26	0	3,03	2237,93	1,71	179	389	3,03	2217,18	1,92	1215,25	**179**	**252**
8_lr_20	34,68	9739,02	156,70	0	2,64	1975,85	0,95	220	398	2,64	1954,07	0,84	953,23	**221**	**302**
9_lr_20	38,28	17971,33	334,23	0	3,05	2366,06	7,80	130	388	3,05	**2344,57**	8,08	1336,49	**130**	**189**
10_lr_20	38,93	18997,36	325,15	0	3,14	2494,74	4,18	155	405	3,14	**2481,43**	4,31	1477,11	**155**	**206**
11_lr_20	38,80	14033,13	258,36	0	5,25	2980,44	9,73	15	135	5,25	2979,47	9,71	1969,76	**15**	**78**
1_lrc_10	42,38	7011,07	69,33	0	17,83	3438,49	16,09	1	73	17,83	3435,37	16,07	2419,30	**1**	**12**
2_lrc_10	40,40	6424,43	62,89	0	13,90	2903,26	8,88	2	103	13,90	2899,02	8,94	1890,08	**2**	**15**
3_lrc_10	41,16	5893,22	45,54	0	12,07	2516,18	3,69	5	195	12,07	2506,21	2,58	1503,64	**5**	**16**
4_lrc_10	40,57	5419,98	17,30	0	10,56	2256,05	2,31	7	210	10,56	2252,36	2,31	1250,05	**7**	**21**
5_lrc_10	42,22	6737,11	54,99	0	16,75	3252,02	16,88	3	141	16,75	3250,98	16,87	2234,11	**3**	**13**
6_lrc_10	39,78	6004,82	47,56	0	14,24	2804,83	7,89	1	80	14,24	2797,00	7,89	1789,11	**1**	**16**
7_lrc_10	37,32	5197,48	31,75	0	13,19	2540,51	3,45	3	146	13,19	2528,85	3,45	1525,39	**3**	**17**
8_lrc_10	36,35	4700,23	26,39	0	12,13	2396,84	3,99	4	155	12,13	2383,95	3,79	1380,16	**4**	**18**
1_lrc_20	35,67	19793,95	387,30	0	4,45	3422,48	27,55	51	306	4,45	3412,37	27,83	2384,54	**51**	**103**
2_lrc_20	37,55	19878,68	400,52	0	4,02	3080,07	19,80	89	383	4,02	3062,50	20,22	2042,28	**89**	**129**
3_lrc_20	35,92	14424,61	371,21	0	3,73	2653,51	4,35	118	384	3,73	**2630,91**	3,78	1627,13	**118**	**168**
4_lrc_20	37,36	12432,99	339,83	0	3,25	2336,05	2,22	140	366	3,25	**2315,22**	2,13	1313,09	**140**	**210**
5_lrc_20	38,02	20475,82	467,07	0	4,27	3281,72	15,76	68	358	4,27	**3264,73**	15,16	2249,58	**68**	**108**
6_lrc_20	37,57	17990,29	366,62	0	4,00	2769,18	17,00	95	365	4,00	2754,23	15,94	1738,28	**95**	**147**
7_lrc_20	38,01	16810,51	263,92	0	3,63	2598,41	10,08	103	390	3,63	2562,73	9,23	1553,50	**103**	**146**
8_lrc_20	39,94	15056,99	251,44	0	6,22	3263,79	11,93	32	254	6,22	3254,13	12,05	2242,08	**32**	**62**
										sum	**274559,59**	**488,20**	**82071,37**	**2882,00**	**4985,00**
										avg	**4902,85**	**8,72**	**1465,56**	**51,46**	**89,02**

angle_r_nVeh_2opt

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	actual cpu[sec]	total cpu[sec]
1_lc_10	20,31	16080,81	209,25	0	10,41	10019,70	9,87	3	96	10,41	10019,70	9,87	1009,84	**3**	**22**
2_lc_10	21,09	16087,17	135,72	0	10,32	9972,42	1,91	8	263	10,32	9970,86	1,89	968,98	**8**	**19**
3_lc_10	22,19	15996,86	144,64	0	10,07	9987,40	2,75	11	343	10,07	**9958,87**	2,45	956,42	**11**	**18**
4_lc_10	20,77	12481,53	108,48	0	10,00	9986,34	0,12	11	303	10,00	**9953,79**	0,12	953,67	**11**	**20**
5_lc_10	20,88	15976,29	207,14	0	10,04	9860,06	1,20	4	143	10,04	9860,07	1,20	858,87	**4**	**20**
6_lc_10	20,17	15864,16	192,12	0	10,11	9886,59	0,97	6	188	10,11	9883,30	0,62	882,69	**6**	**20**
7_lc_10	19,89	14889,61	170,46	0	10,04	9838,06	0,00	4	150	10,04	9838,06	0,00	838,06	**4**	**21**
8_lc_10	20,41	15538,90	167,45	0	10,07	9844,73	0,00	10	288	10,07	9840,63	0,00	840,63	**10**	**19**
9_lc_10	20,27	13952,06	84,70	0	10,00	9835,14	0,00	8	229	10,00	9834,82	0,00	834,82	**8**	**19**
1_lc_20	19,54	43101,99	1408,07	0	3,12	9848,79	9,93	22	137	3,12	9848,79	9,93	838,86	**22**	198
2_lc_20	19,07	37515,12	995,10	0	3,72	10015,56	4,68	94	327	3,72	9980,32	4,13	976,18	94	165
3_lc_20	19,71	34981,02	1097,15	0	3,69	10053,58	4,23	126	400	3,69	9979,19	4,01	975,19	**126**	169
4_lc_20	19,65	29742,41	1299,52	0	3,77	9976,03	0,74	129	420	3,77	9923,51	0,75	922,75	**129**	**161**
5_lc_20	20,27	39880,86	1166,71	0	3,59	10110,86	20,02	74	279	3,59	10066,72	16,50	1050,22	**74**	**170**
6_lc_20	20,19	40554,46	1031,29	0	3,91	10191,57	26,22	76	286	3,91	10120,86	22,79	1098,08	**76**	163
7_lc_20	20,11	36513,09	856,89	0	3,55	10074,12	15,00	74	274	3,55	10038,58	15,73	1022,84	**74**	170
8_lc_20	20,15	36666,34	965,42	0	3,58	10418,64	23,28	74	268	3,58	10391,55	22,44	1369,11	**74**	**145**
1_lr_10	31,95	5586,71	52,49	0	22,30	4039,39	30,82	0	33	22,30	4039,39	30,82	3008,56	**0**	**9**
2_lr_10	27,02	4741,92	31,13	0	18,17	3282,16	16,22	2	77	18,17	3282,10	16,22	2265,87	**2**	**13**
3_lr_10	29,41	4771,30	23,93	0	14,03	2739,33	9,42	3	134	14,03	2738,14	9,42	1728,73	**3**	**14**
4_lr_10	23,38	3575,83	5,33	0	11,33	2235,23	1,31	5	165	11,33	2232,33	1,33	1231,00	**5**	**19**
5_lr_10	26,44	4312,01	29,63	0	15,61	2824,84	13,44	1	75	15,61	2823,61	13,45	1810,15	**1**	**13**
6_lr_10	25,72	4306,28	25,48	0	13,38	2554,65	9,17	3	121	13,38	2552,51	9,13	1543,39	**3**	**15**
7_lr_10	24,91	3992,92	12,04	0	12,07	2389,81	2,42	5	191	12,07	2386,68	2,41	1384,26	**5**	**17**
8_lr_10	23,54	3502,78	8,74	0	12,50	2291,41	0,37	1	46	12,50	2283,83	0,22	1283,61	**1**	**18**
9_lr_10	24,40	3941,22	15,80	0	13,55	2521,93	6,90	2	99	13,55	2516,84	7,07	1509,77	**2**	**16**
10_lr_10	24,47	3612,32	10,07	0	12,73	2357,94	4,84	6	238	12,73	2353,96	4,80	1349,16	**6**	**14**
11_lr_10	24,10	3840,84	16,05	0	11,09	2282,48	5,27	8	265	11,09	2277,41	5,27	1272,14	**8**	**19**
12_lr_10	23,35	3295,39	2,88	0	10,87	2143,25	0,85	9	273	10,87	2138,72	1,09	1137,63	**9**	**19**
1_lr_20	21,93	14110,70	271,16	0	4,23	3262,36	32,54	59	288	4,23	**3255,27**	32,54	2222,73	**59**	**124**
2_lr_20	20,32	12984,73	305,75	0	3,91	2922,05	11,34	84	353	3,91	2914,31	11,24	1903,07	**84**	**136**
3_lr_20	20,92	12019,10	270,95	0	3,31	2498,37	2,82	138	365	3,31	**2488,43**	3,07	1485,36	**138**	**212**
4_lr_20	19,41	8752,77	160,82	0	3,00	2222,55	1,10	176	395	3,00	2212,35	1,49	1210,86	**176**	**240**
5_lr_20	19,92	11641,74	249,60	0	3,08	2505,14	8,46	110	320	3,08	**2496,83**	8,46	1488,37	**110**	**204**
6_lr_20	19,73	11301,67	216,96	0	3,01	2398,47	4,40	134	383	3,01	**2390,64**	4,76	1385,87	**134**	**190**
7_lr_20	19,97	10429,03	176,08	0	3,01	2244,59	1,30	182	399	3,01	2238,04	2,17	1235,87	**182**	**245**
8_lr_20	18,84	7424,26	152,89	0	2,57	1972,27	1,05	214	391	2,57	1961,60	1,10	960,51	**214**	**302**
9_lr_20	20,53	11162,78	242,99	0	3,11	2385,88	8,79	129	380	3,11	**2373,28**	8,73	1364,55	**129**	**188**
10_lr_20	22,26	12781,79	254,41	0	3,05	2474,27	5,39	152	394	3,05	**2461,09**	5,83	1455,26	**152**	**211**
11_lr_20	21,20	9064,82	158,23	0	4,40	2641,10	8,06	57	227	4,40	2638,92	7,95	1630,98	**57**	**124**
1_lrc_10	26,01	4737,02	50,00	0	17,86	3503,81	18,81	1	42	17,86	3499,81	18,81	2480,99	**1**	**12**
2_lrc_10	26,34	4609,19	36,56	0	14,32	2931,12	10,50	2	96	14,32	2930,28	10,60	1919,67	**2**	**15**
3_lrc_10	25,11	4203,35	31,87	0	11,97	2492,80	4,55	6	240	11,97	2488,06	4,55	1483,52	**6**	**15**
4_lrc_10	23,45	3707,70	9,23	0	10,66	2273,05	1,99	6	171	10,66	2270,53	2,13	1268,40	**6**	**22**
5_lrc_10	25,74	4606,37	29,77	0	18,06	3464,30	16,73	2	82	18,06	3463,79	16,73	2447,07	**2**	**13**
6_lrc_10	23,72	4084,01	27,10	0	14,02	2786,86	6,37	1	70	14,02	2782,37	6,37	1776,00	**1**	**16**
7_lrc_10	23,08	3700,45	21,25	0	13,26	2566,35	4,54	3	131	13,26	2554,87	4,41	1550,45	**3**	**17**
8_lrc_10	21,66	3343,12	17,65	0	11,49	2360,73	4,56	3	128	11,49	2344,10	4,78	1339,31	**3**	**18**
1_lrc_20	19,02	11629,32	264,95	0	4,48	3421,05	46,29	50	291	4,48	3411,38	46,14	2365,24	**50**	**106**
2_lrc_20	19,45	12485,28	254,16	0	4,00	3038,06	23,83	99	397	4,00	3026,56	24,28	2002,28	**99**	**135**
3_lrc_20	20,13	9830,04	266,79	0	3,94	2694,95	3,74	118	401	3,94	**2679,52**	4,30	1675,22	**118**	**157**
4_lrc_20	19,30	8414,37	253,89	0	3,21	2328,53	2,66	155	394	3,21	**2309,70**	3,24	1306,46	**155**	**212**
5_lrc_20	20,23	12885,88	300,65	0	4,16	3266,61	18,64	71	362	4,16	**3255,01**	19,22	2235,80	**71**	**110**
6_lrc_20	19,35	11265,09	267,47	0	4,00	2758,47	14,01	94	357	4,00	2747,75	14,83	1732,93	**94**	**150**
7_lrc_20	19,43	9827,67	164,31	0	3,71	2633,69	9,77	99	373	3,71	2613,07	9,93	1603,14	**100**	**146**
8_lrc_20	20,30	8724,24	163,67	0	5,66	3073,63	12,68	47	269	5,66	3064,58	12,77	2051,81	**47**	**81**
										sum	**274007,28**	**504,09**	**81503,20**	**2972,00**	**5106,00**
										avg	**4892,99**	**9,00**	**1455,41**	**53,07**	**91,18**

angle_r_nVeh_rr

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	actual cpu[sec]	total cpu[sec]
1_lc_10	20,24	16104,53	215,70	0	10,41	10033,25	15,13	2	83	10,41	10033,25	15,13	1018,13	**2**	**23**
2_lc_10	20,97	15899,31	149,93	0	10,34	9969,22	1,87	9	282	10,34	9960,57	1,29	959,28	**9**	**19**
3_lc_10	21,94	15808,32	102,34	0	10,06	9997,81	4,49	11	325	10,06	**9991,85**	3,36	988,50	**11**	**18**
4_lc_10	20,88	12545,33	95,14	0	10,00	9983,27	0,05	10	286	10,00	**9966,86**	0,05	966,81	**10**	**20**
5_lc_10	20,84	15956,32	182,91	0	10,06	9863,19	2,39	4	134	10,06	9848,84	1,02	847,82	**4**	**21**
6_lc_10	20,04	15970,71	190,61	0	10,04	9844,97	0,61	6	193	10,04	9841,17	0,00	841,17	**6**	**20**
7_lc_10	19,86	15001,36	113,61	0	10,08	9843,69	0,00	4	146	10,08	9842,41	0,00	842,41	**4**	**22**
8_lc_10	20,41	15492,72	106,10	0	10,05	9838,46	0,00	10	284	10,05	9833,88	0,00	833,88	**10**	**19**
9_lc_10	20,51	14194,74	122,76	0	10,00	9833,00	0,00	7	201	10,00	**9829,23**	0,00	829,23	**7**	**19**
1_lc_20	19,56	43098,07	1247,42	0	3,14	9839,32	13,55	25	147	3,14	9839,05	13,55	825,51	**25**	193
2_lc_20	19,00	36976,73	1100,08	0	3,59	9923,04	2,98	110	369	3,59	9855,46	3,53	851,94	110	167
3_lc_20	19,47	35047,52	946,69	0	3,66	10060,56	4,85	122	394	3,66	9960,20	5,92	954,28	**122**	168
4_lc_20	19,70	29640,92	1412,30	0	3,74	9962,16	1,08	130	417	3,74	9896,93	1,25	895,68	**130**	**163**
5_lc_20	20,03	39326,11	1177,35	0	3,54	10033,46	24,59	72	271	3,54	9969,26	18,30	950,96	**72**	**175**
6_lc_20	20,36	41122,92	1020,17	0	3,88	10408,44	26,68	74	277	3,88	10350,87	22,09	1328,78	**74**	152
7_lc_20	19,98	36374,78	1036,74	0	3,51	10035,37	10,09	78	282	3,51	9992,55	10,31	982,24	**78**	170
8_lc_20	20,21	36604,84	1176,12	0	3,66	10446,21	20,72	70	274	3,66	10417,98	20,68	1397,30	**70**	**138**
1_lr_10	32,42	5639,96	51,78	0	22,77	4105,60	31,26	0	33	22,77	4105,60	31,26	3074,34	**0**	**8**
2_lr_10	26,87	4721,20	31,92	0	17,97	3246,78	14,15	1	74	17,97	3246,78	14,15	2232,63	**1**	**12**
3_lr_10	29,40	4762,37	18,44	0	14,02	2740,06	8,96	3	156	14,02	2739,13	8,93	1730,21	**3**	**13**
4_lr_10	23,66	3594,52	6,13	0	11,44	2239,00	1,20	4	160	11,44	2236,59	1,09	1235,50	**4**	**19**
5_lr_10	26,42	4310,98	31,55	0	15,41	2800,19	12,18	1	74	15,41	2798,67	12,21	1786,47	**1**	**13**
6_lr_10	25,30	4249,88	23,17	0	12,87	2493,49	9,29	2	121	12,87	2490,14	9,26	1480,88	**2**	**15**
7_lr_10	24,78	4000,09	17,05	0	11,66	2345,15	2,59	5	192	11,66	2339,19	2,63	1336,56	**5**	**17**
8_lr_10	23,60	3510,33	9,76	0	12,32	2283,57	0,30	1	53	12,32	2269,62	0,61	1269,01	**1**	**17**
9_lr_10	24,50	3955,85	17,85	0	13,16	2479,66	6,70	2	108	13,16	2472,67	6,76	1465,90	**2**	**15**
10_lr_10	24,60	3636,48	12,17	0	12,77	2355,89	4,98	5	241	12,77	2351,08	4,94	1346,14	**5**	**14**
11_lr_10	24,14	3843,01	16,58	0	11,29	2290,81	5,42	8	269	11,29	2284,66	5,36	1279,31	**8**	**18**
12_lr_10	23,34	3293,88	1,76	0	10,59	2121,63	0,51	9	285	10,59	2112,69	0,55	1112,13	**9**	**19**
1_lr_20	21,96	14232,68	275,14	0	4,21	3258,64	30,89	62	301	4,21	**3250,00**	30,89	2219,11	**62**	**124**
2_lr_20	20,19	13030,87	311,24	0	4,02	2989,77	10,66	88	357	4,02	2982,18	10,68	1971,50	**88**	**137**
3_lr_20	21,17	12182,58	264,45	0	3,26	2493,20	2,75	139	359	3,26	**2478,56**	2,53	1476,02	**139**	**220**
4_lr_20	19,39	8767,77	190,77	0	2,97	2205,72	1,18	182	396	2,97	2194,99	1,54	1193,44	**182**	**248**
5_lr_20	20,16	11701,09	259,63	0	3,11	2514,94	9,09	116	331	3,11	**2503,01**	9,29	1493,71	**116**	**203**
6_lr_20	19,76	11296,26	244,24	0	3,05	2407,50	5,08	132	378	3,05	**2395,61**	5,15	1390,45	**132**	**191**
7_lr_20	20,04	10401,49	186,13	0	3,03	2235,91	1,52	187	402	3,03	2216,48	1,64	1214,84	**187**	**250**
8_lr_20	18,93	7414,00	162,11	0	2,65	1990,55	1,12	201	373	2,65	1972,28	1,26	971,02	**201**	**308**
9_lr_20	20,44	11135,04	226,45	0	3,10	2381,88	8,31	129	374	3,10	**2361,16**	7,51	1353,65	**129**	**193**
10_lr_20	22,56	12876,46	243,29	0	3,08	2476,80	5,53	147	386	3,08	**2461,03**	5,84	1455,19	**147**	**211**
11_lr_20	21,19	9069,56	172,21	0	4,46	2664,06	10,05	55	219	4,46	2657,92	9,68	1648,24	**55**	**129**
1_lrc_10	25,76	4719,62	43,13	0	18,10	3541,36	22,01	1	40	18,10	3539,53	22,00	2517,53	**1**	**12**
2_lrc_10	26,41	4600,46	33,62	0	14,48	2949,81	11,17	2	86	14,48	2947,46	11,28	1936,18	**2**	**15**
3_lrc_10	25,13	4196,80	33,91	0	11,94	2489,62	5,72	6	226	11,94	2482,17	3,35	1478,81	**6**	**16**
4_lrc_10	23,42	3703,85	6,45	0	10,47	2266,24	1,41	5	167	10,47	2258,97	1,66	1257,31	**5**	**23**
5_lrc_10	25,65	4579,92	30,23	0	17,01	3306,74	16,64	2	96	17,01	3305,76	16,75	2289,01	**2**	**14**
6_lrc_10	23,68	4077,62	24,28	0	14,30	2820,51	6,14	1	70	14,30	2814,35	6,00	1808,35	**1**	**16**
7_lrc_10	23,28	3728,91	23,26	0	13,09	2541,46	4,56	3	134	13,09	2529,72	4,49	1525,23	**3**	**17**
8_lrc_10	21,69	3343,40	15,18	0	11,47	2354,32	2,82	3	123	11,47	2332,89	2,83	1330,06	**3**	**18**
1_lrc_20	18,68	11517,56	224,21	0	4,47	3415,52	45,52	50	289	4,47	3406,55	44,33	2362,22	**50**	**106**
2_lrc_20	19,60	12520,25	326,42	0	3,99	3024,29	22,91	95	386	3,99	3004,51	20,71	1983,80	**95**	**135**
3_lrc_20	20,88	10082,09	318,66	0	3,87	2679,15	3,29	114	387	3,87	**2658,08**	3,96	1654,12	**114**	**160**
4_lrc_20	19,41	8347,15	258,90	0	3,31	2334,39	2,74	145	378	3,31	**2307,90**	2,37	1305,52	**145**	**209**
5_lrc_20	19,90	12818,71	270,55	0	4,15	3269,94	17,51	76	384	4,15	**3257,42**	18,09	2239,33	**76**	**110**
6_lrc_20	18,90	11164,23	247,73	0	4,01	2773,77	15,19	94	358	4,01	2757,90	12,63	1745,27	**94**	**148**
7_lrc_20	19,31	9797,94	180,71	0	3,70	2618,74	7,40	106	394	3,70	2585,34	6,57	1578,77	**106**	**146**
8_lrc_20	20,28	8686,01	154,05	0	5,62	3057,49	14,49	48	281	5,62	3045,30	13,08	2032,22	**48**	**81**
										sum	**273584,25**	**490,34**	**81093,90**	**2974,00**	**5127,00**
										avg	**4885,43**	**8,76**	**1448,11**	**53,11**	**91,55**

angle_r_1_2opt

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	actual cpu[sec]	total cpu[sec]
1_lc_10	11,34	10989,75	57,31	0	10,31	10010,42	0,00	4	148	10,31	10010,42	0,00	1010,42	**4**	**22**
2_lc_10	12,00	12348,52	0,00	0	11,13	10272,84	0,00	9	285	11,13	10272,66	0,00	1272,66	**9**	**19**
3_lc_10	11,19	12429,76	57,49	0	10,00	9966,18	0,00	15	408	10,00	**9958,09**	0,00	958,09	**15**	**19**
4_lc_10	10,82	11375,15	0,00	0	10,00	9987,60	0,00	20	478	10,00	**9978,64**	0,00	978,65	**20**	**22**
5_lc_10	11,00	11001,20	0,00	0	10,00	9828,94	0,00	1	31	10,00	**9828,94**	0,00	828,94	**1**	**21**
6_lc_10	13,00	12016,15	33,71	0	10,00	9839,69	0,00	8	229	10,00	9839,21	0,00	839,21	**8**	**20**
7_lc_10	12,63	11800,58	0,00	0	10,00	9828,94	0,00	3	117	10,00	**9828,94**	0,00	828,94	**3**	**21**
8_lc_10	12,00	11871,82	0,00	0	10,00	9829,70	0,00	7	211	10,00	9828,13	0,00	828,13	**7**	**20**
9_lc_10	11,08	11104,22	0,00	0	10,00	9836,70	0,00	14	355	10,00	9836,71	0,00	836,71	**14**	**20**
1_lc_20	5,00	15773,64	12,14	0	3,00	9591,56	0,00	132	403	3,00	**9591,56**	0,00	591,56	132	178
2_lc_20	5,00	13534,75	8,33	0	3,40	9899,18	11,74	132	386	3,40	9853,11	3,28	849,82	132	179
3_lc_20	5,00	13367,64	32,21	0	3,28	9972,32	17,61	134	401	3,28	9882,10	17,96	864,14	**135**	177
4_lc_20	4,00	13027,32	0,53	0	3,31	9933,00	0,96	169	453	3,31	9882,31	0,04	882,27	**169**	**191**
5_lc_20	5,00	12841,37	64,60	0	3,65	9778,02	44,24	33	102	3,65	9682,16	8,40	673,76	**33**	232
6_lc_20	4,30	12463,56	84,81	0	3,86	9702,09	45,01	110	311	3,86	9630,71	9,20	621,51	110	197
7_lc_20	4,95	12731,14	11,43	0	3,78	9788,85	11,26	75	220	3,78	9756,80	11,26	745,54	**75**	206
8_lc_20	4,67	12827,83	43,27	0	3,33	10189,95	14,28	72	211	3,33	10160,49	14,28	1146,21	**72**	**169**
1_lr_10	23,00	4170,77	34,36	0	23,00	4170,77	34,36	0	0	23,00	4170,77	34,36	3136,41	**0**	**9**
2_lr_10	21,00	3963,05	0,00	0	17,00	3117,71	4,72	1	37	17,00	**3117,71**	4,72	2112,99	**1**	**15**
3_lr_10	17,05	3555,17	1,07	0	13,00	2615,86	11,90	9	404	13,00	**2615,86**	11,90	1603,96	**9**	**12**
4_lr_10	15,00	3288,34	0,00	0	11,00	2196,35	0,00	3	109	11,00	2196,35	0,00	1196,35	**3**	**23**
5_lr_10	17,00	3103,03	0,00	0	15,00	2711,28	22,54	1	27	15,00	2711,28	22,54	1688,74	**1**	**16**
6_lr_10	16,00	3044,52	0,00	0	12,83	2519,57	0,08	3	166	12,83	2519,25	0,08	1519,17	**3**	**14**
7_lr_10	16,00	3363,88	0,00	0	10,14	2211,63	2,53	3	134	10,14	**2210,69**	2,53	1208,15	**3**	**20**
8_lr_10	14,70	3076,51	11,32	0	13,24	2416,27	0,00	0	24	13,24	2400,29	0,00	1400,29	**0**	**15**
9_lr_10	15,97	3064,97	0,00	0	14,94	2633,54	13,18	1	29	14,94	2618,10	13,87	1604,22	**1**	**16**
10_lr_10	15,98	3196,96	0,00	0	13,00	2374,84	6,42	10	461	13,00	2369,95	6,42	1363,53	**10**	**12**
11_lr_10	12,00	2542,62	0,00	0	11,00	2283,97	12,72	12	360	11,00	2281,30	12,72	1268,58	**12**	**18**
12_lr_10	15,00	3084,84	0,00	0	11,00	2153,94	0,85	9	310	11,00	2137,82	0,85	1136,97	**9**	**17**
1_lr_20	6,00	4913,75	25,79	0	5,00	3430,39	27,46	19	112	5,00	**3421,48**	27,46	2394,02	**19**	**156**
2_lr_20	5,00	4228,80	0,00	0	3,00	2605,43	10,07	135	405	3,00	**2602,15**	10,07	1592,08	**135**	**178**
3_lr_20	4,00	3829,87	0,00	0	3,00	2594,07	0,35	89	218	3,00	**2581,83**	13,37	1568,46	**89**	**240**
4_lr_20	4,00	3818,41	0,00	0	3,00	2210,05	0,32	174	357	3,00	2197,58	0,83	1196,75	**174**	**257**
5_lr_20	5,00	3836,43	55,00	0	3,00	2482,54	7,82	156	374	3,00	**2478,63**	7,82	1470,80	**156**	**220**
6_lr_20	5,00	3933,38	16,93	0	3,00	2398,91	4,34	163	412	3,00	**2393,34**	4,34	1389,00	**163**	**204**
7_lr_20	4,00	3351,59	0,00	0	3,00	2209,69	0,32	201	406	3,00	2195,23	0,86	1194,37	**201**	**269**
8_lr_20	4,00	3232,63	0,00	0	2,00	1909,15	0,17	202	290	2,00	1889,64	0,17	889,47	**202**	**419**
9_lr_20	5,00	3973,10	4,34	0	3,00	2338,03	10,08	169	401	3,00	**2334,49**	12,00	1322,49	**169**	**220**
10_lr_20	5,00	4049,35	0,00	0	3,00	2420,96	14,31	197	424	3,00	**2413,35**	13,16	1400,19	**197**	**241**
11_lr_20	4,00	3093,74	0,00	0	3,00	2111,80	1,16	1068	467	3,00	2101,60	1,16	1100,44	**1068**	**1088**
1_lrc_10	18,00	3612,94	6,29	0	16,00	3256,61	6,29	0	5	16,00	3245,99	6,29	2239,70	**0**	**14**
2_lrc_10	16,20	3502,60	0,80	0	13,20	2795,78	0,00	1	36	13,20	2794,24	0,00	1794,24	**1**	**19**
3_lrc_10	16,00	3342,29	0,00	0	11,08	2430,71	0,00	5	213	11,08	**2424,98**	0,00	1424,98	**5**	**15**
4_lrc_10	14,58	3278,81	0,00	0	10,00	2252,50	0,00	3	105	10,00	2241,45	0,00	1241,45	**3**	**24**
5_lrc_10	17,00	3470,64	0,00	0	17,00	3470,64	0,00	0	0	17,00	3467,77	0,00	2467,77	**0**	**15**
6_lrc_10	16,00	3355,62	0,00	0	12,97	2650,39	0,02	2	88	12,97	2648,48	0,02	1648,46	**2**	**18**
7_lrc_10	16,52	3465,03	0,00	0	12,20	2442,53	0,00	6	227	12,20	2435,78	0,00	1435,78	**6**	**16**
8_lrc_10	16,47	3481,76	0,00	0	11,87	2408,00	0,00	2	84	11,87	2376,64	0,00	1376,64	**2**	**19**
1_lrc_20	6,00	4576,81	3,92	0	4,31	3380,63	42,83	58	301	4,31	3368,65	32,07	2336,58	**58**	**115**
2_lrc_20	6,00	4680,98	2,45	0	4,00	3025,76	12,27	84	313	4,00	2985,67	12,27	1973,40	**84**	**149**
3_lrc_20	5,00	4374,74	1,61	0	4,00	2696,17	0,81	75	240	4,00	**2687,09**	2,78	1684,31	**75**	**169**
4_lrc_20	4,01	3457,28	0,00	0	3,01	2355,82	0,91	218	485	3,01	**2335,96**	1,62	1334,34	**218**	**227**
5_lrc_20	6,00	4783,24	28,38	0	4,00	3270,04	33,56	18	114	4,00	**3259,95**	33,56	2226,39	**18**	**122**
6_lrc_20	5,17	3904,91	22,75	0	4,00	2776,79	17,86	123	419	4,00	2760,87	18,85	1742,01	**123**	**154**
7_lrc_20	5,02	3847,38	0,79	0	3,39	2528,36	3,54	110	318	3,39	2496,99	11,74	1485,25	**110**	**203**
8_lrc_20	5,00	3433,89	0,00	0	3,00	2146,01	6,91	164	397	3,00	**2129,63**	6,86	1122,77	**164**	**221**
										sum	**269439,81**	**391,71**	**77048,06**	**4433,00**	**6892,00**
										avg	**4811,43**	**6,99**	**1375,86**	**79,16**	**123,07**

angle_r_1_rr

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	actual cpu[sec]	total cpu[sec]
1_lc_10	11,40	11015,37	57,31	0	10,39	10057,25	0,00	4	137	10,39	10057,25	0,00	1057,25	**4**	**22**
2_lc_10	12,00	12350,61	0,00	0	11,22	10321,37	0,00	9	288	11,22	10320,45	0,00	1320,45	**9**	**18**
3_lc_10	11,16	12423,53	57,49	0	10,00	9966,41	0,00	15	409	10,00	**9965,70**	0,00	965,70	**15**	**19**
4_lc_10	10,81	11377,78	0,00	0	10,00	9987,66	0,00	20	477	10,00	**9980,05**	0,00	980,05	**20**	**21**
5_lc_10	11,00	11003,77	0,00	0	10,00	9828,94	0,00	1	31	10,00	**9828,94**	0,00	828,94	**1**	**21**
6_lc_10	13,00	12019,22	33,71	0	10,00	9838,93	0,00	6	189	10,00	**9828,94**	0,00	828,94	**6**	**20**
7_lc_10	12,59	11796,54	0,00	0	10,00	9828,94	0,00	3	117	10,00	**9828,94**	0,00	828,94	**3**	**21**
8_lc_10	12,00	11882,71	0,00	0	10,00	9830,01	0,00	7	210	10,00	9828,28	0,00	828,28	**7**	**20**
9_lc_10	11,04	11067,25	0,00	0	10,00	9838,15	0,00	13	354	10,00	**9828,94**	0,00	828,94	**13**	**20**
1_lc_20	5,00	15773,64	12,14	0	3,00	9591,56	0,00	134	403	3,00	**9591,56**	0,00	591,56	134	180
2_lc_20	5,00	13536,65	8,33	0	3,38	9894,51	12,44	135	389	3,38	9845,27	3,62	841,65	135	181
3_lc_20	5,00	13370,39	32,58	0	3,26	9966,86	17,48	136	403	3,26	9887,71	17,56	870,15	**136**	178
4_lc_20	4,00	13023,90	0,53	0	3,30	9938,05	0,93	171	456	3,30	9851,89	0,08	851,81	**171**	**192**
5_lc_20	5,00	12841,36	58,75	0	3,69	9801,77	53,88	37	113	3,69	9696,71	10,16	686,54	**37**	236
6_lc_20	4,22	12458,38	72,21	0	3,92	9710,74	47,29	103	294	3,92	9623,25	3,48	619,77	103	198
7_lc_20	4,95	12737,93	11,39	0	3,76	9771,31	9,27	78	225	3,76	9734,71	9,27	725,44	**78**	206
8_lc_20	4,66	12826,81	43,27	0	3,34	10207,92	14,71	71	206	3,34	10177,19	14,71	1162,48	**71**	**170**
1_lr_10	23,00	4170,77	34,36	0	23,00	4170,77	34,36	0	0	23,00	4170,77	34,36	3136,41	**0**	**9**
2_lr_10	21,00	3963,05	0,00	0	17,00	3117,71	4,72	1	37	17,00	**3117,71**	4,72	2112,99	**1**	**16**
3_lr_10	17,14	3559,02	1,07	0	13,00	2617,53	10,87	8	369	13,00	**2617,53**	10,87	1606,66	**8**	**12**
4_lr_10	15,00	3288,36	0,00	0	11,00	2198,47	0,00	2	96	11,00	2198,47	0,00	1198,47	**2**	**23**
5_lr_10	17,00	3103,03	0,00	0	15,00	2711,28	22,54	1	27	15,00	2711,28	22,54	1688,74	**1**	**16**
6_lr_10	16,00	3051,04	0,00	0	13,19	2558,33	0,06	3	141	13,19	2556,78	0,06	1556,72	**3**	**14**
7_lr_10	16,00	3362,57	0,00	0	10,22	2220,13	2,91	3	133	10,22	**2217,24**	2,91	1214,32	**3**	**20**
8_lr_10	14,83	3089,25	11,32	0	13,07	2381,69	0,00	0	27	13,07	2363,06	0,00	1363,06	**0**	**15**
9_lr_10	15,98	3065,88	0,00	0	14,96	2635,39	13,28	1	28	14,96	2617,23	13,28	1603,95	**1**	**16**
10_lr_10	15,99	3197,39	0,00	0	13,01	2375,59	6,48	11	465	13,01	2370,60	6,48	1364,12	**11**	**12**
11_lr_10	12,00	2542,62	0,00	0	11,00	2283,97	12,72	12	360	11,00	2264,44	12,72	1251,72	**12**	**18**
12_lr_10	15,00	3083,08	0,00	0	11,00	2157,09	0,72	9	291	11,00	2136,61	0,72	1135,89	**9**	**18**
1_lr_20	6,00	4913,75	25,79	0	5,00	3430,39	27,46	19	112	5,00	**3423,60**	27,46	2396,14	**19**	**156**
2_lr_20	5,00	4206,53	0,00	0	3,00	2602,15	9,40	133	404	3,00	**2599,49**	9,40	1590,09	**133**	**177**
3_lr_20	4,00	3830,18	0,00	0	3,00	2594,04	0,31	92	224	3,00	**2564,70**	13,27	1551,44	**92**	**239**
4_lr_20	4,00	3817,67	0,00	0	3,00	2216,34	0,32	179	362	3,00	2205,90	0,34	1205,56	**180**	**260**
5_lr_20	5,00	3856,40	55,00	0	3,00	2485,72	7,51	152	366	3,00	**2477,48**	6,39	1471,09	**152**	**220**
6_lr_20	5,00	3929,61	16,93	0	3,00	2397,52	2,99	162	407	3,00	**2388,34**	9,40	1378,94	**162**	**205**
7_lr_20	4,00	3359,30	0,00	0	3,00	2207,29	0,47	186	377	3,00	2176,07	0,47	1175,60	**186**	**279**
8_lr_20	4,00	3232,61	0,00	0	2,00	1902,70	0,27	211	299	2,00	**1850,54**	0,23	850,32	**211**	**419**
9_lr_20	5,00	3972,29	4,34	0	3,00	2338,35	11,50	177	416	3,00	**2331,21**	11,61	1319,60	**177**	**220**
10_lr_20	5,00	4041,96	0,00	0	3,00	2423,90	13,31	190	412	3,00	**2406,01**	5,18	1400,83	**190**	**241**
11_lr_20	4,00	3088,90	0,00	0	3,00	2104,95	1,03	210	470	3,00	2075,03	1,03	1074,01	**210**	**226**
1_lrc_10	18,00	3612,94	6,29	0	16,00	3256,61	6,29	0	5	16,00	3249,95	6,29	2243,66	**0**	**13**
2_lrc_10	16,12	3494,13	0,48	0	13,12	2787,14	0,00	1	35	13,12	2784,82	0,00	1784,82	**1**	**18**
3_lrc_10	16,00	3342,29	0,00	0	11,01	2428,47	0,00	5	211	11,01	**2421,97**	0,00	1421,97	**5**	**15**
4_lrc_10	14,42	3232,99	0,00	0	10,00	2245,29	0,00	3	113	10,00	**2233,70**	0,00	1233,70	**3**	**23**
5_lrc_10	17,00	3470,64	0,00	0	17,00	3470,64	0,00	0	0	17,00	3465,32	0,00	2465,32	**0**	**15**
6_lrc_10	16,00	3355,62	0,00	0	13,00	2653,79	0,00	2	86	13,00	2651,84	0,00	1651,84	**2**	**17**
7_lrc_10	16,65	3495,73	0,00	0	12,10	2440,29	0,00	6	255	12,10	2431,55	0,00	1431,55	**6**	**15**
8_lrc_10	16,60	3511,60	0,00	0	12,45	2450,34	0,00	2	74	12,45	2426,64	0,00	1426,64	**2**	**18**
1_lrc_20	6,00	4562,24	3,92	0	4,23	3353,66	38,59	57	287	4,23	**3352,82**	38,59	3314,23	**57**	**118**
2_lrc_20	6,00	4682,48	3,49	0	4,00	3024,22	11,59	73	274	4,00	2985,12	11,59	2973,53	**73**	**153**
3_lrc_20	5,00	4377,55	1,61	0	4,00	2724,21	1,07	61	205	4,00	2716,80	1,07	2715,73	**61**	**167**
4_lrc_20	4,02	3458,59	0,00	0	3,02	2352,18	0,83	223	489	3,02	**2325,06**	1,15	2323,91	**223**	**229**
5_lrc_20	6,00	4783,24	28,38	0	4,00	3270,04	33,56	18	114	4,00	**3259,95**	33,56	3226,39	**18**	**123**
6_lrc_20	5,08	3862,26	20,73	0	4,00	2772,88	17,94	123	417	4,00	2748,86	17,95	2730,91	**123**	**155**
7_lrc_20	5,01	3826,75	0,63	0	3,44	2547,51	2,99	96	283	3,44	2501,45	10,46	2490,99	**96**	**208**
8_lrc_20	5,00	3445,47	0,00	0	3,00	2141,74	7,60	164	397	3,00	**2114,50**	7,57	2106,93	**164**	**222**
										sum	**269386,22**	**380,55**	**85005,68**	**3540,00**	**6063,00**
										avg	**4810,47**	**6,80**	**1517,96**	**63,21**	**108,27**

SUMMARY OF THE BEST VALUES OF RESULTS OBTAINED FROM MULTIPLE EXECUTIONS OF THE METHODS INITIALLY ORDERING CUSTOMERS USING THE SWEEP ALGORITHM WITH RANDOMLY CHOSEN STARTING POINT

angle_r_nCust_2opt

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	best cpu[sec]	total cpu[sec]
1_lc_10	45	30015,48	608,95	0	10	9828,94	0,00	1	45	10	**9828,94**	0,00	828,94	**1**	**25**
2_lc_10	41	26715,85	134,03	0	10	9828,94	0,00	6	216	10	**9828,94**	0,00	828,94	**6**	**19**
3_lc_10	42	23950,07	153,87	0	10	9931,33	0,00	11	326	10	**9914,76**	0,00	914,76	**11**	**19**
4_lc_10	41	16654,73	0,00	0	10	9942,61	0,00	20	488	10	**9909,73**	0,00	909,73	**20**	**21**
5_lc_10	39	27290,99	226,30	0	10	9828,94	0,00	2	72	10	**9828,94**	0,00	828,94	**2**	**20**
6_lc_10	40	28582,23	347,21	0	10	9828,94	0,00	1	62	10	**9828,94**	0,00	828,94	**1**	**21**
7_lc_10	43	28629,40	369,00	0	10	9828,94	0,00	1	59	10	**9828,94**	0,00	828,94	**1**	**26**
8_lc_10	44	28889,91	226,94	0	10	9826,44	0,00	2	88	10	**9826,44**	0,00	826,44	**2**	**20**
9_lc_10	41	23225,81	91,88	0	10	9830,94	0,00	1	49	10	**9828,94**	0,00	828,94	**1**	**20**
1_lc_20	39	82489,00	2654,79	0	3	9591,56	0,00	11	86	3	**9591,56**	0,00	591,56	**11**	226
2_lc_20	38	72018,76	2355,64	0	3	9785,71	0,00	139	445	3	9753,83	0,00	753,83	139	163
3_lc_20	36	56629,76	880,16	0	3	9749,60	7,03	113	395	3	9731,79	7,03	724,76	**113**	163
4_lc_20	38	40754,68	2179,94	0	3	9772,71	2,55	136	422	3	9711,08	0,00	711,08	**136**	**173**
5_lc_20	39	76095,62	2778,47	0	3	9595,19	0,00	28	147	3	**9588,88**	0,00	588,88	**28**	195
6_lc_20	38	70735,92	2356,48	0	3	9591,17	0,00	85	297	3	**9588,49**	0,00	588,49	**85**	177
7_lc_20	35	63208,57	108,38	0	3	9602,66	0,00	58	240	3	**9588,32**	0,00	588,32	**58**	179
8_lc_20	38	67450,21	2127,24	0	3	9646,94	0,00	79	271	3	**9595,99**	0,00	595,99	**79**	184
1_lr_10	46	7495,84	152,66	0	19	3558,56	32,49	1	50	19	**3558,56**	32,49	2526,07	**1**	**10**
2_lr_10	41	6430,60	38,20	0	17	3091,81	9,53	1	37	17	**3091,81**	9,53	2082,28	**1**	**13**
3_lr_10	46	6521,07	14,21	0	13	2617,42	5,50	8	397	13	**2617,42**	5,50	1611,92	**8**	**11**
4_lr_10	40	4953,01	0,00	0	10	2095,50	0,00	6	226	10	2095,50	0,00	1095,50	**6**	**18**
5_lr_10	43	6443,78	16,48	0	14	2622,14	4,18	2	116	14	**2614,21**	4,18	1610,03	**2**	**11**
6_lr_10	41	6277,88	41,63	0	12	2402,19	0,00	2	110	12	**2390,19**	0,00	1390,19	**2**	**17**
7_lr_10	39	5538,38	57,02	0	10	2179,40	0,00	15	497	10	**2178,69**	0,00	1178,69	**15**	**15**
8_lr_10	38	4679,45	0,00	0	10	2101,97	0,00	2	102	10	2093,94	0,00	1093,94	**2**	**19**
9_lr_10	43	5926,95	23,50	0	11	2285,38	6,02	3	142	11	**2282,20**	6,02	1276,18	**3**	**18**
10_lr_10	43	5438,27	0,00	0	11	2265,12	18,97	13	448	11	2263,58	18,97	1244,61	**13**	**15**
11_lr_10	42	5621,28	16,90	0	10	2194,15	0,00	13	398	10	**2186,63**	0,00	1186,63	**13**	**18**
12_lr_10	43	4794,86	0,00	0	9	2019,60	0,00	4	166	9	2017,98	0,00	1017,98	**4**	**25**
1_lr_20	39	22695,26	308,54	0	4	3068,97	31,38	55	287	4	**3053,08**	31,38	2021,70	**55**	**123**
2_lr_20	35	19593,24	328,54	0	3	2588,29	3,54	113	370	3	**2588,29**	3,54	1584,75	**113**	**173**
3_lr_20	38	16381,30	746,36	0	3	2369,94	1,07	186	475	3	**2369,94**	1,07	1368,87	**186**	**201**
4_lr_20	36	11957,76	127,85	0	2	1980,93	3,08	128	301	2	**1961,11**	3,08	958,03	**128**	**324**
5_lr_20	35	17805,74	102,33	0	3	2441,49	0,61	158	416	3	**2427,05**	0,61	1426,44	**158**	**203**
6_lr_20	40	18754,46	314,98	0	3	2331,54	0,00	144	394	3	**2305,44**	0,00	1305,44	**144**	**203**
7_lr_20	39	14347,63	248,26	0	3	2024,80	6,01	140	270	3	2001,94	6,01	995,93	**140**	**397**
8_lr_20	35	9653,64	25,86	0	2	1799,78	0,00	359	484	2	**1793,35**	2,66	790,69	**359**	**375**
9_lr_20	38	17076,96	322,49	0	3	2321,75	0,96	105	319	3	**2302,36**	0,96	1301,40	**105**	**197**
10_lr_20	37	18943,01	405,45	0	3	2405,79	0,00	148	379	3	**2379,16**	1,97	1377,19	**148**	**217**
11_lr_20	37	12937,86	448,90	0	3	2061,58	0,00	157	426	3	2044,72	0,56	1044,16	**157**	**206**
1_lrc_10	43	7123,23	54,68	0	14	2963,58	31,78	1	84	14	**2955,98**	31,78	1924,20	**1**	**13**
2_lrc_10	38	6085,71	91,15	0	12	2676,30	6,37	1	62	12	**2676,29**	6,37	1669,92	**1**	**18**
3_lrc_10	40	5768,14	0,00	0	11	2397,82	0,00	10	377	11	**2397,82**	0,00	1397,82	**10**	**14**
4_lrc_10	39	5176,64	80,61	0	10	2198,85	8,30	2	91	10	**2198,31**	8,30	1190,01	**2**	**20**
5_lrc_10	40	6481,21	61,19	0	13	2851,32	0,43	3	158	13	2851,32	0,43	1850,89	**3**	**15**
6_lrc_10	42	6406,85	113,07	0	12	2531,47	4,19	4	187	12	2525,36	4,19	1521,17	**4**	**14**
7_lrc_10	37	5213,55	25,71	0	11	2384,08	10,19	13	447	11	2377,77	10,19	1367,58	**13**	**15**
8_lrc_10	34	4405,92	48,00	0	10	2230,83	0,00	13	459	10	**2226,81**	0,00	1226,81	**13**	**15**
1_lrc_20	36	19447,26	100,29	0	4	3245,84	9,88	58	337	4	**3240,57**	9,88	2230,69	**58**	**102**
2_lrc_20	38	20090,91	303,52	0	4	2762,91	0,00	94	357	4	2758,40	0,00	1758,40	**94**	**150**
3_lrc_20	34	14272,44	344,60	0	3	2437,82	4,82	166	416	3	**2435,55**	4,82	1430,73	**166**	**211**
4_lrc_20	38	12717,26	506,12	0	3	2195,03	0,15	189	463	3	**2153,89**	0,15	1153,74	**189**	**209**
5_lrc_20	36	18978,68	771,69	0	4	3130,47	4,50	58	310	4	**3113,04**	4,50	2108,54	**58**	**113**
6_lrc_20	38	18425,95	195,38	0	3	2452,63	10,33	27	153	3	2452,63	10,33	1442,30	**27**	**162**
7_lrc_20	34	15090,79	201,00	0	3	2345,02	63,10	64	291	3	**2342,59**	63,10	1279,49	**64**	**171**
8_lrc_20	41	15577,25	95,71	0	3	2131,33	0,00	91	314	3	**2124,69**	1,18	1123,51	**91**	**197**
										sum	**261222,68**	**290,78**	**68931,90**	**3251,00**	**5899,00**
										avg	**4664,69**	**5,19**	**1230,93**	**58,05**	**105,34**

angle_r_nCust_rr

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	best cpu[sec]	total cpu[sec]
1_lc_10	42	29121,17	339,92	0	10	9828,94	0,00	1	44	10	**9828,94**	0,00	828,94	**1**	**25**
2_lc_10	42	26539,27	337,64	0	10	9831,73	0,00	4	159	10	**9828,94**	0,00	828,94	**4**	**19**
3_lc_10	40	22583,40	230,39	0	10	9951,04	0,00	16	429	10	**9934,70**	0,00	934,70	**16**	**19**
4_lc_10	43	17605,73	0,00	0	10	9933,87	0,00	17	441	10	**9932,05**	0,00	932,05	**17**	**20**
5_lc_10	39	26640,82	139,23	0	10	9848,93	0,00	1	51	10	**9828,94**	0,00	828,94	**1**	**23**
6_lc_10	38	27016,69	511,69	0	10	9828,94	0,00	1	65	10	**9828,94**	0,00	828,94	**1**	**20**
7_lc_10	43	28502,72	177,28	0	10	9838,59	0,00	1	47	10	**9828,94**	0,00	828,94	**1**	**22**
8_lc_10	40	26430,12	162,12	0	10	9834,46	0,00	2	94	10	**9826,44**	0,00	826,44	**2**	**20**
9_lc_10	43	24676,15	92,28	0	10	9830,94	0,00	1	54	10	**9828,94**	0,00	828,94	**1**	**20**
1_lc_20	36	76399,14	1972,64	0	3	9591,56	0,00	11	97	3	**9591,56**	0,00	591,56	**11**	218
2_lc_20	39	73150,77	1149,79	0	3	9841,70	14,40	46	212	3	9729,69	14,40	715,29	**46**	176
3_lc_20	36	60470,70	1126,57	0	3	9908,71	9,79	150	487	3	9729,53	9,80	719,73	151	157
4_lc_20	39	45260,45	2577,68	0	3	9748,90	0,00	128	384	3	9689,95	6,01	683,94	**128**	**176**
5_lc_20	38	74909,09	542,19	0	3	9636,66	0,00	25	156	3	**9588,88**	0,00	588,88	**25**	**167**
6_lc_20	38	72985,93	996,18	0	3	9609,77	0,00	92	323	3	**9588,49**	0,00	588,49	92	173
7_lc_20	35	63208,57	108,38	0	3	9602,66	0,00	58	240	3	**9588,32**	0,00	588,32	**58**	180
8_lc_20	43	74659,82	512,52	0	3	9624,22	0,00	54	217	3	**9595,99**	0,00	595,99	**54**	181
1_lr_10	46	7507,23	81,15	0	19	3558,56	45,50	1	54	19	**3558,56**	45,50	2513,06	**1**	**9**
2_lr_10	45	6848,74	38,99	0	17	3091,81	7,87	0	37	17	**3091,81**	7,87	2083,94	**0**	**14**
3_lr_10	44	6315,40	0,20	0	13	2630,00	7,54	5	273	13	**2629,27**	7,54	1621,73	**5**	**12**
4_lr_10	41	5014,55	0,00	0	10	2095,50	0,00	10	315	10	2095,50	0,00	1095,50	**10**	**18**
5_lr_10	44	6593,10	25,08	0	14	2615,59	14,13	1	83	14	**2614,21**	14,13	1600,08	**1**	**11**
6_lr_10	43	6401,60	35,73	0	12	2390,63	2,55	1	89	12	**2390,19**	2,55	1387,64	**1**	**16**
7_lr_10	40	5670,98	0,00	0	10	2183,15	0,00	15	494	10	**2178,69**	0,00	1178,69	**15**	**15**
8_lr_10	38	4679,45	0,00	0	10	2101,97	0,00	2	102	10	2091,89	0,00	1091,89	**2**	**19**
9_lr_10	43	5926,95	18,28	0	11	2285,38	0,00	3	142	11	**2282,20**	0,00	1282,20	**3**	**18**
10_lr_10	41	5282,65	11,46	0	12	2290,07	13,69	6	301	12	2290,07	13,69	1276,38	**6**	**13**
11_lr_10	45	5898,27	16,90	0	10	2189,75	0,00	4	187	10	**2186,63**	0,00	1186,63	**4**	**22**
12_lr_10	40	4550,30	0,00	0	9	2017,85	1,24	6	224	9	2013,60	1,24	1012,36	**6**	**23**
1_lr_20	39	22209,16	790,75	0	4	3098,53	60,20	108	432	4	**3073,06**	60,20	2012,86	**108**	**131**
2_lr_20	38	21260,12	402,36	0	3	2591,74	8,32	89	357	3	**2591,74**	8,32	1583,42	**89**	**155**
3_lr_20	39	16163,29	137,50	0	3	2398,42	9,93	229	476	3	**2325,81**	9,93	1315,88	**229**	**245**
4_lr_20	34	11833,25	58,96	0	2	1967,54	0,00	152	327	2	**1954,12**	3,26	950,86	**152**	**323**
5_lr_20	38	19056,17	219,24	0	3	2472,98	58,68	115	332	3	**2472,98**	58,68	1414,30	**115**	**204**
6_lr_20	32	16642,68	260,55	0	3	2326,44	0,88	180	447	3	**2315,72**	0,88	1314,84	**180**	**209**
7_lr_20	36	14886,03	183,14	0	3	2028,74	0,00	238	442	3	1991,89	0,00	991,89	**238**	**303**
8_lr_20	36	10045,57	212,74	0	2	1796,58	2,53	340	478	2	**1793,46**	2,53	790,93	**340**	**362**
9_lr_20	37	17771,22	192,85	0	3	2292,13	10,79	142	402	3	**2285,56**	10,79	1274,77	**142**	**200**
10_lr_20	39	18832,70	172,44	0	3	2405,62	14,14	213	474	3	**2386,91**	14,14	1372,77	**213**	**228**
11_lr_20	35	12441,04	153,26	0	3	2043,31	5,62	115	325	3	2043,31	5,62	1037,69	**115**	**219**
1_lrc_10	42	6912,37	82,18	0	14	2959,93	2,93	3	194	14	2959,93	2,93	1957,00	**3**	**12**
2_lrc_10	42	6642,43	50,53	0	12	2683,84	3,23	3	170	12	**2676,29**	3,23	1673,06	**3**	**17**
3_lrc_10	41	5763,82	0,00	0	11	2410,39	38,56	4	188	11	**2396,89**	0,00	1396,89	**4**	**16**
4_lrc_10	41	5516,74	0,00	0	10	2199,99	2,46	4	160	10	**2197,40**	2,46	1194,94	**4**	**20**
5_lrc_10	44	6976,51	104,33	0	13	2835,31	0,00	3	189	13	**2828,28**	0,00	1828,28	**3**	**15**
6_lrc_10	41	6323,69	113,07	0	12	2535,59	4,19	2	123	12	2523,30	4,19	1519,11	**2**	**19**
7_lrc_10	39	5416,92	25,71	0	12	2398,69	12,46	9	341	12	2395,92	12,46	1383,46	**9**	**15**
8_lrc_10	35	4638,54	37,37	0	10	2249,44	0,00	2	88	10	**2222,15**	0,00	1222,15	**2**	**22**
1_lrc_20	35	19161,10	316,50	0	4	3248,32	25,77	70	388	4	**3240,57**	25,77	2214,80	**70**	**100**
2_lrc_20	38	19859,92	62,71	0	4	2883,82	65,08	95	374	4	2876,88	65,08	1811,80	**95**	**144**
3_lrc_20	35	14307,95	344,60	0	3	2447,92	1,33	116	317	3	**2431,21**	1,33	1429,88	**116**	**214**
4_lrc_20	41	12303,48	0,00	0	3	2205,76	17,46	166	405	3	**2184,43**	6,58	1177,85	**166**	**220**
5_lrc_20	37	20089,53	343,53	0	4	3128,19	31,44	112	491	4	**3099,10**	31,44	2067,66	**112**	**115**
6_lrc_20	41	19339,55	602,69	0	4	2682,88	0,00	90	345	4	2653,80	14,60	1639,20	**90**	**151**
7_lrc_20	34	15090,79	201,00	0	3	2345,02	63,10	65	291	3	**2308,13**	3,85	1304,28	**66**	**172**
8_lrc_20	39	14599,18	132,78	0	3	2184,47	10,66	102	319	3	**2126,71**	10,66	1116,05	**102**	**199**
										sum	**261547,41**	**481,66**	**69065,75**	**3431,00**	**5836,00**
										avg	**4670,49**	**8,60**	**1233,32**	**61,27**	**104,21**

angle_r_nVeh_2opt

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	best cpu[sec]	total cpu[sec]
1_lc_10	21	15766,47	65,15	0	10	9828,94	0,00	1	35	10	**9828,94**	0,00	828,94	**1**	**25**
2_lc_10	23	17299,05	383,38	0	10	9828,94	0,00	2	58	10	**9828,94**	0,00	828,94	**2**	**19**
3_lc_10	22	15401,52	145,93	0	10	9937,33	0,00	10	299	10	**9906,15**	0,00	906,15	**10**	**18**
4_lc_10	20	12083,50	50,37	0	10	9949,85	0,00	12	348	10	**9901,70**	0,00	901,70	**12**	**19**
5_lc_10	20	15429,43	188,46	0	10	9828,94	0,00	1	52	10	**9828,94**	0,00	828,94	**1**	**20**
6_lc_10	20	16248,72	34,94	0	10	9828,94	0,00	1	37	10	**9828,94**	0,00	828,94	**1**	**24**
7_lc_10	19	15448,45	0,00	0	10	9828,94	0,00	1	53	10	**9828,94**	0,00	828,94	**1**	**24**
8_lc_10	21	16235,92	167,42	0	10	9838,44	0,00	2	57	10	**9826,44**	0,00	826,44	**2**	**20**
9_lc_10	21	14112,39	186,04	0	10	9830,94	0,00	1	37	10	**9828,94**	0,00	828,94	**1**	**19**
1_lc_20	20	41675,95	1515,91	0	3	9591,56	0,00	10	84	3	**9591,56**	0,00	591,56	**10**	224
2_lc_20	18	37318,89	547,93	0	3	9741,35	0,00	139	481	3	9695,75	0,00	695,75	139	148
3_lc_20	21	35670,32	583,79	0	3	9845,88	7,78	163	463	3	9774,59	7,78	766,81	163	180
4_lc_20	20	29227,94	1660,52	0	3	9810,83	0,00	176	500	3	9710,31	1,08	709,23	**176**	**176**
5_lc_20	23	46111,59	1597,98	0	3	9596,47	0,00	30	145	3	**9588,88**	0,00	588,88	**30**	**174**
6_lc_20	20	40414,12	148,00	0	3	9595,40	0,00	81	274	3	**9588,49**	0,00	588,49	**81**	184
7_lc_20	21	38006,88	893,38	0	3	9604,49	0,00	57	230	3	**9588,32**	0,00	588,32	**57**	180
8_lc_20	22	39152,32	171,13	0	3	9605,26	0,00	48	217	3	**9595,99**	0,00	595,99	**48**	**176**
1_lr_10	33	5742,20	32,19	0	19	3558,56	32,49	1	46	19	**3558,56**	32,49	2526,07	**1**	**10**
2_lr_10	26	4604,81	7,87	0	17	3091,81	7,87	1	36	17	**3091,81**	7,87	2083,94	**1**	**12**
3_lr_10	31	4943,99	17,61	0	13	2610,99	12,47	6	280	13	**2610,99**	12,47	1598,52	**6**	**12**
4_lr_10	22	3477,15	31,54	0	10	2096,10	3,42	11	353	10	2096,10	3,42	1092,68	**11**	**17**
5_lr_10	27	4342,26	47,87	0	14	2614,21	3,65	1	75	14	**2614,21**	3,65	1610,56	**1**	**11**
6_lr_10	26	4460,66	13,07	0	12	2391,88	13,07	1	50	12	**2390,19**	13,07	1377,12	**1**	**15**
7_lr_10	26	4113,16	43,47	15	10	2179,40	22,00	4	179	10	**2178,69**	22,00	1156,69	**4**	**18**
8_lr_10	22	3319,68	7,86	0	9	2034,15	0,00	3	142	9	**2015,53**	0,00	1015,53	**3**	**23**
9_lr_10	24	3902,31	8,24	0	12	2331,43	23,00	1	60	12	2331,43	23,00	1308,43	**1**	**21**
10_lr_10	22	3383,32	12,46	0	11	2270,10	10,24	14	473	11	2267,80	10,24	1257,56	**14**	**15**
11_lr_10	23	3678,19	0,00	0	10	2190,17	3,84	16	480	10	**2186,63**	3,84	1182,79	**16**	**17**
12_lr_10	23	3252,03	0,00	0	10	2068,15	1,24	13	333	10	2056,20	1,24	1054,96	**13**	**24**
1_lr_20	23	14541,03	233,50	0	4	3062,98	70,53	85	366	4	**3062,98**	70,53	1992,45	**85**	**127**
2_lr_20	20	12801,82	233,50	0	3	2602,86	5,18	53	221	3	**2588,26**	5,18	1583,08	**53**	**179**
3_lr_20	22	12898,60	223,38	0	3	2352,87	0,00	214	455	3	**2337,11**	2,10	1335,01	**214**	**240**
4_lr_20	19	9251,76	0,00	0	2	1978,42	1,05	83	206	2	**1965,13**	1,05	964,08	**83**	**393**
5_lr_20	20	11407,68	107,48	0	3	2430,76	0,55	104	311	3	**2421,25**	0,55	1420,70	**104**	**202**
6_lr_20	21	12218,10	453,74	0	3	2315,46	2,20	173	445	3	**2300,84**	1,29	1299,55	**173**	**206**
7_lr_20	20	10706,92	60,15	0	2	1989,16	0,00	93	214	2	1965,57	0,00	965,57	**93**	**379**
8_lr_20	19	7131,20	78,31	0	2	1805,92	0,00	326	436	2	**1782,74**	1,86	780,88	**326**	**389**
9_lr_20	20	11400,57	214,45	0	3	2316,21	0,20	159	454	3	**2300,67**	2,17	1298,50	**159**	**183**
10_lr_20	24	13184,99	151,31	0	3	2399,42	5,25	171	378	3	**2382,93**	5,25	1377,68	**171**	**244**
11_lr_20	21	9319,51	208,5247	0	3	2043,29	0,00	208	500	3	2035,60	0,00	1035,60	**208**	**208**
1_lrc_10	26	4671,21	129,75	0	14	2959,93	27,24	1	62	14	**2955,98**	27,24	1928,74	**1**	**14**
2_lrc_10	27	4643,39	19,60	0	12	2676,38	0,00	2	134	12	**2676,29**	0,00	1676,29	**2**	**16**
3_lrc_10	23	3758,76	0,94	0	11	2398,69	0,00	9	337	11	**2396,89**	0,00	1396,89	**9**	**16**
4_lrc_10	23	3540,61	0,00	0	10	2199,98	9,14	5	166	10	**2198,31**	9,14	1189,17	**5**	**20**
5_lrc_10	27	4749,48	22,56	0	14	2905,36	6,06	8	355	14	2905,36	6,06	1899,30	**8**	**12**
6_lrc_10	23	4108,46	2,27	0	12	2549,82	16,78	2	119	12	2541,22	16,78	1524,44	**2**	**17**
7_lrc_10	25	3910,32	0,00	0	11	2380,27	0,03	10	358	11	2361,59	0,00	1361,59	**10**	**16**
8_lrc_10	20	3079,83	6,71	0	10	2233,10	4,42	4	150	10	**2222,21**	4,42	1217,79	**4**	**20**
1_lrc_20	20	12048,71	221,98	0	4	3220,13	57,61	66	351	4	**3184,54**	57,61	2126,93	**66**	**107**
2_lrc_20	20	13037,33	70,38	0	4	2913,11	74,80	95	372	4	2897,47	74,80	1822,67	**95**	**143**
3_lrc_20	20	9967,05	27,94	0	3	2502,51	0,00	147	465	3	**2472,91**	0,00	1472,91	**147**	**165**
4_lrc_20	19	8497,56	287,86	0	3	2197,90	9,81	176	419	3	**2190,32**	9,81	1180,51	**176**	**225**
5_lrc_20	24	14928,34	174,42	0	4	3129,39	6,10	91	406	4	**3118,52**	6,10	2112,42	**91**	**119**
6_lrc_20	18	10558,71	238,30	0	4	2670,36	42,67	139	456	4	2640,23	42,67	1597,56	**139**	**159**
7_lrc_20	19	9334,49	153,53	0	3	2349,01	11,15	150	420	3	**2333,43**	11,15	1322,28	**150**	**190**
8_lrc_20	20	8810,20	343,38	0	3	2175,38	3,46	119	475	3	**2140,81**	3,46	1137,35	**119**	**135**
										sum	**261519,12**	**501,37**	**69017,75**	**3500,00**	**5949,00**
										avg	**4669,98**	**8,95**	**1232,46**	**62,50**	**106,23**

angle_r_nVeh_rr

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	best cpu[sec]	total cpu[sec]
1_lc_10	22,0	16296,49	0,00	0	10	9828,94	0,00	1	32	10	**9828,94**	0,00	828,94	**1**	**24**
2_lc_10	20,0	14507,62	0,00	0	10	9834,48	0,00	1	53	10	**9828,94**	0,00	828,94	**1**	**21**
3_lc_10	23,0	15770,64	145,93	0	10	9937,33	0,00	15	414	10	**9937,33**	0,00	937,33	**15**	**19**
4_lc_10	21,0	12740,97	0,00	0	10	9935,61	0,00	20	490	10	**9922,66**	0,00	922,66	**20**	**20**
5_lc_10	20,0	15784,30	0,00	0	10	9848,93	18,47	1	22	10	**9828,94**	0,00	828,94	**1**	**21**
6_lc_10	20,0	15762,84	67,81	0	10	9828,94	0,00	1	41	10	**9828,94**	0,00	828,94	**1**	**24**
7_lc_10	20,0	14679,50	2,53	0	10	9830,17	0,00	1	24	10	**9828,94**	0,00	828,94	**1**	**21**
8_lc_10	20,0	14662,63	0,00	0	10	9834,52	0,00	1	32	10	**9826,44**	0,00	826,44	**1**	**26**
9_lc_10	21,0	14938,84	0,00	0	10	9842,42	0,00	1	25	10	**9828,94**	0,00	828,94	**1**	**19**
1_lc_20	18,0	40063,61	247,21	0	3	9591,56	0,00	11	102	3	**9591,56**	0,00	591,56	**11**	218
2_lc_20	18,0	35864,25	568,88	0	3	9755,48	11,96	100	320	3	9678,14	11,96	666,18	100	182
3_lc_20	20,0	36203,80	1424,89	0	3	9921,36	9,79	145	434	3	9694,79	9,79	685,00	**145**	175
4_lc_20	20,0	30950,47	665,60	0	3	9836,18	1,85	122	366	3	9674,68	0,00	674,68	**122**	**177**
5_lc_20	19,0	36943,29	440,52	0	3	9602,28	0,00	28	171	3	**9588,88**	0,00	588,88	**28**	199
6_lc_20	23,0	44383,89	564,72	0	3	9621,60	0,00	70	263	3	**9588,49**	0,00	588,49	**70**	183
7_lc_20	19,0	36538,68	1585,95	0	3	9605,26	0,00	42	194	3	**9588,32**	0,00	588,32	**42**	179
8_lc_20	20,0	36612,82	988,12	0	3	9620,70	0,00	21	127	3	**9595,99**	0,00	595,99	**21**	179
1_lr_10	32,0	5600,02	32,19	0	19	3558,56	32,49	0	34	19	**3558,56**	32,49	2526,07	**0**	**9**
2_lr_10	26,0	4740,48	0,00	0	17	3091,81	0,00	0	33	17	**3091,81**	0,00	2091,81	**0**	**11**
3_lr_10	30,0	4756,43	68,14	0	13	2610,99	16,89	2	140	13	**2610,99**	16,89	1594,10	**2**	**12**
4_lr_10	26,0	3706,79	0,00	0	10	2095,50	4,06	15	442	10	2095,50	4,06	1091,44	**15**	**18**
5_lr_10	26,0	4237,08	27,46	0	14	2614,21	27,46	1	66	14	**2614,21**	27,46	1586,75	**1**	**11**
6_lr_10	26,0	4460,66	13,07	0	12	2391,88	13,07	1	50	12	**2390,19**	13,07	1377,12	**1**	**15**
7_lr_10	24,0	4005,10	0,00	0	10	2179,40	0,00	2	89	10	**2178,69**	0,00	1178,69	**2**	**22**
8_lr_10	25,0	3550,76	20,06	0	9	2027,73	0,00	3	146	9	**2005,94**	2,60	1003,34	**3**	**21**
9_lr_10	26,0	4054,89	5,13	0	11	2285,38	5,13	2	82	11	**2282,20**	5,13	1277,07	**2**	**20**
10_lr_10	25,0	3677,98	21,39	0	11	2264,92	6,54	12	481	11	2264,92	6,54	1258,38	**12**	**13**
11_lr_10	23,0	3678,19	0,00	0	10	2190,17	3,84	17	480	10	**2186,63**	3,84	1182,79	**17**	**18**
12_lr_10	24,0	3390,43	1,24	0	10	2062,35	1,24	7	233	10	2046,64	1,24	1045,40	**7**	**20**
1_lr_20	20,0	13699,39	125,00	0	4	3057,85	73,53	26	157	4	**3057,85**	73,53	1984,32	**26**	**132**
2_lr_20	20,0	12919,12	92,71	0	3	2591,74	13,78	87	340	3	**2591,74**	13,78	1577,96	**87**	**160**
3_lr_20	22,0	12174,13	233,50	0	3	2355,20	0,00	209	471	3	**2325,28**	0,00	1325,28	**209**	**228**
4_lr_20	19,0	8944,48	0,00	0	2	1987,51	1,01	97	201	2	**1962,05**	0,00	962,05	**97**	**411**
5_lr_20	20,0	11407,68	107,48	0	3	2430,76	0,55	108	311	3	**2423,90**	0,55	1423,35	**108**	**211**
6_lr_20	21,0	12218,10	453,74	0	3	2315,46	2,20	174	445	3	**2286,88**	1,29	1285,59	**174**	**206**
7_lr_20	19,0	10008,05	344,34	0	3	2009,18	0,00	273	448	3	1999,78	0,00	999,78	**273**	**330**
8_lr_20	21,0	7101,75	167,71	0	2	1804,68	1,97	223	333	2	**1790,86**	1,97	788,89	**223**	**389**
9_lr_20	21,0	11173,30	214,45	0	3	2301,12	6,15	100	314	3	**2286,14**	6,15	1279,99	**100**	**200**
10_lr_20	24,0	13307,43	213,19	0	3	2402,70	0,30	114	318	3	**2379,79**	1,43	1378,36	**114**	**226**
11_lr_20	21,0	9564,634	218,75	0	3	2054,19	0,03	182	474	3	2029,70	0,03	1029,67	**182**	**199**
1_lrc_10	25,0	4595,71	15,06	0	14	2959,93	0,00	1	41	14	2959,93	0,00	1959,93	**1**	**14**
2_lrc_10	27,0	4597,53	5,72	0	12	2676,30	1,17	1	78	12	**2676,30**	1,17	1675,13	**1**	**18**
3_lrc_10	26,0	4281,34	0,00	0	11	2399,05	0,00	5	207	11	**2397,73**	0,00	1397,73	**5**	**17**
4_lrc_10	24,0	3711,29	0,00	0	10	2204,25	0,00	5	157	10	**2197,40**	2,46	1194,94	**5**	**20**
5_lrc_10	27,0	4817,38	33,82	0	14	2900,90	1,13	3	126	14	2900,90	1,13	1899,77	**3**	**13**
6_lrc_10	23,0	4075,31	4,91	0	12	2531,90	0,00	5	227	12	2526,16	0,00	1526,16	**5**	**14**
7_lrc_10	24,0	3923,69	6,11	0	11	2351,26	0,47	8	296	11	2344,95	0,47	1344,48	**8**	**16**
8_lrc_10	23,0	3488,97	0,00	0	10	2244,70	0,00	3	141	10	**2222,15**	0,00	1222,15	**3**	**20**
1_lrc_20	20,0	12048,71	221,98	0	4	3220,13	57,61	66	351	4	**3185,68**	57,61	2128,07	**66**	**108**
2_lrc_20	18,0	12186,04	520,07	0	3	2646,97	30,17	94	355	3	**2628,69**	30,17	1598,52	**94**	**169**
3_lrc_20	17,0	8822,64	494,20	0	3	2424,24	0,00	178	495	3	**2410,71**	0,00	1410,71	**178**	**182**
4_lrc_20	20,0	8769,15	7,23	0	3	2211,74	11,44	208	474	3	**2172,79**	0,00	1172,79	**208**	**222**
5_lrc_20	20,0	13188,25	343,53	0	4	3118,29	3,42	55	321	4	**3112,23**	5,92	2106,31	**55**	**106**
6_lrc_20	19,0	11623,98	91,67	0	4	2518,20	0,24	37	195	4	2517,65	0,24	1517,41	**37**	**154**
7_lrc_20	19,0	9334,49	153,53	0	3	2349,01	11,15	149	420	3	**2312,41**	4,55	1307,86	**150**	**190**
8_lrc_20	20,0	8485,03	150,69	0	3	2128,47	33,34	161	441	3	**2107,46**	1,00	1106,46	**161**	**195**
										sum	**260794,31**	**338,52**	**68455,79**	**3216,00**	**6027,00**
										avg	**4657,04**	**6,05**	**1222,42**	**57,43**	**107,63**

angle_r_1_2opt

	initial_solution				tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	best cpu[sec]	total cpu[sec]
1_lc_10	11	10853,65	57,31	0	10	9828,94	0,00	3	78	10	**9828,94**	0,00	828,94	**3**	**25**
2_lc_10	12	12377,84	0,00	0	10	9828,94	0,00	14	401	10	**9828,94**	0,00	828,94	**14**	**19**
3_lc_10	11	12390,27	57,49	0	10	9946,11	0,00	17	454	10	**9914,76**	0,00	914,76	**17**	**20**
4_lc_10	10	11602,73	0,00	0	10	9978,23	0,00	17	435	10	**9956,20**	0,00	956,20	**17**	**20**
5_lc_10	11	11001,20	0,00	0	10	9828,94	0,00	1	31	10	**9828,94**	0,00	828,94	**1**	**20**
6_lc_10	13	12024,67	33,71	0	10	9838,93	0,00	3	112	10	9838,93	0,00	838,93	**3**	**19**
7_lc_10	13	11730,31	0,00	0	10	9828,94	0,00	3	109	10	**9828,94**	0,00	828,94	**3**	**20**
8_lc_10	12	12190,45	0,00	0	10	9831,34	0,00	4	144	10	**9826,44**	0,00	826,44	**4**	**19**
9_lc_10	12	11266,98	0,00	0	10	9828,94	0,00	3	92	10	**9828,94**	0,00	828,94	**3**	**20**
1_lc_20	5	15773,64	12,14	0	3	9591,56	0,00	131	403	3	**9591,56**	0,00	591,56	131	176
2_lc_20	5	13566,47	8,33	0	3	9815,87	23,47	166	463	3	9777,18	5,28	771,90	166	182
3_lc_20	5	13382,10	33,69	0	3	9892,12	11,49	154	454	3	9812,19	11,49	800,70	154	175
4_lc_20	4	13125,03	0,53	0	4	9796,68	0,00	153	414	4	9745,06	0,00	745,06	**154**	**191**
5_lc_20	5	12830,17	84,84	0	3	9626,34	0,00	19	66	3	**9588,88**	0,00	588,88	**20**	244
6_lc_20	5	12550,36	151,96	0	3	9595,56	0,00	148	385	3	**9588,49**	0,00	588,49	148	203
7_lc_20	4	12390,00	13,68	0	3	9589,95	0,00	92	286	3	**9588,32**	0,00	588,32	**92**	193
8_lc_20	5	12894,33	43,27	0	3	9605,98	0,00	93	270	3	**9595,99**	0,00	595,99	**93**	195
1_lr_10	23	4170,77	34,36	0	23	4170,77	34,36	0	0	23	4170,77	34,36	3136,41	**0**	**9**
2_lr_10	21	3963,05	0,00	0	17	3117,71	4,72	1	37	17	**3117,71**	4,72	2112,99	**1**	**15**
3_lr_10	17	3553,03	1,07	0	13	2615,06	12,47	10	423	13	**2615,06**	12,47	1602,59	**10**	**12**
4_lr_10	15	3287,74	0,00	0	11	2149,71	0,00	12	396	11	2149,71	0,00	1149,71	**12**	**16**
5_lr_10	17	3103,03	0,00	0	15	2711,28	22,54	0	27	15	2711,28	22,54	1688,74	**0**	**16**
6_lr_10	16	3032,42	0,00	0	12	2409,48	0,10	4	219	12	**2409,04**	0,10	1408,94	**4**	**14**
7_lr_10	16	3366,13	0,00	0	10	2196,62	1,87	3	133	10	**2195,91**	1,87	1194,04	**3**	**20**
8_lr_10	14	2988,28	11,32	0	12	2296,25	0,00	0	28	12	2278,88	0,00	1278,88	**0**	**18**
9_lr_10	15	2976,67	0,00	0	13	2453,96	3,00	2	96	13	2452,75	26,20	1426,55	**2**	**17**
10_lr_10	15	3154,48	0,00	0	12	2299,00	0,73	3	157	12	2299,00	0,73	1298,27	**3**	**14**
11_lr_10	12	2542,62	0,00	0	11	2283,97	12,72	12	360	11	2281,30	12,72	1268,58	**12**	**18**
12_lr_10	15	3089,72	0,00	0	11	2144,65	1,24	12	368	11	2133,38	1,24	1132,14	**12**	**17**
1_lr_20	6	4913,75	25,79	0	5	3430,39	27,46	18	112	5	**3421,48**	27,46	2394,02	**18**	**155**
2_lr_20	5	4112,50	0,00	0	3	2588,29	6,58	123	396	3	**2588,29**	6,58	1581,71	**123**	**170**
3_lr_20	4	3832,93	0,00	0	3	2593,86	0,00	113	279	3	**2575,77**	21,71	1554,06	**113**	**226**
4_lr_20	4	3808,93	0,00	0	3	2091,64	0,00	246	500	3	2068,28	3,61	1064,67	**246**	**246**
5_lr_20	5	3756,04	55,00	0	3	2473,57	6,43	148	355	3	**2467,45**	6,43	1461,02	**148**	**222**
6_lr_20	5	3910,50	16,93	0	3	2389,16	0,00	171	423	3	**2385,53**	0,00	1385,53	**171**	**206**
7_lr_20	4	3283,66	0,00	0	3	2064,95	0,00	88	160	3	2037,61	6,01	1031,60	**88**	**429**
8_lr_20	4	3232,44	0,00	0	2	1816,45	3,33	374	490	2	**1807,82**	3,33	804,49	**374**	**384**
9_lr_20	5	3966,18	4,34	0	3	2328,92	0,83	162	388	3	**2323,92**	0,83	1323,09	**162**	**220**
10_lr_20	5	4034,65	0,00	0	3	2412,06	3,72	233	495	3	**2402,12**	3,72	1398,40	**233**	**236**
11_lr_20	4	3063,12	0,00	0	3	2061,38	0,00	210	479	3	2041,17	0,00	1041,17	**211**	**223**
1_lrc_10	18	3612,94	6,29	0	16	3256,61	6,29	0	5	16	3245,99	6,29	2239,70	**0**	**13**
2_lrc_10	16	3481,43	0,00	0	12	2677,99	0,00	1	65	12	**2676,29**	0,00	1676,29	**2**	**19**
3_lrc_10	16	3342,29	0,00	0	11	2403,73	0,00	12	391	11	**2403,22**	0,00	1403,22	**12**	**16**
4_lrc_10	15	3330,59	0,00	0	10	2207,40	0,00	5	176	10	**2203,75**	0,00	1203,75	**5**	**20**
5_lrc_10	17	3470,64	0,00	0	17	3470,64	0,00	0	0	17	3467,77	0,00	2467,77	**0**	**15**
6_lrc_10	16	3355,62	0,00	0	11	2475,10	2,34	3	144	11	**2472,52**	2,34	1470,18	**3**	**19**
7_lrc_10	16	3395,53	0,00	0	11	2360,47	0,00	10	342	11	**2339,67**	0,00	1339,67	**10**	**17**
8_lrc_10	16	3373,55	0,00	0	10	2272,14	0,00	3	121	10	**2226,82**	0,00	1226,82	**3**	**21**
1_lrc_20	6	4520,34	3,92	0	4	3276,14	26,41	50	248	4	**3259,44**	10,82	2248,62	**50**	**121**
2_lrc_20	6	4730,10	26,50	0	4	2951,97	0,52	100	363	4	2951,97	0,52	1951,45	**100**	**150**
3_lrc_20	5	4368,04	1,61	0	4	2615,22	0,14	119	357	4	**2594,98**	4,61	1590,37	**119**	**177**
4_lrc_20	4	3428,18	0,00	0	3	2254,76	0,00	110	296	3	**2251,67**	0,28	1251,39	**110**	**229**
5_lrc_20	6	4783,24	28,38	0	4	3270,04	33,56	18	114	4	**3259,95**	33,56	2226,39	**18**	**121**
6_lrc_20	5	3739,36	17,96	0	4	2677,25	25,00	107	377	4	2657,33	25,00	1632,33	**107**	**154**
7_lrc_20	5	4225,21	3,93	0	3	2373,53	0,00	154	405	3	**2361,72**	29,32	1332,40	**154**	**200**
8_lrc_20	5	3482,21	0,00	0	3	2132,47	9,26	154	388	3	**2114,31**	9,26	1105,05	**154**	**215**
										sum	**265390,33**	**335,40**	**73054,93**	**3816,00**	**6151,00**
										avg	**4739,11**	**5,99**	**1304,55**	**68,14**	**109,84**

angle_r_1_rr

initial_solution					tabu serch					final solution					
instance	number of routes	schedule cost	waiting time	cpu [sec]	number of routes	schedule cost	waiting time	cpu [sec]	kappa	number of routes	schedule cost	waiting time	travel cost	best cpu[sec]	total cpu[sec]
1_lc_10	12	11142,70	57,31	0	10	9828,94	0,00	5	174	10	**9828,94**	0,00	828,94	**5**	**22**
2_lc_10	12	12377,84	0,00	0	10	9831,98	0,00	15	444	10	**9828,94**	0,00	828,94	**15**	**18**
3_lc_10	12	12598,13	57,49	0	10	9965,51	0,00	15	391	10	**9961,11**	0,00	961,11	**15**	**19**
4_lc_10	10	11602,73	0,00	0	10	9978,23	0,00	17	435	10	**9969,28**	0,00	969,28	**17**	**20**
5_lc_10	11	11001,20	0,00	0	10	9828,94	0,00	1	31	10	**9828,94**	0,00	828,94	**1**	**20**
6_lc_10	13	12007,63	33,71	0	10	9838,93	0,00	13	354	10	**9828,94**	0,00	828,94	**13**	**19**
7_lc_10	13	11730,31	0,00	0	10	9828,94	0,00	3	109	10	**9828,94**	0,00	828,94	**3**	**20**
8_lc_10	12	12047,53	0,00	0	10	9834,15	0,00	2	80	10	**9826,44**	0,00	826,44	**2**	**20**
9_lc_10	12	11266,98	0,00	0	10	9828,94	0,00	3	92	10	**9828,94**	0,00	828,94	**3**	**20**
1_lc_20	5	15773,64	12,14	0	3	9591,56	0,00	131	403	3	**9591,56**	0,00	591,56	131	177
2_lc_20	5	13503,03	8,33	0	3	9916,15	0,00	157	440	3	9697,24	0,00	697,24	158	184
3_lc_20	5	13382,10	33,69	0	3	9892,12	11,49	155	454	3	9827,56	11,49	816,07	155	176
4_lc_20	4	13125,03	0,53	0	4	9796,68	0,00	154	414	4	9740,67	0,00	740,67	**154**	**192**
5_lc_20	5	12830,17	84,84	0	3	9626,34	0,00	20	66	3	**9588,88**	0,00	588,88	**20**	246
6_lc_20	5	12550,36	151,96	0	3	9595,56	0,00	148	385	3	**9588,49**	0,00	588,49	148	204
7_lc_20	5	13152,32	13,68	0	3	9606,71	0,00	65	203	3	**9588,32**	0,00	588,32	**65**	202
8_lc_20	5	12844,43	43,27	0	3	9607,43	0,00	125	369	3	**9595,99**	0,00	595,99	**125**	184
1_lr_10	23	4170,77	34,36	0	23	4170,77	34,36	0	0	23	4170,77	34,36	3136,41	**0**	**9**
2_lr_10	21	3963,05	0,00	0	17	3117,71	4,72	1	37	17	**3117,71**	4,72	2112,99	**1**	**15**
3_lr_10	17	3553,03	1,07	0	13	2615,06	12,47	10	423	13	**2615,06**	12,47	1602,59	**10**	**12**
4_lr_10	15	3287,74	0,00	0	11	2149,71	0,00	12	396	11	2149,71	0,00	1149,71	**12**	**16**
5_lr_10	17	3103,03	0,00	0	15	2711,28	22,54	0	27	15	2711,28	22,54	1688,74	**0**	**16**
6_lr_10	16	3032,42	0,00	0	12	2409,48	0,10	4	219	12	**2406,94**	0,10	1406,84	**4**	**14**
7_lr_10	16	3366,60	0,00	0	10	2198,20	1,87	3	155	10	**2192,24**	1,87	1190,37	**3**	**20**
8_lr_10	14	2988,28	11,32	0	12	2296,25	0,00	0	28	12	2278,88	0,00	1278,88	**0**	**18**
9_lr_10	15	2976,67	0,00	0	13	2453,96	3,00	2	96	13	2453,96	3,00	1450,96	**2**	**17**
10_lr_10	16	3198,13	0,00	0	13	2374,19	6,54	11	469	13	2369,21	6,54	1362,67	**11**	**12**
11_lr_10	12	2542,62	0,00	0	11	2283,97	12,72	12	360	11	2264,44	12,72	1251,72	**12**	**18**
12_lr_10	15	3089,72	0,00	0	11	2144,65	1,24	12	368	11	2128,31	1,24	1127,07	**12**	**17**
1_lr_20	6	4913,75	25,79	0	5	3430,39	27,46	18	112	5	**3423,60**	27,46	2396,14	**18**	**154**
2_lr_20	5	4112,50	0,00	0	3	2588,29	6,58	123	396	3	**2588,29**	6,58	1581,71	**123**	**170**
3_lr_20	4	3832,93	0,00	0	3	2593,86	0,00	113	279	3	**2549,47**	20,24	1529,23	**113**	**226**
4_lr_20	4	3808,93	0,00	0	3	2091,64	0,00	246	500	3	2039,11	0,16	1038,95	**246**	**246**
5_lr_20	5	3743,54	55,00	0	3	2466,32	5,12	36	119	3	**2448,11**	5,12	1442,99	**36**	**222**
6_lr_20	5	3910,50	16,93	0	3	2389,16	0,00	171	423	3	**2384,31**	11,27	1373,04	**171**	**206**
7_lr_20	4	3283,66	0,00	0	3	2064,95	0,00	88	160	3	2001,13	0,00	1001,13	**88**	**428**
8_lr_20	4	3232,44	0,00	0	2	1816,45	3,33	373	490	2	**1789,68**	2,81	786,87	**373**	**383**
9_lr_20	5	3985,28	4,34	0	3	2348,51	34,84	168	412	3	**2328,86**	34,84	1294,02	**168**	**213**
10_lr_20	5	4037,39	0,00	0	3	2417,16	39,00	200	432	3	**2407,81**	39,00	1368,81	**200**	**241**
11_lr_20	4	3063,12	0,00	0	3	2061,38	0,00	211	479	3	2039,60	0,00	1039,60	**211**	**224**
1_lrc_10	18	3612,94	6,29	0	16	3256,61	6,29	0	5	16	3249,95	6,29	2243,66	**0**	**13**
2_lrc_10	16	3481,43	0,00	0	13	2773,33	0,00	1	35	13	2770,91	0,00	1770,91	**1**	**18**
3_lrc_10	16	3342,29	0,00	0	11	2428,07	0,00	5	213	11	**2421,57**	0,00	1421,57	**5**	**15**
4_lrc_10	15	3330,59	0,00	0	10	2207,40	0,00	5	176	10	**2203,88**	0,00	1203,88	**5**	**20**
5_lrc_10	17	3470,64	0,00	0	17	3470,64	0,00	0	0	17	3465,32	0,00	2465,32	**0**	**14**
6_lrc_10	16	3355,62	0,00	0	13	2653,79	0,00	2	86	13	2651,84	0,00	1651,84	**2**	**17**
7_lrc_10	16	3395,53	0,00	0	12	2397,83	0,00	6	260	12	2395,55	0,00	1395,55	**6**	**15**
8_lrc_10	16	3373,55	0,00	0	10	2272,14	0,00	3	121	10	**2238,27**	0,00	1238,27	**3**	**21**
1_lrc_20	6	4520,34	3,92	0	4	3276,14	26,41	49	248	4	**3276,14**	26,41	3249,73	**49**	**121**
2_lrc_20	6	4730,10	26,50	0	4	2951,97	0,52	100	363	4	2951,97	0,52	2951,45	**100**	**150**
3_lrc_20	5	4368,04	1,61	0	4	2615,22	0,14	119	357	4	**2587,87**	0,14	2587,73	**119**	**176**
4_lrc_20	4	3428,18	0,00	0	3	2254,76	0,00	111	296	3	**2250,34**	0,28	2250,06	**112**	**232**
5_lrc_20	6	4783,24	28,38	0	4	3270,04	33,56	18	114	4	**3259,95**	33,56	3226,39	**18**	**120**
6_lrc_20	5	3739,36	17,96	0	4	2677,25	25,00	108	377	4	2654,28	25,00	2629,28	**108**	**155**
7_lrc_20	6	4465,41	3,93	0	3	2386,79	15,60	172	425	3	**2353,89**	15,60	2338,29	**172**	**209**
8_lrc_20	5	3482,21	0,00	0	3	2132,47	9,26	153	388	3	**2103,89**	9,26	2094,63	**154**	**215**
										sum	**265643,28**	**375,59**	**81267,69**	**3698,00**	**6151,00**
										avg	**4743,63**	**6,71**	**1451,21**	**66,04**	**109,84**

The second part of the current annex provides the tables resuming all the obtained results. The goal is to facilitate the comparison of the methods.

As in the previous case, the outcome was compared with the figures obtained by Li nad Lim (2001). Hence, in order to facilitate the analysis of the data, similarly as before, all the values of interest were highlighted either by distinctive colour or underlined:

- red – marks the result of better value than the one obtained by Li nad Lim (2001),
- green – marks the result of the same value as the one obtained by Li nad Lim (2001),
- underline – depicts the best result obtained with respect to all the tested strategies.

The first Tables: B.1, B.2 and B.3 provide information on final solutions achieved by each reviewed method. They contain the data regarding the final schedule costs as well as the best and total cpu times, correspondingly. Underneath every listing, there was placed a brief summary of its contents addressing:

- number and percentage of instances, which result with better or equal outcome as the one obtained by Li nad Lim (2001),
- number of instances with the best result with respect to all the tested approaches,
- value of the total and average improvement with respect to the outcome obtained by Li nad Lim (2001).

The resume of Table B.3 contains additionally the calculation of the difference between the sum of the total and actual cpu of each method. It represents the accumulated amount of time during which, the PTS routine was working without bringing any improvement to the last best found solution. This estimate is also represented as the percentage of the total routines' execution time.

Due to the fact, that the methods, which use to construct the initial set of routes the approach based on the Sweep Algorithm with randomly chosen starting point, were performed 100 times, there arose a question whether it is beneficial to execute such approach multiple times in order to choose from among obtained solutions the one that is the most beneficial. To advance the search of the answer, there was created a summary Table B.4 containing the best and total cpu times aggregated during carrying out of one hundred repetitions of the same procedure. These values got compared to the figures obtained by Li nad Lim (2001).

In order to facilitate the mutual comparison of all the tested routines, there was also prepared a summary Table B.5 containing the best schedule cost results obtained. Its task was to show how many tested instances and by how much can be improved with respect to the result obtained by Li nad Lim (2001). Moreover, it indicates the method resulting with the highest number of improved benchmark cases.

Tables: B.6 and B.7 have the same objective. They contain respectfully the information on the best and the total cpu time of the program's execution needed to obtain the best schedule cost values presented in Table B.5. Again, these figures are compared with the outcome reached by Li nad Lim (2001). The listings present not only the overviews of the best achieved rates, but also depict the collection of methods, providing the corresponding result. At the bottom of each table, there is placed a short summary containing the information concerning:

- number of instances, in which each method has achieved the best result,
- number and percentage of the tested benchmarks, for which there was obtained the result at least as good as that of Li nad Lim (2001),
- percentage of the outcome's improvement/deterioration in relation to the values reached by Li nad Lim (2001).

The subsequent data listings are to support the assessment of not the whole method, but its individual components. The objective is to facilitate the selection of a routine, which provides the greatest benefits from the point of view of the whole analysed approach.

Hence, Table B.8 presents the schedule costs of the collections of routes provided by the initial solution constructing algorithms. These data are compared with the final results and concluded in a summary drawn underneath. In this case, the CPU time needed to perform the routes' building procedure is not considered, since in either case, it takes less than one second.

The additional review concerns evaluation of the strategies used to post-optimize the sets of routes obtained from the PTS step. For this purpose, there were built additional summary Tables B.9 and B.10, which contain selected data regarding: process' duration, final schedule costs and number of instances which got improved.

Table B.9 focuses on variables demonstrating the efficiency of the two employed procedures in terms of results' improvement and velocity, both summarized for the complete collection of the benchmark cases and average per instance. It contains:

- value of which the schedule cost obtained in the PTS procedure got improved in the post-optimization step,
- actual cpu value, which corresponds to the duration of the post-optimization routine till finding the best solution, summarized for all the tested instances,
- total cpu value, which corresponds to the total duration of the post-optimization method, summarized for all the tested instances,
- number of the instances which did not get improved.

Table B.10 concentrates on the information regarding the number and percentage of the benchmark cases for which, the obtained result was:

- the same for both post-optimization methods,
- better for the NPDPRO,
- better for the PDP adapted 2-opt.

In order to be able to compare with one another the methods, which construct the initial solution using the Sweep Algorithm, it was decided to execute them starting each time the process of customers' ordering from the same point equal to -π. The results of experiments have been collected in three tables and contain, respectively: final schedule cost (Table B.11), actual cpu (Table B.12) and total cpu (Table B.13). All values have been compared with the outcomes obtained by Li nad Lim (2001) and resumed in a short summary placed underneath each listing. It determines the number and percentage of the instances for which it was possible to reach better or equal estimates as these of reference.

To present the manner of operation of the PTS heuristic, staring from an initial solution built using different methods, there was prepared a summary Table B.14 containing the number of iterations needed to find the best solution: κ. For the complete picture, there were gathered the data regarding all the reviewed procedures, which initially order the customers listings by: area, pair, angle with the fixed starting point, as well as the expected value of κ for the methods organizing the customers by angle with randomly chosen starting point. A graphic supplement to the description consist a set of graphs depicting the performance of the PTS heuristic when solving a randomly chosen example: 9_lc_10, shown in Figure B.1.

For better understanding of the way in which the PTS heuristic operates, using the same example as in the previous case, there was constructed a collection of diagrams shown in Figure B.2. They are to demonstrate in which particular iteration of the complete process a specific operator has provided a solution better, than the one known so far.

Each chart is composed of two overlaping diagrams. The first one, marked in red, is a scatter plot indicating the operator proving an improved solution in a specific iteration κ. In the case, when there was not found a feasible upgrading movement, it is marked as: NONE for the corresponding κ.

The second plot demonstrates a relation between the two variables: κ and κ^*. When the first one indicates the current iteration of the PTS process, the utter corresponds to an aggregated value of the indexes defining the specific operator bringing the upgraded solution: 1 – NPDPSO and 2 – NPDPEO. In this way, it is clear to distinguish, the stages of intense improvement of the solution, as well as the intervals when no feasible and schedule cost decreasing movement was found.

To conclude, under each diagram there was placed a data summary regarding the number of PTS iterations for which each particular operator has provided the best solution.

The final two Tables: B.15 and B.16 include the results obtained by other authors addressing the same PDVRPTW.

					expected value						
instance	**area_2opt**	**area_rr**	**pair_2opt**	**pair_rr**	**angle_r_ nCust_2opt**	**angle_r_ nCust_rr**	**angle_r_ nVeh_2opt**	**angle_r_ nVeh_rr**	**angle_r_ 1_2opt**	**angle_r_ 1_rr**	**Metaheuristic LiLi_2001]**
1_lc_10	**9828,94**	**9828,94**	**9828,94**	**9828,94**	10202,02	10088,65	10019,70	10033,25	10010,4171	10057,25	**9828,94**
2_lc_10	10242,02	10242,02	10147,04	10147,04	9951,15	9956,04	9970,86	9960,57	10272,6565	10320,45	**9828,94**
3_lc_10	**10016,68**	**10045,75**	**10048,50**	**10048,50**	**10006,76**	**10008,31**	**9958,87**	**9991,86**	**9958,09**	**9965,71**	**10058,03**
4_lc_10	**9925,59**	**9946,90**	**9961,90**	**9961,90**	**9950,33**	**9972,73**	**9953,79**	**9966,86**	**9978,65**	**9980,05**	**10006,90**
5_lc_10	9848,93	**9828,94**	**9828,94**	**9828,94**	9893,27	9890,04	9860,07	9848,84	**9828,94**	**9828,94**	**9828,94**
6_lc_10	**9828,94**	**9828,94**	10700,61	10700,61	9856,02	9854,39	9883,30	9841,17	9839,21	**9828,94**	**9828,94**
7_lc_10	**9828,94**	**9828,94**	**9828,94**	**9828,94**	9859,71	9874,79	9838,06	9842,41	**9828,94**	**9828,94**	**9828,94**
8_lc_10	9828,04	**9826,44**	**9826,44**	**9826,44**	9838,79	9839,81	9840,63	9833,88	9828,13	9828,28	**9826,94**
9_lc_10	**9828,94**	**9828,94**	**9828,94**	**9828,94**	**9831,06**	**9829,14**	9834,82	**9829,23**	9836,71	**9828,94**	**9831,78**
1_lc_20	**9591,56**	**9591,56**	22812,42	22812,42	9891,32	9821,40	9848,79	9839,05	**9591,56**	**9591,56**	**9591,56**
2_lc_20	9777,18	9814,43	10005,95	9935,85	10099,44	9967,85	9980,32	9855,46	9853,11	9845,27	**9591,56**
3_lc_20	10062,28	10062,28	9881,75	9954,72	9957,14	9932,86	9979,19	9960,21	9882,10	9887,71	**9521,66**
4_lc_20	9940,44	9802,07	9917,73	9917,72	9924,85	9903,18	9923,51	9896,93	9882,31	9851,89	**9591,17**
5_lc_20	**9588,88**	**9588,88**	**9588,88**	**9588,88**	10427,31	10348,71	10066,72	9969,26	9682,16	9696,71	**9588,88**
6_lc_20	9707,72	9707,72	9630,21	9626,27	10337,25	10304,83	10120,86	10350,87	9630,71	9623,25	**9588,49**
7_lc_20	**9588,32**	**9588,32**	11081,87	11081,87	10073,32	10114,09	10038,58	9992,55	9756,80	9734,71	**9660,40**
8_lc_20	**9595,99**	**9601,45**	10438,95	10438,95	10764,94	10814,27	10391,55	10417,98	10160,49	10177,19	**9744,23**
1_lr_10	**3559,97**	**3559,97**	4131,85	4131,85	3713,23	3686,60	4039,39	4105,60	4170,77	4170,77	**3599,45**
2_lr_10	3592,03	3592,03	3335,82	3335,82	**3158,06**	**3147,88**	3282,10	3246,78	**3117,71**	**3117,71**	**3202,46**
3_lr_10	**2672,36**	**2672,36**	3202,36	3202,36	2824,85	2811,73	2738,14	2739,13	**2615,86**	**2617,53**	**2729,15**
4_lr_10	2168,17	2168,17	2093,70	2099,75	2204,61	2219,22	2232,33	2236,56	2196,35	2198,47	**2050,85**
5_lr_10	3197,78	3197,78	3001,98	3001,98	2868,65	2843,15	2823,61	2798,67	2711,28	2711,28	**2631,56**
6_lr_10	2611,45	2611,45	2563,26	2563,26	2495,00	2485,44	2447,00	2490,14	2519,25	2556,79	**2412,11**
7_lr_10	2414,93	2414,93	2360,80	2352,47	2329,64	2305,18	2386,68	2339,19	**2210,69**	**2217,24**	**2220,27**
8_lr_10	2204,50	2204,50	2105,01	2104,64	2309,79	2309,90	2283,83	2144,96	2400,29	2363,056	**2029,93**
9_lr_10	2576,03	2558,76	2378,77	2442,95	2516,38	2491,12	2516,84	2472,67	2618,10	2617,23	**2311,37**
10_lr_10	2371,50	2371,50	2298,51	2440,98	2346,45	2338,66	2353,96	2351,08	2369,95	2370,60	**2222,99**
11_lr_10	2250,70	2250,32	**2186,63**	2233,65	2287,58	2267,21	2277,41	2284,67	2281,30	2264,44	**2189,53**
12_lr_10	2114,29	2111,45	2127,94	2397,57	2119,54	2129,82	2138,72	2112,69	2137,82	2136,61	**2013,17**
1_lr_20	**3105,46**	**3110,11**	**3104,09**	**3079,36**	**3247,05**	**3217,75**	**3255,27**	**3250,00**	**3421,48**	**3423,60**	**3495,81**
2_lr_20	2939,60	2939,60	2946,78	2946,78	2890,09	2877,41	2914,31	2982,18	**2602,15**	**2599,49**	**2749,39**
3_lr_20	**2403,06**	**2402,78**	**2403,77**	**2398,36**	**2502,16**	**2491,18**	**2488,43**	**2478,56**	**2581,83**	**2564,70**	**2762,80**
4_lr_20	2243,99	2247,25	2253,09	2244,82	2215,63	2220,50	2212,35	2194,99	2197,58	2205,90	**1988,57**
5_lr_20	**2480,29**	**2480,29**	**2490,58**	**2490,58**	**2493,13**	**2497,59**	**2496,83**	**2503,01**	**2478,63**	**2477,48**	**2550,13**
6_lr_20	**2423,41**	**2419,42**	**2385,79**	**2390,53**	**2388,45**	**2389,70**	**2390,64**	**2395,61**	**2393,348**	**2388,34**	**2502,46**
7_lr_20	2061,83	2011,78	2208,56	2204,02	2221,23	2217,18	2238,04	2216,48	2195,24	2176,07	**1936,44**
8_lr_20	2030,12	2028,68	2004,46	2004,39	1972,99	1984,61	1992,34	2012,66	2014,69	2035,92	**1858,36**
9_lr_20	**2368,02**	2368,02	2611,94	2617,86	**2373,12**	**2344,57**	**2373,28**	**2361,16**	**2334,49**	**2331,21**	**2432,61**
10_lr_20	**2450,28**	2438,96	**2422,19**	**2419,82**	**2500,53**	**2484,98**	**2464,68**	**2464,65**	**2546,72**	**2432,96**	**2782,06**
11_lr_20	2055,47	2055,47	3315,03	3315,03	2051,77	2056,96	2022,94	2024,84	**1875,79**	1966,61	**1954,57**
1_lrc_10	3245,99	3249,95	3103,81	3658,80	3510,58	3435,37	3499,81	3539,53	3245,99	3249,96	**2956,32**
2_lrc_10	2771,63	2770,91	**2760,90**	**2760,90**	2931,95	2899,02	2930,28	2947,46	2794,24	2784,82	**2764,14**
3_lrc_10	**2422,22**	**2421,57**	2602,68	2602,68	2522,09	2506,21	2488,06	2482,17	**2424,98**	**2421,97**	**2443,68**
4_lrc_10	2578,47	2575,36	**2236,67**	**2233,38**	**2227,58**	2252,36	2270,53	2258,98	2241,45	**2233,70**	**2238,17**
5_lrc_10	3467,77	3465,32	3297,41	3297,31	3252,43	3250,98	3463,79	3305,76	3467,77	3465,32	**2830,16**
6_lrc_10	2651,84	2651,84	2726,65	2718,71	2814,10	2797,00	2782,37	2814,35	2648,48	2651,84	**2475,01**
7_lrc_10	2602,85	2596,62	2616,30	2611,07	2540,20	2528,85	2554,87	2529,72	2435,78	2431,55	**2344,94**
8_lrc_10	**2226,82**	**2238,27**	**2223,39**	**2222,21**	2452,04	2383,95	2344,10	2332,89	2376,64	2426,64	**2245,30**
1_lrc_20	3611,74	3609,55	3492,28	3491,75	3425,30	**3358,41**	3411,38	3406,55	3368,65	**3352,82**	**3358,41**
2_lrc_20	2993,31	2993,31	3149,70	3146,85	3041,91	3062,50	3026,56	3004,51	2985,67	2916,63	**2657,14**
3_lrc_20	**2594,98**	**2587,87**	2736,44	2722,74	**2669,90**	**2630,91**	**2679,529**	**2658,08**	**2687,098**	2716,80	**2700,30**
4_lrc_20	**2358,25**	**2350,42**	**2260,70**	**2253,71**	**2326,35**	**2315,22**	**2309,70**	**2307,90**	**2335,96**	**2325,06**	**2537,83**
5_lrc_20	**3259,95**	**3259,95**	**3447,38**	**3444,89**	**3272,31**	**3264,73**	**3255,01**	**3257,42**	**3259,95**	**3259,95**	**3464,61**
6_lrc_20	2784,99	2784,56	2662,16	2662,16	2759,43	2754,23	**2444,87**	2757,90	2760,87	2748,86	**2444,87**
7_lrc_20	**2372,90**	**2365,90**	2690,63	2680,38	2578,50	**2461,42**	2613,07	2585,34	2496,99	2501,45	**2461,42**
8_lrc_20	**2151,28**	**2140,17**	3569,67	3569,05	3222,85	3254,13	3064,58	3045,30	**2129,63**	**2114,50**	**2271,19**
Sum	269419,62	269239,67	288867,69	289852,35	274442,11	273494,64	273017,21	272870,49	269472,38	269421,64	**264565,83**

Number of instances for which the tested method obtained better or equal result as the meta-heuristic by Li nad Lim (2001)

better	20	19	15	14	14	13	11	12	18	19
equal	5	6	4	4	0	2	1	0	3	4
total	25	25	19	18	14	15	12	12	21	23
%	45	45	34	32	25	27	21	21	38	41

Number of instances in which the obtained result is the best from all the considered methods

	11	16	14	13	3	1	3	1	10	15

Improvement of the schedule cost value summarised for all the improved instances with respect to the values obtained by meta-heuristic Li nad Lim (2001)

sum	2475,37	2453,22	1668,62	1707,44	1619,16	1733,09	1667,53	1661,01	1911,23	1984,78

Table B.1 Values of the final schedule costs and their comparison with the results obtained by Li nad Lim (2001)

					expected value						
instance	area_2opt	area_rr	pair_2opt	pair_rr	angle_r_ nCust_2opt	angle_r_ nCust_rr	angle_r_ nVeh_2opt	angle_r_ nVeh_rr	angle_r_ 1_2opt	angle_r_ 1_rr	Metaheuristic Li and Lim (2001)
1_lc_10	3	3	2	2	3	3	3	2	4	4	33
2_lc_10	16	17	9	9	11	10	8	9	9	9	71
3_lc_10	17	17	15	15	11	11	11	11	15	15	191
4_lc_10	1	2	8	8	13	12	11	10	20	20	1254
5_lc_10	3	3	1	1	4	4	4	5	1	1	47
6_lc_10	2	2	3	3	7	6	6	6	8	6	43
7_lc_10	7	7	1	1	4	4	4	4	3	3	54
8_lc_10	4	4	5	5	10	10	10	10	7	7	82
9_lc_10	1	1	6	6	8	8	8	7	14	13	255
1_lc_20	132	132	1	1	22	27	22	25	10	134	27
2_lc_20	167	166	100	97	90	96	94	110	132	135	94
3_lc_20	72	72	156	153	127	126	126	122	135	136	145
4_lc_20	139	140	121	120	121	129	129	130	169	171	746
5_lc_20	20	20	62	62	49	58	74	72	33	37	190
6_lc_20	61	61	17	17	59	70	76	74	110	103	88
7_lc_20	93	92	6	6	896	70	74	78	75	78	102
8_lc_20	68	69	55	54	55	60	74	70	72	71	178
1_lr_10	0	0	0	0	4	1	0	0	0	0	87
2_lr_10	0	0	0	0	3	1	2	1	1	1	1168
3_lr_10	1	1	0	0	3	2	3	3	10	9	169
4_lr_10	7	7	16	16	2	4	5	4	2	2	459
5_lr_10	0	0	1	1	3	2	1	1	1	1	69
6_lr_10	1	1	1	1	2	3	3	2	3	2	87
7_lr_10	2	2	4	4	2	6	5	5	3	3	287
8_lr_10	1	1	3	3	2	1	1	1	0	0	415
9_lr_10	1	1	6	5	2	2	2	2	0	0	348
10_lr_10	3	3	3	1	2	6	6	5	11	11	547
11_lr_10	10	10	11	17	2	8	8	8	12	12	179
12_lr_10	16	16	18	1	2	6	9	9	10	9	638
1_lr_20	93	93	108	107	58	62	59	62	19	19	193
2_lr_20	77	77	74	74	89	98	84	88	135	133	885
3_lr_20	170	171	223	224	138	143	138	139	89	92	1950
4_lr_20	194	192	191	191	185	177	176	182	174	180	2655
5_lr_20	148	148	166	165	124	105	111	116	156	152	585
6_lr_20	194	193	39	38	121	128	134	132	163	162	747
7_lr_20	311	310	230	230	178	179	182	188	201	186	1594
8_lr_20	198	197	223	223	210	221	214	201	202	211	3572
9_lr_20	220	220	104	105	177	158	157	184	169	177	2773
10_lr_20	145	144	108	109	154	155	152	147	197	190	1482
11_lr_20	232	231	1	1	24	15	57	55	1068	210	4204
1_lrc_10	0	0	2	0	1	1	1	1	0	3	119
2_lrc_10	1	1	4	4	2	2	2	2	1	1	152
3_lrc_10	5	5	2	2	4	5	6	6	5	5	175
4_lrc_10	1	1	5	6	6	7	6	5	3	3	202
5_lrc_10	0	0	1	1	3	3	2	2	0	0	179
6_lrc_10	2	2	2	1	2	2	1	1	2	2	459
7_lrc_10	1	1	1	1	3	3	3	3	6	6	154
8_lrc_10	3	3	4	4	3	4	3	3	2	2	650
1_lrc_20	76	76	35	36	51	51	50	50	59	57	266
2_lrc_20	21	21	29	29	90	89	99	95	84	73	987
3_lrc_20	120	120	57	60	116	118	118	114	75	61	1605
4_lrc_20	149	150	179	179	144	140	155	145	218	223	3634
5_lrc_20	18	18	95	95	68	68	71	77	18	18	639
6_lrc_20	139	139	147	148	93	95	94	94	123	123	445
7_lrc_20	157	156	19	20	110	103	100	106	110	96	607
8_lrc_20	196	198	3	3	36	32	47	48	164	164	4106
Sum	3719	3717	2683	2665	3709	2910	3001	3032	4313	3542	43072

Number of instances for which the tested method obtained better or equal result as the meta-heuristic by Li and Lim (2001)

better	52	54	54	54	55	54	55	55	53	52
equal	0	0	0	0	0	1	1	0	0	0
total	52	54	54	54	55	55	56	55	53	52
%	93	96	96	96	98	98	100	98	95	93

Number of instances in which the obtained result is the best from all the considered methods

	10	18	20	22	7	3	4	4	13	10

Improvement of the actual cpu value summarised for all the improved instances with respect to the values obtained by meta-heuristic by Li and Lim (2001)

sum	39531,00	39532,00	40278,00	40418,00	40016,00	40164,00	40071,00	40056,00	38819,00	39693,00

Table B.2 Values of the actual cpu [sec] and their comparison with the results obtained by Li and Lim (2001)

					expected value						
instance	area_2opt	area_rr	pair_2opt	pair_rr	angle_r_ nCust_2opt	angle_r_ nCust_rr	angle_r_ nVeh_2opt	angle_r_ nVeh_rr	angle_r_ 1_2opt	angle_r_ 1_rr	Metaheuristic Li and Lim (2001)
1_lc_10	23	23	24	24	24	23	23	23	22	22	33
2_lc_10	17	17	17	17	19	19	19	19	19	18	71
3_lc_10	18	18	19	19	18	19	18	18	19	19	191
4_lc_10	20	20	20	20	20	20	20	20	21	21	1254
5_lc_10	21	21	20	20	21	21	20	21	21	21	47
6_lc_10	20	20	21	21	21	21	20	20	20	20	43
7_lc_10	20	20	20	20	23	23	21	22	21	21	54
8_lc_10	20	20	19	19	20	20	19	19	20	20	82
9_lc_10	20	20	19	19	20	20	19	19	20	20	255
1_lc_20	178	177	241	237	183	186	198	193	9592	180	27
2_lc_20	183	182	178	173	153	158	165	167	179	181	94
3_lc_20	176	175	176	173	166	168	169	168	177	178	145
4_lc_20	187	188	154	154	159	163	161	163	191	192	746
5_lc_20	246	246	190	188	190	162	170	175	232	236	190
6_lc_20	229	229	230	228	156	160	160	152	197	198	88
7_lc_20	194	193	124	123	988	160	170	170	206	206	102
8_lc_20	204	205	135	134	126	127	145	138	169	170	178
1_lr_10	9	9	8	8	9	9	9	8	9	9	87
2_lr_10	13	13	14	14	12	13	13	12	15	16	1168
3_lr_10	15	15	12	11	12	12	14	13	107	12	169
4_lr_10	16	16	18	18	19	20	19	19	23	23	459
5_lr_10	13	14	12	12	12	12	13	13	16	16	69
6_lr_10	16	16	16	15	15	15	15	15	14	14	87
7_lr_10	17	17	16	15	16	16	17	17	20	20	287
8_lr_10	19	19	18	18	17	17	18	17	15	20	415
9_lr_10	17	17	14	13	16	16	16	15	16	16	348
10_lr_10	14	14	14	14	14	14	14	14	12	12	547
11_lr_10	18	18	20	17	17	18	19	18	18	18	179
12_lr_10	17	17	18	24	20	20	19	19	17	17	638
1_lr_20	134	134	115	115	119	121	124	124	156	156	193
2_lr_20	174	174	136	135	139	139	136	137	178	177	885
3_lr_20	261	262	243	244	215	215	212	220	240	239	1950
4_lr_20	244	242	229	230	241	242	240	248	257	260	2655
5_lr_20	221	220	214	214	197	201	205	203	220	220	585
6_lr_20	207	206	204	203	188	188	190	191	204	243	747
7_lr_20	326	324	233	233	253	252	245	250	269	279	1594
8_lr_20	280	279	225	225	302	302	302	308	419	419	3572
9_lr_20	223	222	146	148	186	189	188	193	220	220	2773
10_lr_20	249	247	218	221	205	206	211	211	241	241	1482
11_lr_20	238	238	55	52	86	78	124	129	1088	226	4204
1_lrc_10	13	13	12	12	11	12	12	12	13	13	119
2_lrc_10	19	19	15	15	15	15	15	15	19	19	152
3_lrc_10	15	15	19	19	15	16	15	16	15	15	175
4_lrc_10	21	21	23	23	21	21	22	23	24	22	202
5_lrc_10	15	15	13	14	13	13	13	14	15	15	179
6_lrc_10	17	17	16	20	16	16	16	16	18	17	459
7_lrc_10	17	17	18	18	17	17	17	17	16	16	154
8_lrc_10	21	21	19	20	18	18	18	18	19	18	650
1_lrc_20	98	98	101	103	102	103	106	106	115	118	266
2_lrc_20	161	160	125	125	131	129	135	135	149	153	987
3_lrc_20	178	179	141	144	172	168	157	160	75	167	1605
4_lrc_20	221	222	217	217	210	210	212	209	227	229	3634
5_lrc_20	122	123	102	101	109	108	110	110	122	123	639
6_lrc_20	152	152	167	169	145	147	150	148	154	155	445
7_lrc_20	207	207	144	145	142	146	146	146	203	208	607
8_lrc_20	224	225	43	44	66	62	81	81	221	222	4106
Sum	6018	6011	4980	4977	5820	4986	5105	5127	16305	6106	43072
Difference between total and actual cpu [sec]											
	2299	2294	2297	2312	2111	2076	2104	2095	11992	2564	
The percentage of total cpu value that constitutes the actual cpu											
	62	62	54	54	64	58	59	59	26	58	
Number of instances for which the algorithm obtained better or equal result as the meta-heuristic by Li and Lim (2001)											
better	49	49	50	51	50	51	51	51	50	50	
equal	0	0	1	0	1	0	0	0	0	0	
total	49	49	51	51	51	51	51	51	50	50	
%	88	88	91	91	91	91	91	91	89	89	
Number of instances in which the obtained result is the best from all the considered methods											
	10	11	19	22	20	9	12	12	9	8	
Increment of the total cpu value summarised for all the improved instances with respect to the values obtained by meta-heuristic by Li and Lim (2001)											
sum	37640,00	37644,00	38585,00	38573,00	38443,97	38466,71	38368,45	38339,60	36700,66	37500,21	

Table B.3 Values of the total cpu [sec] and their comparison with the results obtained by Li and Lim (2001)

	angle_r_nCust_2opt		angle_r_nCust_rr		angle_r_Veh_2opt		angle_r_nVeh_rr		angle_r_1_2opt		Angle_r_1_rr		Metaheuristic Li and Lim (2001)
instance	**actual cpu**	**total cpu**	**actual cpu**	**total cpu**	**actual cpu**	**total cpu**	**actual cpu**	**total cpu**	**actual cpu**	**total cpu**	**actual cpu**	**total cpu**	
1_lc_10	304	2319	297	2313	304	2319	217	2286	427	2204	389	2178	**33**
2_lc_10	1112	1906	1045	1910	1112	1906	934	1932	941	1857	931	1808	**71**
3_lc_10	1106	1845	1137	1846	1106	1845	1066	1818	1513	1930	1494	1900	**191**
4_lc_10	1260	2018	**1186**	2013	1260	2018	**1014**	1978	**2045**	2157	2007	2128	**1254**
5_lc_10	416	2092	405	2108	416	2092	408	2056	100	2088	99	2053	**47**
6_lc_10	664	2046	635	2070	664	2046	623	2020	802	1990	634	1954	**43**
7_lc_10	391	2258	356	2277	391	2258	438	2161	343	2141	337	2103	**54**
8_lc_10	1023	1999	1022	1988	1023	1999	960	1941	678	2003	665	1973	**82**
9_lc_10	811	2019	804	2012	811	2019	685	1941	1357	2014	1322	1984	**255**
1_lc_20	2156	18315	2659	18607	2171	19763	2456	19277	13250	17849	13358	18016	**27**
2_lc_20	8961	15348	9591	15790	9376	16490	11024	16661	13215	17931	13515	18133	**94**
3_lc_20	12706	16563	12597	16755	12588	16886	12183	16772	13457	17677	13602	17804	**145**
4_lc_20	12128	15936	12854	16251	12946	16142	12960	16331	16906	19120	17086	19189	**746**
5_lc_20	4902	16504	5798	16170	7447	17002	7216	17475	3272	23171	3742	23628	**190**
6_lc_20	5908	15615	6952	16005	7629	16261	7418	15166	11034	19661	10326	19756	**88**
7_lc_20	89638	98815	6962	15999	7404	16976	7826	16951	7506	20551	7781	20620	**102**
8_lc_20	5484	12585	6042	12701	7427	14502	6966	13776	7237	16938	7094	17016	**178**
1_lr_10	93	874	100	879	**40**	900	**37**	839	**1**	940	**0**	947	**87**
2_lr_10	**130**	1203	**101**	1261	**156**	1267	**142**	1222	**83**	1548	**83**	1558	**1168**
3_lr_10	222	1243	251	1246	260	1365	296	1297	927	1200	850	1240	**169**
4_lr_10	509	1891	**4**	**20**	474	1929	**447**	1880	**272**	2291	**229**	2336	**459**
5_lr_10	242	1208	**2**	**12**	150	1345	140	1306	54	1587	**54**	1597	**69**
6_lr_10	265	1445	**3**	**15**	256	1541	238	1484	329	1413	280	1435	**87**
7_lr_10	646	1617	**6**	**16**	528	1725	503	1684	292	1999	292	1995	**287**
8_lr_10	**78**	1655	**79**	1670	**96**	1775	**110**	1715	**42**	1487	**45**	1530	**415**
9_lr_10	**198**	1577	**2**	**16**	**228**	1616	**226**	1538	**54**	1560	**53**	1568	**348**
10_lr_10	625	1349	**6**	**14**	565	1408	**543**	1355	**1050**	1165	1064	1170	**547**
11_lr_10	819	1731	**8**	**18**	819	1924	802	1806	1203	1790	1211	1804	**179**
12_lr_10	724	1975	**6**	**20**	855	1919	859	1869	948	1733	875	1752	**638**
1_lr_20	5786	11910	6198	12110	5863	12354	6188	12413	1858	15558	1856	15563	**193**
2_lr_20	8860	13893	9755	13890	8440	13637	8761	13656	13515	17811	13330	17732	**885**
3_lr_20	13841	21458	14346	21464	13760	21217	13881	21970	8947	23952	9193	23861	**1950**
4_lr_20	18484	24088	17705	24190	17630	23966	18162	24778	17406	25681	17954	25986	**2655**
5_lr_20	12364	19695	10524	20079	11045	20449	11554	20327	15597	22015	15163	22012	**585**
6_lr_20	12083	18804	12788	18770	13359	19018	13167	19054	16321	20434	16192	20524	**747**
7_lr_20	17806	25259	17934	25201	18212	24531	18748	25040	20059	26915	18626	27937	**1594**
8_lr_20	20963	30217	22056	30229	21426	30226	20132	30840	20180	41917	21102	41895	**3572**
9_lr_20	12121	18643	13049	18872	12918	18767	12860	19250	16889	21975	17675	22015	**2773**
10_lr_20	15412	20522	15535	20632	15192	21110	14709	21080	19680	24133	19012	24119	**1482**
11_lr_20	**2384**	8627	**1471**	7758	5656	12393	5541	12943	106792	108846	20992	22578	**4204**
1_lrc_10	**112**	1129	**105**	1179	**65**	1205	**61**	1192	**11**	1355	**11**	1355	**119**
2_lrc_10	169	1491	181	1524	192	1485	165	1482	74	1901	74	1901	**152**
3_lrc_10	444	1542	451	1592	599	1550	557	1561	508	1535	508	1535	**175**
4_lrc_10	650	2102	664	2146	562	2204	549	2277	303	2364	303	2364	**202**
5_lrc_10	262	1262	257	1283	**163**	1335	193	1367	1	1533	1	1533	**179**
6_lrc_10	**153**	1584	**148**	1603	**141**	1616	**139**	1592	**181**	1779	**181**	1779	**459**
7_lrc_10	310	1654	334	1672	323	1718	332	1741	559	1614	559	1614	**154**
8_lrc_10	**291**	1798	**381**	1797	**311**	1757	**291**	1791	**181**	1930	**181**	1930	**650**
1_lrc_20	5049	10181	5055	10293	4966	10560	4985	10574	5843	11522	5676	11798	**266**
2_lrc_20	8986	13082	8891	12860	9906	13510	9523	13512	8365	14935	7311	15298	**987**
3_lrc_20	11635	17191	11778	16771	11827	15737	11423	16009	7487	16895	6127	16713	**1605**
4_lrc_20	14446	20982	13959	21045	15529	21198	14470	20904	21805	22686	22309	22918	**3634**
5_lrc_20	6825	10879	6819	10767	7072	10962	7647	11014	1791	12182	1800	12284	**639**
6_lrc_20	9324	14536	9522	14709	9370	15043	9440	14825	12332	15419	12322	15524	**445**
7_lrc_20	10977	14187	10333	14583	9952	14630	10586	14574	11019	20286	9589	20751	**607**
8_lrc_20	**3631**	6594	**3217**	6164	4739	8146	4843	8090	16369	22053	16428	22165	**4106**
Sum	366890	579260	284365	485185	297724	511563	297644	512392	443410	689222	353893	606861	**43072**

Number of instances for which the algorithm obtained better result than the meta-heuristic by Li and Lim (2001)

better	8	0	16	8	8	0	10	0	11	0	11	0
%	14	0	29	14	14	0	18	0	20	0	20	0

Number of instances in which the obtained result is the best from all the considered random methods

	12	17	13	15	2	6	9	8	11	5	14	7

Table B.4 Aggregated values of the actual and total cpu [sec] time of performing 100 times each instance by a specific method and their comparison with the results obtained by Li and Lim (2001)

nstance	Metaheuristic [LiLi_2001]	the best schedule cost	value of imp/det	% of imp/det	method									
LC101	9828,94	9828,94	0	0	area_2opt	area_rr	pair_2opt	pair_rr	ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr	ang_r_1_2opt	ang_r_1_rr
LC102	9828,94	9828,94	0	0					ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr	ang_r_1_2opt	ang_r_1_rr
LC103	10058,03	9906,15	151,88	2							ang_r_nVeh_2opt			
LC104	10006,9	9901,7	105,2	1							ang_r_nVeh_2opt			
LC105	9828,94	9828,94	0	0		area_rr	pair_2opt	pair_rr	ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr	ang_r_1_2opt	ang_r_1_rr
LC106	9828,94	9828,94	0	0	area_2opt	area_rr			ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr		ang_r_1_rr
LC107	9828,94	9828,94	0	0	area_2opt	area_rr	pair_2opt	pair_rr	ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr	ang_r_1_2opt	ang_r_1_rr
LC108	9826,94	9826,44	0,5	0		area_rr	pair_2opt	pair_rr	ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr	ang_r_1_2opt	ang_r_1_rr
LC109	9831,78	9828,94	2,84	0	area_2opt	area_rr	pair_2opt	pair_rr	ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr	ang_r_1_2opt	ang_r_1_rr
LC201	9591,56	9591,56	0	0	area_2opt	area_rr			ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr	ang_r_1_2opt	ang_r_1_rr
LC202	9591,56	9678,14	-86,58	-1								ang_r_nVeh_rr		
LC203	9521,66	9694,79	-173,13	-2								ang_r_nVeh_rr		
LC204	9591,17	9674,68	-83,51	-1								ang_r_nVeh_rr		
LC205	9588,88	9588,88	0	0	area_2opt	area_rr	pair_2opt	pair_rr	ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr	ang_r_1_2opt	ang_r_1_rr
LC206	9588,49	9588,49	0	0					ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr	ang_r_1_2opt	ang_r_1_rr
LC207	9660,40	9588,32	72,08	1	area_2opt	area_rr			ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr	ang_r_1_2opt	ang_r_1_rr
LC208	9744,23	9595,99	148,24	2	area_2opt				ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr	ang_r_1_2opt	ang_r_1_rr
LR101	3599,45	3558,56	40,89	1					ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr		
LR102	3202,46	3091,81	110,65	3					ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr		
LR103	2729,15	2610,99	118,16	4							ang_r_nVeh_2opt	ang_r_nVeh_rr		
LR104	2050,85	2093,7	-42,85	-2			pair_2opt							
LR105	2631,56	2614,21	17,35	1					ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr		
LR106	2412,11	2390,19	21,92	1					ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr		
LR107	2220,27	2178,69	41,58	2					ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr		
LR108	2029,93	2005,94	23,99	1								ang_r_nVeh_rr		
LR109	2311,37	2282,2	29,17	1					ang_r_nCust_2opt	ang_r_nCust_rr		ang_r_nVeh_rr		
LR110	2222,99	2263,58	-40,59	-2					ang_r_nCust_2opt					
LR111	2189,53	2186,63	2,9	0			pair_2opt		ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr		
LR112	2013,17	2013,6	-0,43	0						ang_r_nCust_rr				
LR201	3495,81	3053,08	442,73	13					ang_r_nCust_2opt					
LR202	2749,39	2588,26	161,13	6							ang_r_nVeh_2opt			
LR203	2762,80	2325,28	437,52	<u>16</u>								ang_r_nVeh_rr		
LR204	1988,57	1954,12	34,45	2						ang_r_nCust_rr				
LR205	2550,13	2421,25	128,88	5							ang_r_nVeh_2opt			
LR206	2502,46	2286,88	215,58	9								ang_r_nVeh_rr		
LR207	1936,44	1965,57	-29,13	-2							ang_r_nVeh_2opt			
LR208	1858,36	1782,74	75,62	4							ang_r_nVeh_2opt			
LR209	2432,61	2285,56	147,05	6						ang_r_nCust_rr				
LR210	2782,06	2379,16	402,9	14					ang_r_nCust_2opt					
LR211	1954,57	2029,7	-75,13	<u>-4</u>								ang_r_nVeh_rr		
LRC101	2956,32	2955,98	0,34	0					ang_r_nCust_2opt		ang_r_nVeh_2opt			
LRC102	2764,14	2676,29	87,85	3					ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt		ang_r_1_2opt	
LRC103	2443,68	2396,89	46,79	2						ang_r_nCust_rr	ang_r_nVeh_2opt			
LRC104	2238,17	2197,4	40,77	2						ang_r_nCust_rr		ang_r_nVeh_rr		
LRC105	2830,16	2828,28	1,88	0						ang_r_nCust_rr				
LRC106	2475,01	2472,52	2,49	0									ang_r_1_2opt	
LRC107	2344,94	2339,67	5,27	0									ang_r_1_2opt	
LRC108	2245,30	2222,15	23,15	1						ang_r_nCust_rr		ang_r_nVeh_rr		
LRC 201	3358,41	3184,54	173,87	5							ang_r_nVeh_2opt			
LRC202	2657,14	2628,69	28,45	1								ang_r_nVeh_rr		
LRC 203	2700,30	2410,71	289,59	11								ang_r_nVeh_rr		
LRC 204	2537,83	2153,89	383,94	15					ang_r_nCust_2opt					
LRC 205	3464,61	3099,1	365,51	11						ang_r_nCust_rr				
LRC 206	2444,87	2452,63	-7,76	0					ang_r_nCust_2opt					
LRC 207	2461,42	2308,13	153,29	6						ang_r_nCust_rr				
LRC 208	2271,19	2103,89	167,3	7										ang_r_1_rr
Number of iterations with the outcome at least as good as this of [LiLi_2001]				47	Number of instances in which the obtained result is the best from all the considered random methods									
% of improved instances				84	8	9	8	6	26	29	29	<u>31</u>	14	13
% of the biggest improvement value				16										
% of the biggest deterioration value				-4										

Table B.5 The best obtained values of the final schedule cost and their comparison with the results obtained by Li and Lim (2001)

instance	Metaheuristic [LiLi_2001]	the best best cpu [s]	value of imp/det	% of imp/det	method									
1_lc_10	33	1	32	97					ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr		
2_lc_10	71	1	70	99								ang_r_nVeh_rr		
3_lc_10	191	10	181	95							ang_r_nVeh_2opt			
4_lc_10	1254	1	1253	100	area_2opt									
5_lc_10	47	1	46	98			pair_2opt	pair_rr		ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr	ang_r_1_2opt	ang_r_1_rr
6_lc_10	43	1	42	98					ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr		
7_lc_10	54	1	53	98			pair_2opt	pair_rr	ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr		
8_lc_10	82	1	81	99								ang_r_nVeh_rr		
9_lc_10	255	1	254	100	area_2opt	area_rr			ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr		
1_lc_20	27	1	26	96			pair_2opt	pair_rr						
2_lc_20	94	46	48	51						ang_r_nCust_rr				
3_lc_20	145	72	73	50	area_2opt	area_rr								
4_lc_20	746	120	626	84				pair_rr						
5_lc_20	190	20	170	89	area_2opt	area_rr							ang_r_1_2opt	ang_r_1_rr
6_lc_20	88	17	71	81			pair_2opt	pair_rr						
7_lc_20	102	6	96	94			pair_2opt	pair_rr						
8_lc_20	178	21	157	88								ang_r_nVeh_rr		
1_lr_10	87	0	87	100	area_2opt	area_rr	pair_2opt	pair_rr				ang_r_nVeh_rr	ang_r_1_2opt	ang_r_1_rr
2_lr_10	1168	0	1168	100	area_2opt	area_rr	pair_2opt	pair_rr		ang_r_nCust_rr		ang_r_nVeh_rr		
3_lr_10	169	0	169	100			pair_2opt	pair_rr						
4_lr_10	459	6	453	99					ang_r_nCust_2opt					
5_lr_10	69	0	69	100	area_2opt	area_rr							ang_r_1_2opt	ang_r_1_rr
6_lr_10	87	1	86	99	area_2opt	area_rr	pair_2opt	pair_rr		ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr		
7_lr_10	287	2	285	99	area_2opt	area_rr						ang_r_nVeh_rr		
8_lr_10	415	0	415	100									ang_r_1_2opt	ang_r_1_rr
9_lr_10	348	1	347	100	area_2opt	area_rr					ang_r_nVeh_2opt			
10_lr_10	547	1	546	100				pair_rr						
11_lr_10	179	4	175	98						ang_r_nCust_rr				
12_lr_10	638	1	637	100				pair_rr						
1_lr_20	193	18	175	91									ang_r_1_2opt	ang_r_1_rr
2_lr_20	885	53	832	94							ang_r_nVeh_2opt			
3_lr_20	1950	113	1837	94									ang_r_1_2opt	ang_r_1_rr
4_lr_20	2655	83	2572	97							ang_r_nVeh_2opt			
5_lr_20	585	36	549	94										ang_r_1_rr
6_lr_20	747	38	709	95				pair_rr						
7_lr_20	1594	88	1506	94									ang_r_1_2opt	ang_r_1_rr
8_lr_20	3572	197	3375	94		area_rr								
9_lr_20	2773	100	2673	96								ang_r_nVeh_rr		
10_lr_20	1482	108	1374	93			pair_2opt							
11_lr_20	4204	1	4203	100			pair_2opt	pair_rr						
1_lrc_10	119	0	119	100	area_2opt	area_rr		pair_rr					ang_r_1_2opt	ang_r_1_rr
2_lrc_10	152	1	151	99	area_2opt	area_rr			ang_r_nCust_2opt			ang_r_nVeh_rr		ang_r_1_rr
3_lrc_10	175	2	173	99			pair_2opt	pair_rr						
4_lrc_10	202	1	201	100	area_2opt	area_rr								
5_lrc_10	179	0	179	100	area_2opt	area_rr							ang_r_1_2opt	ang_r_1_rr
6_lrc_10	459	1	458	100				pair_rr						
7_lrc_10	154	1	153	99	area_2opt	area_rr	pair_2opt	pair_rr						
8_lrc_10	650	2	648	100						ang_r_nCust_rr				
1_lrc_20	266	35	231	87			pair_2opt							
2_lrc_20	987	21	966	98	area_2opt	area_rr								
3_lrc_20	1605	57	1548	96			pair_2opt							
4_lrc_20	3634	110	3524	97									ang_r_1_2opt	
5_lrc_20	639	18	621	97	area_2opt	area_rr							ang_r_1_2opt	ang_r_1_rr
6_lrc_20	445	27	418	94					ang_r_nCust_2opt					
7_lrc_20	607	19	588	97			pair_2opt							
8_lrc_20	4106	3	4103	100			pair_2opt	pair_rr						
Number of iterations with the outcome at least as good as this of [LiLi_2001]				56	Number of instances in which the obtained result is the best from all the considered random methods									
% of improved instances				100	17	17	17	19	7	10	10	14	12	13
The percentage of the biggest improvement				100										
The percentage of the smallest improvement				50										

Table B.6 Values of the actual cpu [sec] necessary to obtain the best values of the final schedule cost and their comparison with the results obtained by Li and Lim (2001)

instance	Metaheuristic [LiLi_2001]	the best total cpu [s]	value of imp/det	% of imp/det	method									
1_lc_10	33	22	11	33										ang_r_1_rr
2_lc_10	71	17	54	76	area_2opt	area_rr	pair_2opt	pair_2opt						
3_lc_10	191	18	173	91	area_2opt	area_rr					ang_r_nVeh_2opt			
4_lc_10	1254	19	1235	98							ang_r_nVeh_2opt			
5_lc_10	47	20	27	57			pair_2opt	pair_2opt	ang_r_nCust_2opt		ang_r_nVeh_2opt		ang_r_1_2opt	ang_r_1_rr
6_lc_10	43	19	24	56									ang_r_1_2opt	ang_r_1_rr
7_lc_10	54	20	34	63	area_2opt	area_rr	pair_2opt	pair_2opt					ang_r_1_2opt	ang_r_1_rr
8_lc_10	82	19	63	77			pair_2opt	pair_2opt					ang_r_1_2opt	
9_lc_10	255	19	236	93			pair_2opt	pair_2opt			ang_r_nVeh_2opt	ang_r_nVeh_rr		
1_lc_20	27	176	-149	-552									ang_r_1_2opt	
2_lc_20	94	148	-54	-57							ang_r_nVeh_2opt			
3_lc_20	145	157	-12	-8						ang_r_nCust_rr				
4_lc_20	746	154	592	79			pair_2opt	pair_2opt						
5_lc_20	190	167	23	12						ang_r_nCust_rr				
6_lc_20	88	173	-85	-97						ang_r_nCust_rr				
7_lc_20	102	123	-21	-21				pair_2opt						
8_lc_20	178	134	44	25				pair_2opt						
1_lr_10	87	8	79	91			pair_2opt	pair_2opt						
2_lr_10	1168	11	1157	99								ang_r_nVeh_rr		
3_lr_10	169	11	158	93				pair_2opt	ang_r_nCust_2opt					
4_lr_10	459	16	443	97	area_2opt	area_rr							ang_r_1_2opt	ang_r_1_rr
5_lr_10	69	11	58	84					ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr		
6_lr_10	87	14	73	84									ang_r_1_2opt	ang_r_1_rr
7_lr_10	287	15	272	95				pair_2opt	ang_r_nCust_2opt	ang_r_nCust_rr				
8_lr_10	415	18	397	96			pair_2opt	pair_2opt					ang_r_1_2opt	ang_r_1_rr
9_lr_10	348	13	335	96				pair_2opt						
10_lr_10	547	12	535	98										ang_r_1_rr
11_lr_10	179	17	162	91				pair_2opt			ang_r_nVeh_2opt			
12_lr_10	638	17	621	97	area_2opt	area_rr							ang_r_1_2opt	ang_r_1_rr
1_lr_20	193	115	78	40			pair_2opt	pair_2opt						
2_lr_20	885	135	750	85				pair_2opt						
3_lr_20	1950	201	1749	90					ang_r_nCust_2opt					
4_lr_20	2655	229	2426	91			pair_2opt							
5_lr_20	585	202	383	65							ang_r_nVeh_2opt			
6_lr_20	747	203	544	73				pair_2opt	ang_r_nCust_2opt					
7_lr_20	1594	233	1361	85			pair_2opt	pair_2opt						
8_lr_20	3572	225	3347	94			pair_2opt	pair_2opt						
9_lr_20	2773	146	2627	95			pair_2opt							
10_lr_20	1482	217	1265	85					ang_r_nCust_2opt					
11_lr_20	4204	52	4152	99				pair_2opt						
1_lrc_10	119	12	107	90			pair_2opt	pair_2opt		ang_r_nCust_rr				
2_lrc_10	152	15	137	90			pair_2opt	pair_2opt						
3_lrc_10	175	14	161	92					ang_r_nCust_2opt					
4_lrc_10	202	20	182	90					ang_r_nCust_2opt	ang_r_nCust_rr	ang_r_nVeh_2opt	ang_r_nVeh_rr	ang_r_1_2opt	ang_r_1_rr
5_lrc_10	179	12	167	93							ang_r_nVeh_2opt			
6_lrc_10	459	14	445	97					ang_r_nCust_2opt			ang_r_nVeh_rr		
7_lrc_10	154	15	139	90					ang_r_nCust_2opt	ang_r_nCust_rr				ang_r_1_rr
8_lrc_10	650	15	635	98					ang_r_nCust_2opt					
1_lrc_20	266	98	168	63	area_2opt	area_rr								
2_lrc_20	987	125	862	87			pair_2opt	pair_2opt						
3_lrc_20	1605	141	1464	91			pair_2opt							
4_lrc_20	3634	209	3425	94					ang_r_nCust_2opt					
5_lrc_20	639	101	538	84				pair_2opt						
6_lrc_20	445	151	294	66						ang_r_nCust_rr				
7_lrc_20	607	144	463	76			pair_2opt							
8_lrc_20	4106	43	4063	99			pair_2opt							
Number of iterations with the outcome at least as good as this of [LiLi_2001]				51	Number of instances in which the obtained result is the best from all the considered random methods									
% of improved instances				91	8	6	19	24	13	9	10	5	10	11
The percentage of the biggest improvement				99										
The percentage of the biggest deterioration				-552										

Table B.7 Values of the total cpu [sec] necessary to obtain the best values of the final schedule cost and their comparison with the results obtained by Li and Lim (2001)

					expected value					
instance	**area_2opt**	**area_rr**	**pair_2opt**	**pair_rr**	**angle_r_ nCust_2opt**	**angle_r_ nCust_rr**	**angle_r_ nVeh_2opt**	**angle_r_ nVeh_rr**	**angle_r_ 1_2opt**	**angle_r_ 1_rr**
1_lc_10	12593,87	12593,87	35333,95	35333,95	29030,65	29079,14	16080,81	16104,53	10989,75	11015,37
2_lc_10	13040,75	13040,75	31668,84	31668,84	26083,30	26349,96	16087,17	15899,31	12347,45	12350,61
3_lc_10	12623,02	12623,02	27696,83	27696,83	23087,64	23246,19	15996,86	15808,32	12408,47	12423,53
4_lc_10	11317,09	11317,09	19829,90	19829,90	16860,35	17025,16	12481,53	12545,33	11362,65	11377,78
5_lc_10	13366,61	13366,61	34640,63	34640,63	28570,46	28532,07	15976,29	15956,32	11041,97	11003,77
6_lc_10	13999,28	13999,28	34935,92	34935,92	28038,34	27933,39	15864,16	15970,71	12005,92	12019,22
7_lc_10	13523,15	13523,15	33581,41	33581,41	28186,44	28258,88	14889,61	15001,36	11797,79	11796,54
8_lc_10	12818,83	12818,83	32795,59	32795,59	27012,46	27169,94	15538,90	15492,72	11817,15	11882,71
9_lc_10	10828,29	10828,29	27567,60	27567,60	23656,18	23575,24	13952,06	14194,74	11005,36	11067,25
1_lc_20	15773,64	15773,64	102505,62	102505,62	80145,52	79496,45	43101,99	43098,07	15773,64	15773,64
2_lc_20	13566,47	13566,47	91317,33	91317,33	72374,25	72152,98	37515,12	36976,73	13534,75	13536,65
3_lc_20	13344,71	13344,71	73231,71	73231,71	61570,74	61568,31	37515,12	35047,52	13367,64	13370,39
4_lc_20	13067,58	13067,58	47718,36	47718,36	42902,75	42821,64	29742,41	29640,92	13027,32	13023,90
5_lc_20	12830,17	12830,17	94266,58	94266,58	77582,09	77411,30	39880,86	39326,11	12841,37	12841,36
6_lc_20	12485,90	12485,90	95753,52	95753,52	75304,23	75304,21	40554,46	41122,92	12463,56	12458,38
7_lc_20	12390,00	12390,00	85804,12	85804,12	69321,55	69080,84	36513,09	36374,78	12731,14	12737,93
8_lc_20	12844,43	12844,43	85839,43	85839,43	70070,02	69762,17	36666,34	36604,84	12827,83	12826,81
1_lr_10	4270,24	4270,24	8381,80	8381,80	7411,89	7451,45	5586,71	5639,96	4170,77	4170,77
2_lr_10	3592,03	3592,03	7647,44	7647,44	6717,22	6730,30	4741,92	4721,20	3963,05	3963,05
3_lr_10	3662,51	3662,51	7019,41	7019,41	6378,04	6398,49	4771,30	4762,37	3555,17	3559,02
4_lr_10	3216,17	3216,17	5691,53	5691,53	4872,54	4865,04	3575,83	3594,52	3288,34	3288,36
5_lr_10	3307,87	3307,87	7687,61	7687,61	6550,73	6533,91	4312,01	4310,98	3103,03	2711,28
6_lr_10	3209,83	3209,83	7250,26	7250,26	6291,74	6315,02	4306,28	4249,88	3044,52	3051,04
7_lr_10	3190,01	3190,01	6716,31	6716,31	5578,12	5600,17	3992,92	4000,09	3363,88	3362,57
8_lr_10	3212,18	3212,18	5486,53	5486,53	4787,75	4769,19	3502,78	2144,96	3076,51	3089,25
9_lr_10	3151,24	3151,24	6988,82	6988,82	5910,85	5847,08	3941,22	3955,85	3064,97	3065,88
10_lr_10	3217,18	3217,18	6302,48	6302,48	5318,85	5324,39	3612,32	3636,48	3196,96	3197,39
11_lr_10	2956,15	2956,15	6683,68	6683,68	5612,21	5635,30	3840,84	3843,01	2542,62	2542,62
12_lr_10	3028,16	3028,16	5502,13	5502,13	4625,78	4616,35	3295,39	3151,76	3084,84	3083,08
1_lr_20	4811,66	4811,66	26796,13	26796,13	21976,79	21968,96	14110,70	14232,68	4913,75	4913,75
2_lr_20	4274,08	4274,08	24929,34	24929,34	20604,97	20571,09	12984,73	13030,87	4228,80	4206,53
3_lr_20	4170,46	4170,46	20256,08	20256,08	16758,25	16883,89	12019,10	12182,58	3829,87	3830,18
4_lr_20	3784,26	3784,26	13629,57	13629,57	11754,08	11723,06	8752,77	8767,77	3818,41	3817,67
5_lr_20	3802,82	3802,82	23474,88	23474,88	18242,95	18297,75	11641,74	11701,09	3836,43	3856,40
6_lr_20	4272,78	4272,78	22360,12	22360,12	17942,40	17963,60	11301,67	11296,26	3933,38	4042,56
7_lr_20	3591,27	3591,27	17494,60	17494,60	14966,54	15024,70	10429,03	10401,49	3351,59	3359,30
8_lr_20	3315,28	3315,28	11707,01	11707,01	9697,42	9739,02	7424,26	7414,00	3232,63	3232,61
9_lr_20	3691,78	3691,78	21525,22	21525,22	17890,44	17971,33	11162,78	11135,04	3973,10	3972,29
10_lr_20	3753,85	3753,85	22951,93	22951,93	18794,10	18860,18	12624,38	12797,63	3862,98	3745,97
11_lr_20	3104,66	3104,66	16734,23	16734,23	13967,38	14033,13	9064,82	9069,56	3093,74	3088,90
1_lrc_10	3612,94	3612,94	8439,52	8439,52	7001,39	7011,07	4737,02	4719,62	3612,94	3612,94
2_lrc_10	3481,43	3481,43	8008,14	8008,14	6434,03	6424,43	4609,19	4600,46	3501,21	3494,13
3_lrc_10	3342,29	3342,29	7100,61	7100,61	5883,15	5893,22	4203,35	4196,80	3341,04	3342,29
4_lrc_10	3348,96	3348,96	6539,00	6539,00	5417,63	5419,98	3707,70	3703,85	3286,28	3232,99
5_lrc_10	3470,64	3470,64	8239,12	8239,12	6715,36	6737,11	4606,37	4579,92	3466,04	3470,64
6_lrc_10	3355,62	3355,62	7664,31	7664,31	6018,29	6004,82	4084,01	4077,62	3361,72	3355,62
7_lrc_10	3557,00	3557,00	6920,66	6920,66	5221,30	5197,48	3700,45	3728,91	3457,91	3495,73
8_lrc_10	3373,55	3373,55	6253,26	6253,26	4713,73	4700,23	3343,12	3343,40	3421,65	3511,60
1_lrc_20	4702,49	4702,49	26309,96	26309,96	19782,41	19793,95	11629,32	11517,56	4576,81	4576,81
2_lrc_20	4673,44	4673,44	24393,34	24393,34	19883,85	19878,68	12485,28	12520,25	4680,98	4680,98
3_lrc_20	4368,04	4368,04	18430,53	18430,53	13077,70	14424,61	9830,04	10082,09	4374,74	4374,74
4_lrc_20	3698,70	3698,70	14292,10	14292,10	12373,54	12432,99	8414,37	8347,15	3457,28	3457,28
5_lrc_20	4783,24	4783,24	24876,00	24876,00	20461,01	20475,82	12885,88	12818,71	4783,24	4783,24
6_lrc_20	3804,83	3804,83	22861,43	22861,43	17991,51	17990,29	11265,09	11164,23	3904,91	3904,91
7_lrc_20	3764,76	3764,76	21000,16	21000,16	16627,36	16810,51	9827,67	9797,94	3847,38	3847,38
8_lrc_20	3314,54	3314,54	18216,25	18216,25	15129,26	15056,99	8724,24	8686,01	3433,89	3433,89
Initial solution sum	363652,70	363652,70	1487248,82	1487248,82	1215179,55	1216143,46	727405,39	723089,77	353381,10	353231,44
Final solution sum	269419,62	269239,67	288867,69	289852,35	274442,109	273494,64	273017,21	272870,49	269472,38	269421,6377
Number of instances that obtained the smallest result in comparison with the rest of the methods										
Initial solution	23	23	0	0	0	0	2	1	23	19
Final solution	11	16	14	13	3	1	3	1	10	15

Table B.8 Values of the initial schedule costs and their comparison with the final schedule cost obtained by each reviewed method

	PDP adapted 2-opt			NPDPRO		
	value of the schedule cost's improvement	best cpu [sec]	total cpu [sec]	value of the schedule cost's improvement	best cpu [sec]	total cpu [sec]
area						
total improvement	865,89	0	2551,00	**1045,84**	0	**2295,00**
average improvement	15,46	0	45,55	**18,68**	0	**40,98**
number of not improved instances	12			**7**		
pair						
total improvement	535,34	0	**2297,00**	**656,56**	0	2315,00
average improvement	9,56	0	**41,02**	**11,72**	0	41,34
number of not improved instances	14			**12**		
angle_s_nCust						
total improvement	596,89	2	1790,00	**838,41**	0	**1771,00**
average improvement	10,66	0	31,96	**14,97**	0	**31,63**
number of not improved instances	17			**15**		
angle_s_nVeh						
total improvement	744,06	1	2103,00	**776,81**	0	**2096,00**
average improvement	13,29	0	37,55	**13,87**	0	**37,43**
number of not improved instances	15			**14**		
angle_s_1						
total improvement	879,86	2	2421,30	**1055,89**	2	**2410,67**
average improvement	15,71	0	43,24	**18,86**	0	**43,05**
number of not improved instances	15			**12**		

Table B.9 Comparison of performance of two employed post-optimization methods: PDP adapted 2-opt and NPDPRO, regarding the value of schedule cost improvement and summarized amount of both the best and total cpu

		final schedule cost		actual cpu [sec]		total cpu [sec]	
		number	*%*	*number*	*%*	*number*	*%*
area	equal	26	0,46	40	0,71	35	0,63
	NPDPRO	**22**	**0,39**	**9**	**0,16**	**13**	**0,23**
	PDP adapted 2-opt	8	0,14	7	0,13	8	0,14
pair	equal	24	0,43	34	0,61	27	0,48
	NPDPRO	**23**	**0,41**	**12**	**0,21**	**16**	**0,29**
	PDP adapted 2-opt	9	0,16	10	0,18	13	0,23
ang_s_nCust	equal	23	0,41	35	0,63	25	0,45
	NPDPRO	**27**	**0,48**	**20**	**0,36**	**29**	**0,52**
	PDP adapted 2-opt	6	0,11	1	0,02	2	0,04
ang_s_nVeh	equal	19	0,34	37	0,66	31	0,55
	NPDPRO	**27**	0,48	**19**	**0,34**	**25**	**0,45**
	PDP adapted 2-opt	10	0,18	0	0,00	0	0,00
ang_s_1	equal	22	0,39	37	0,66	31	0,55
	NPDPRO	**24**	**0,43**	**18**	**0,32**	**24**	**0,43**
	PDP adapted 2-opt	10	0,18	1	0,02	1	0,02

Table B.10 Comparison of the methods, which create an initial solution using the same algorithm but apply a different post-optimization strategy. The table contains number of instances in which both methods provide the same result and in which each strategy has achieved a better outcome

Instance	Metaheuristic Li and Lim (2001)	angle_s_ nCust_2opt	angle_s_ nCust_rr	angle_s_ nVeh_2opt	angle_s_ nVeh_rr	angle_s_ 1_2opt	angle_s_ 1_rr
1_lc_10	9828,94	**9828,94**	**9828,94**	**9828,94**	**9828,94**	**9828,94**	**9828,94**
2_lc_10	9828,94	**9828,94**	**9828,94**	9830,17	**9828,94**	**9828,94**	**9828,94**
3_lc_10	10058,03	10169,99	10182,95	**9929,31**	**9960,49**	**9915,99**	**9937,38**
4_lc_10	10006,90	**9976,45**	**9997,39**	**9922,25**	**9935,11**	**9960,59**	**9964,51**
5_lc_10	9828,94	**9828,94**	**9828,94**	9848,93	**9828,94**	**9828,94**	**9828,94**
6_lc_10	9828,94	**9828,94**	**9828,94**	**9828,94**	**9828,94**	9838,93	**9828,94**
7_lc_10	9828,94	9838,59	**9828,94**	9830,17	**9828,94**	**9828,94**	**9828,94**
8_lc_10	9826,94	9830,57	**9826,44**	**9826,44**	**9826,44**	**9826,44**	**9826,44**
9_lc_10	9831,78	**9828,94**	**9828,94**	**9828,94**	**9828,94**	**9828,94**	**9828,94**
1_lc_20	9591,56	**9591,56**	**9591,56**	**9591,56**	**9591,56**	**9591,56**	**9591,56**
2_lc_20	9591,56	9961,39	9961,39	9887,58	9916,44	9777,18	9814,43
3_lc_20	9521,66	9952,47	9927,73	9860,00	9878,11	9812,19	9827,56
4_lc_20	9591,17	9928,60	9916,43	9847,47	9827,58	9941,58	9871,28
5_lc_20	9588,88	9601,66	**9588,88**	**9588,88**	**9588,88**	9756,94	9756,94
6_lc_20	9588,49	9819,85	9787,99	9794,85	9794,47	9626,65	9626,27
7_lc_20	9660,40	11112,88	11112,88	11313,78	11313,78	9722,02	9710,70
8_lc_20	9744,23	11280,01	11280,01	**9691,86**	**9689,37**	11291,24	11289,15
1_lr_10	3599,45	3673,84	3691,67	3740,15	3740,15	4170,77	4170,77
2_lr_10	3202,46	3264,86	3264,86	**3091,81**	**3091,81**	**3117,71**	**3117,71**
3_lr_10	2729,15	**2645,44**	**2647,57**	**2647,44**	**2655,14**	**2615,06**	**2615,06**
4_lr_10	2050,85	2156,33	2156,33	2271,54	2271,54	2202,71	2202,71
5_lr_10	2631,56	**2614,50**	**2614,50**	2719,67	2719,67	**2614,21**	**2614,21**
6_lr_10	2412,11	**2393,30**	**2393,30**	2577,66	2576,90	**2409,04**	**2406,94**
7_lr_10	2220,27	**2193,93**	**2193,93**	2254,29	2254,29	**2195,91**	**2195,91**
8_lr_10	2029,93	2759,23	2758,44	2429,21	2429,21	2339,48	2338,12
9_lr_10	2311,37	2652,96	2652,96	2755,73	2754,15	2623,21	2620,56
10_lr_10	2222,99	2305,16	2305,16	2420,47	2420,47	2369,21	2369,21
11_lr_10	2189,53	2331,38	2328,17	2351,23	2350,85	2268,92	2255,73
12_lr_10	2013,17	2107,72	2105,34	2250,58	2243,91	2133,38	2128,31
1_lr_20	3495,81	**3173,94**	**3168,02**	**3115,61**	**3115,61**	**3421,48**	**3423,60**
2_lr_20	2749,39	2941,39	2930,97	2952,26	2950,60	**2588,29**	**2588,29**
3_lr_20	2762,80	**2531,16**	**2494,50**	**2408,60**	**2407,52**	**2575,77**	**2549,47**
4_lr_20	1988,57	2226,75	2226,75	2228,94	2232,37	2236,12	2236,12
5_lr_20	2550,13	**2460,30**	**2454,94**	2640,15	2638,44	**2467,45**	**2467,45**
6_lr_20	2502,46	**2383,21**	**2383,21**	**2370,54**	**2362,91**	**2385,53**	**2384,31**
7_lr_20	1936,44	2171,92	2150,59	2188,88	2181,63	2182,55	2158,82
8_lr_20	1858,36	1954,57	1954,31	1984,53	1984,53	**1807,82**	**1789,68**
9_lr_20	2432,61	**2343,71**	**2321,04**	**2340,36**	**2337,19**	**2323,92**	**2323,92**
10_lr_20	2782,06	**2405,42**	**2395,88**	**2468,78**	**2459,95**	**2438,67**	**2438,04**
11_lr_20	1954,57	3.315,03	3315,03	2872,05	2872,05	2041,17	2039,60
1_lrc_10	2956,32	3345,09	3343,25	3106,84	3106,04	3245,99	3249,95
2_lrc_10	2764,14	2909,79	2909,79	**2744,58**	**2744,60**	**2745,31**	**2744,60**
3_lrc_10	2443,68	2666,79	2663,39	**2398,47**	**2397,82**	**2422,22**	**2421,57**
4_lrc_10	2238,17	**2208,38**	**2207,45**	**2203,75**	**2203,88**	**2233,91**	**2234,45**
5_lrc_10	2830,16	3842,94	3842,70	2906,42	2906,42	3498,97	3496,51
6_lrc_10	2475,01	2676,13	2671,99	2642,76	2638,62	2651,84	2651,84
7_lrc_10	2344,94	2479,11	2484,52	2587,82	2581,91	2393,76	2395,55
8_lrc_10	2245,3	2378,13	2379,20	2323,31	2313,66	**2226,82**	**2238,27**
1_lrc_20	3358,41	3684,76	3681,87	3527,32	3526,91	**3259,44**	**3276,14**
2_lrc_20	2657,14	2985,45	2975,04	2942,24	2915,12	2993,31	2993,31
3_lrc_20	2700,30	**2416,27**	**2386,23**	2706,70	2701,41	2861,16	2860,75
4_lrc_20	2537,83	**2270,60**	**2255,74**	**2455,96**	**2451,62**	**2372,88**	**2357,76**
5_lrc_20	3464,61	**3322,11**	**3322,11**	**3237,68**	**3237,68**	**3259,95**	**3259,95**
6_lrc_20	2444,87	2749,74	2749,74	2806,56	2806,29	2657,33	2654,28
7_lrc_20	2461,42	**2351,95**	**2350,54**	3666,03	3672,89	**2426,65**	**2358,99**
8_lrc_20	2271,19	4380,42	4380,42	**2157,82**	**2160,43**	**2114,31**	**2103,89**
Sum	264565,80	275882,43	275658,74	271744,81	271712,06	269098,24	268922,21
Number of instances in which the obtained result is the best from all the considered random methods							
		7	12	22	13	21	16
Number of instances for which the algorithm obtained better or equal result as this of Li and Lim (2001)							
better		17	18	18	18	26	26
equal		5	7	4	7	5	6
Improvement with respect to the Li and Lim's (2001) meta-heuristic							
sum		39531,00	39532,00	40278,00	40418,00	40016,00	40164,00

Table B.11 Final schedule cost obtained by methods creating the initial solution using Sweep Algorithm with fixed starting point =-π

instance	Metaheuristic Li and Lim (2001)	angle_s_ nCust_2opt	angle_s_ nCust_rr	angle_s_ nVeh_2opt	angle_s_ nVeh_rr	angle_s_ 1_2opt	angle_s_ 1_rr
1_lc_10	33	2	2	4	4	6	6
2_lc_10	71	4	4	4	4	13	13
3_lc_10	191	13	12	4	4	16	16
4_lc_10	1254	20	20	20	19	20	20
5_lc_10	47	9	8	2	2	2	2
6_lc_10	43	1	1	6	6	5	5
7_lc_10	54	3	3	3	3	4	4
8_lc_10	82	8	8	8	8	12	11
9_lc_10	255	5	5	14	14	15	15
1_lc_20	27	19	19	19	19	132	131
2_lc_20	94	113	112	113	112	167	166
3_lc_20	145	114	113	130	129	155	154
4_lc_20	746	139	136	153	152	170	169
5_lc_20	190	50	49	43	43	12	12
6_lc_20	88	44	43	38	38	120	121
7_lc_20	102	10	10	9	9	95	94
8_lc_20	178	13	13	129	129	3	3
1_lr_10	87	1	2	0	0	0	0
2_lr_10	1168	1	1	1	1	1	1
3_lr_10	169	3	3	4	4	10	10
4_lr_10	459	5	5	3	3	1	1
5_lr_10	69	6	6	1	1	9	9
6_lr_10	87	3	3	1	1	4	4
7_lr_10	287	7	7	12	12	3	3
8_lr_10	415	0	0	0	0	0	0
9_lr_10	348	1	1	0	0	0	0
10_lr_10	547	2	2	1	1	11	11
11_lr_10	179	13	13	3	3	2	2
12_lr_10	638	4	4	1	1	12	12
1_lr_20	193	116	116	107	106	19	19
2_lr_20	885	121	121	90	90	125	124
3_lr_20	1950	166	165	161	160	114	113
4_lr_20	2655	176	175	154	153	140	140
5_lr_20	585	105	105	26	26	150	149
6_lr_20	747	87	87	167	165	173	172
7_lr_20	1594	238	237	179	177	223	221
8_lr_20	3572	240	238	247	245	379	375
9_lr_20	2773	134	132	199	198	164	163
10_lr_20	1482	190	188	188	187	121	120
11_lr_20	4204	2	2	8	8	212	211
1_lrc_10	119	1	1	1	1	0	0
2_lrc_10	152	1	1	2	2	1	1
3_lrc_10	175	1	1	12	12	5	5
4_lrc_10	202	8	8	3	3	4	4
5_lrc_10	179	0	0	6	5	0	0
6_lrc_10	459	1	1	3	3	2	2
7_lrc_10	154	12	12	1	1	6	6
8_lrc_10	650	1	1	3	3	3	3
1_lrc_20	266	33	33	23	23	50	50
2_lrc_20	987	98	97	114	113	21	21
3_lrc_20	1605	203	199	131	131	73	73
4_lrc_20	3634	229	224	127	127	206	206
5_lrc_20	639	94	91	100	99	18	18
6_lrc_20	445	64	62	143	142	108	107
7_lrc_20	607	145	142	3	2	37	37
8_lrc_20	4106	1	1	169	168	155	154
Sum	43072	3080	3045	3093	3072	3509	3489
Number of instances in which the obtained result is the best from all the considered random methods							
		18	24	22	26	18	20
Number of instances for which the algorithm obtained better or equal result as this of Li and Lim (2001)							
better		55	55	55	55	52	52
equal		0	0	0	0	0	0

Table B.12 Values of actual cpu [sec] obtained by methods creating the initial solution using Sweep Algorithm with fixed starting point =-π

instance	Metaheuristic Li and Lim (2001)	angle_s_ nCust_2opt	angle_s_ nCust_rr	angle_s_ nVeh_2opt	angle_s_ nVeh_rr	angle_s_ 1_2opt	angle_s_ 1_rr
1_lc_10	33	25	25	22	22	20	20
2_lc_10	71	19	19	18	18	18	18
3_lc_10	191	15	15	19	19	18	18
4_lc_10	1254	20	20	20	20	21	21
5_lc_10	47	20	19	20	20	21	21
6_lc_10	43	20	20	19	19	20	19
7_lc_10	54	20	20	24	24	20	19
8_lc_10	82	20	20	19	19	20	20
9_lc_10	255	20	20	20	19	20	20
1_lc_20	27	210	209	217	217	178	177
2_lc_20	94	144	143	159	158	183	182
3_lc_20	145	170	168	162	160	176	175
4_lc_20	746	171	167	168	167	190	189
5_lc_20	190	169	167	184	183	250	250
6_lc_20	88	173	171	201	200	197	198
7_lc_20	102	111	110	111	111	202	201
8_lc_20	178	107	106	149	149	125	124
1_lr_10	87	9	8	9	9	9	9
2_lr_10	1168	13	13	11	11	15	15
3_lr_10	169	13	12	12	12	12	12
4_lr_10	459	17	17	20	20	24	24
5_lr_10	69	11	11	14	14	11	11
6_lr_10	87	15	15	16	16	14	14
7_lr_10	287	17	17	16	16	20	20
8_lr_10	415	13	13	16	16	15	15
9_lr_10	348	16	16	12	12	16	16
10_lr_10	547	13	14	15	15	12	12
11_lr_10	179	15	15	18	18	18	18
12_lr_10	638	20	20	18	18	17	17
1_lr_20	193	118	118	127	126	156	156
2_lr_20	885	127	127	130	129	172	171
3_lr_20	1950	180	179	226	224	228	227
4_lr_20	2655	233	231	222	221	261	261
5_lr_20	585	204	203	240	240	224	222
6_lr_20	747	190	189	190	189	209	208
7_lr_20	1594	243	242	246	245	258	256
8_lr_20	3572	280	277	263	262	389	385
9_lr_20	2773	186	183	206	205	222	221
10_lr_20	1482	202	200	202	201	243	241
11_lr_20	4204	54	55	83	82	224	223
1_lrc_10	119	12	12	13	13	13	13
2_lrc_10	152	17	16	18	18	18	18
3_lrc_10	175	16	16	15	15	15	15
4_lrc_10	202	21	21	21	20	22	22
5_lrc_10	179	12	12	13	12	15	15
6_lrc_10	459	18	17	17	17	17	17
7_lrc_10	154	14	13	19	19	15	15
8_lrc_10	650	19	19	17	17	21	21
1_lrc_20	266	95	94	111	111	122	121
2_lrc_20	987	133	131	147	146	161	160
3_lrc_20	1605	206	202	149	148	159	157
4_lrc_20	3634	238	233	146	145	206	206
5_lrc_20	639	104	101	107	106	122	121
6_lrc_20	445	157	154	146	145	156	154
7_lrc_20	607	158	156	235	234	202	201
8_lrc_20	4106	25	25	177	176	216	215
Sum	43072	4868	4816	5195	5168	5928	5897
Number of instances in which the obtained result is the best from all the considered random methods							
		12	33	11	22	9	12
Number of instances for which the algorithm obtained better or equal result as this of Li and Lim (2001)							
better		51	51	51	51	50	50
equal		0	0	0	0	0	0

Table B.13 Values of total cpu [sec] obtained by methods creating the initial solution using Sweep Algorithm with fixed starting point =-π

						expected value					
instance	**area_2opt**	**pair_2opt**	**s_nCust**	**s_nVeh**	**s_1**	**angle_r_nCust_2opt**	**angle_r_nCust_rr**	**angle_r_nVeh_2opt**	**angle_r_nVeh_rr**	**angle_r_1_2opt**	**angle_r_1_rr**
1_lc_10	106	103	80	146	218	114	113	96	83	148	137
2_lc_10	490	314	159	170	389	335	318	263	282	285	288
3_lc_10	476	414	431	142	450	337	344	343	325	408	409
4_lc_10	56	263	493	493	482	344	329	303	286	478	477
5_lc_10	82	50	272	89	46	145	139	143	134	31	31
6_lc_10	71	130	66	224	165	210	203	188	193	229	189
7_lc_10	227	47	99	94	155	137	125	150	146	117	117
8_lc_10	126	204	245	273	321	294	296	288	284	211	210
9_lc_10	41	195	170	387	390	232	234	229	201	355	354
1_lc_20	403	34	134	118	403	148	164	137	147	403	403
2_lc_20	463	322	423	395	463	331	347	327	369	386	389
3_lc_20	247	453	374	433	454	411	405	400	394	401	403
4_lc_20	401	414	423	464	460	406	416	420	417	453	456
5_lc_20	66	232	224	208	44	210	228	279	271	102	113
6_lc_20	193	88	195	191	341	236	267	286	277	311	294
7_lc_20	286	62	97	83	265	264	268	274	282	220	225
8_lc_20	203	247	118	456	15	241	250	268	274	211	206
1_lr_10	41	37	77	20	0	80	86	33	33	0	0
2_lr_10	0	38	42	42	37	84	67	77	74	37	37
3_lr_10	61	40	172	203	423	84	144	134	156	404	369
4_lr_10	277	456	196	123	70	187	157	165	160	109	96
5_lr_10	1	82	293	52	413	137	123	75	74	27	27
6_lr_10	31	79	179	54	219	143	141	121	121	166	141
7_lr_10	120	213	277	403	133	143	234	191	192	134	133
8_lr_10	67	170	22	21	29	52	52	46	53	24	27
9_lr_10	31	261	53	28	27	104	115	99	108	29	28
10_lr_10	166	146	120	74	469	280	264	238	241	461	465
11_lr_10	316	325	458	143	84	291	282	265	269	360	360
12_lr_10	458	493	152	62	368	246	220	273	285	310	291
1_lr_20	369	479	494	439	112	300	313	288	301	112	112
2_lr_20	289	311	482	375	396	363	391	353	357	405	404
3_lr_20	352	469	476	393	279	363	373	365	359	218	224
4_lr_20	407	431	401	375	292	407	392	395	396	357	362
5_lr_20	358	407	311	134	355	357	316	320	331	374	366
6_lr_20	472	140	280	449	423	360	374	383	331	412	407
7_lr_20	485	495	494	403	450	390	389	399	402	406	377
8_lr_20	368	497	443	477	490	388	398	391	373	290	299
9_lr_20	496	392	403	487	388	365	388	380	374	401	416
10_lr_20	324	317	479	475	284	406	407	397	389	457	464
11_lr_20	490	49	58	96	479	164	135	227	219	467	470
1_lrc_10	5	129	59	41	5	77	73	42	40	5	5
2_lrc_10	35	220	61	91	68	98	103	96	86	36	35
3_lrc_10	213	94	67	434	213	195	195	240	226	213	211
4_lrc_10	31	189	251	113	150	210	210	171	167	105	113
5_lrc_10	0	79	20	263	0	144	141	82	96	0	0
6_lrc_10	86	94	83	137	86	83	80	70	70	88	86
7_lrc_10	72	54	451	69	260	139	146	131	134	227	255
8_lrc_10	121	200	60	120	121	126	155	128	123	84	74
1_lrc_20	419	231	250	182	248	306	306	291	289	301	287
2_lrc_20	95	192	406	416	95	380	383	397	386	313	274
3_lrc_20	357	256	495	454	267	425	384	401	387	240	205
4_lrc_20	369	433	484	449	500	377	366	394	378	485	489
5_lrc_20	114	473	464	477	114	357	358	362	384	114	114
6_lrc_20	466	461	267	491	377	358	365	357	358	419	417
7_lrc_20	399	124	473	46	138	416	390	373	394	318	283
8_lrc_20	451	88	47	486	388	259	254	269	281	397	397
Sum	13149	13216	14303	13963	14311	14037	14119	13815	13761	14055	13822
Avg	235	236	255	249	256	251	252	247	246	251	247

Table B.14 Numbers of the PTS iterations the corresponding method needed to execute in order to find the best solution

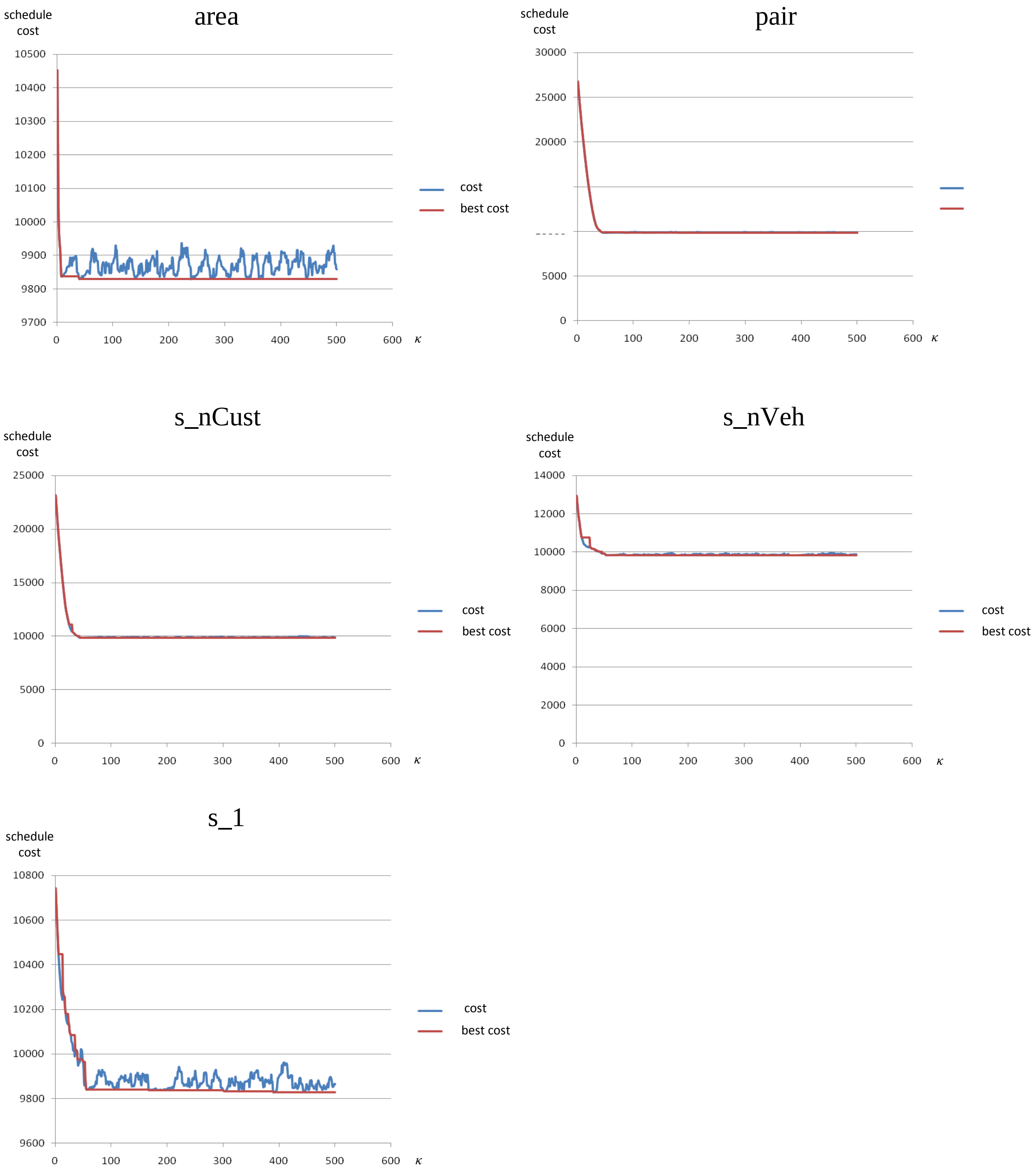
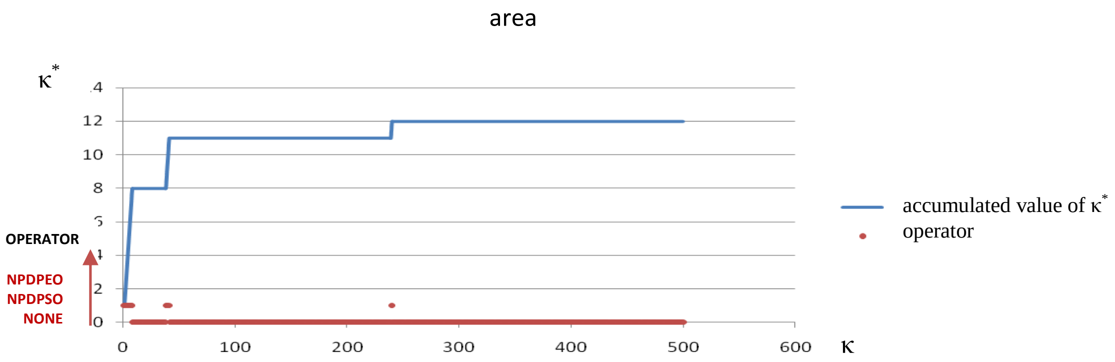
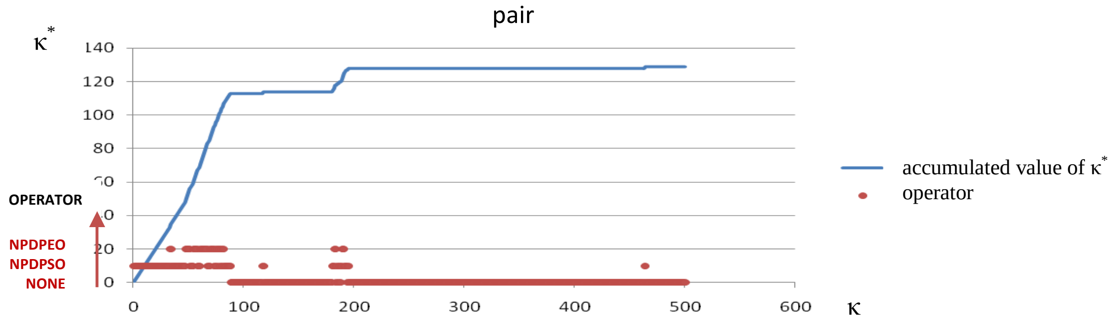


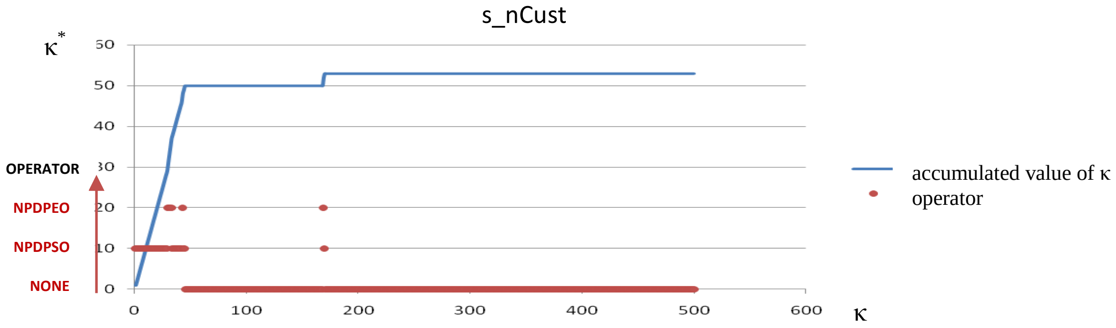
Figure B.1 Performance of PTS heuristic when solving the instance 9 from the data set lc_10, using as input a set of routes provided by a different initial solution constricting method



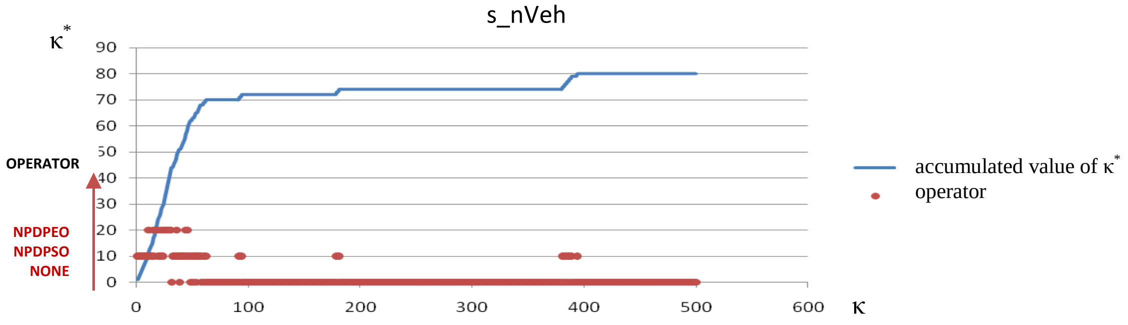
Numbers of iterations when the operators provide improvement: NPDPSO – 12, NPDPEO – 0, NONE - 488



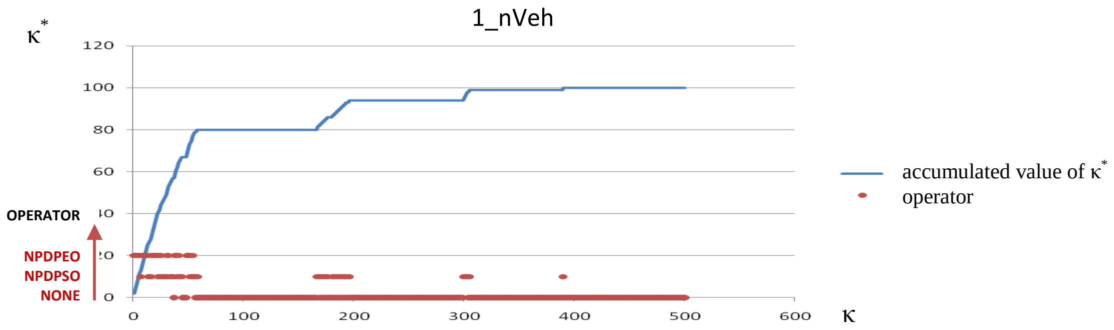
Numbers of iterations when the operators provide improvement: NPDPSO – 73, NPDPEO – 28, NONE - 399



Numbers of iterations when the operators provide improvement: NPDPSO – 41, NPDPEO – 6, NONE - 453



Numbers of iterations when the operators provide improvement: NPDPSO – 48, NPDPEO – 16, NONE – 436



Numbers of iterations when the operators provide improvement: NPDPSO – 44, NPDPEO – 28, NONE - 428

Figure B.2 Collection of double diagrams showing the performance of two operators: NPDPSO and NPDPEO, when solving the instance 9 from the data set lc_10, using as input a set of routes provided by a different initial solution constricting method

	Lu and Dessouky (2006) Sequential Insertion			Lu and Dessouky (2006) Parallel Insertion			Lu and Dessouky (2006) Insertion-Based Construction Heuristic		
instant	**number of vehicles**	**travel cost**	**average cpu[sec]**	**number of vehicles**	**travel cost**	**average cpu[sec]**	**number of vehicles**	**travel cost**	**average cpu[sec]**
LC101	11	867,3	0,00	10	828,9	0,00	10	828,9	0,00
LC102	13	1129,1	0,11	12	1001,9	0,08	11	912,0	0,01
LC103	12	1172,1	0,16	12	1205,5	0,14	11	882,5	0,00
LC104	11	966,1	0,06	11	915,5	0,01	9	861,9	0,01
LC105	12	1037,6	0,07	11	828,9	0,00	10	828,9	0,00
LC106	13	1139,6	0,16	13	1035,6	0,15	10	931,5	0,03
LC107	11	924,8	0,00	11	899,8	0,01	10	828,9	0,00
LC108	12	1247,5	0,33	11	1251,9	0,33	11	1063,5	0,00
LC109	11	1293,8	0,05	11	1273,8	0,05	11	924,5	0,00
LC201	3	591,5	0,03	3	591,5	0,03	3	591,5	0,03
LC202	5	972,3	0,13	4	759,9	0,05	3	663,5	0,02
LC203	4	849,5	0,06	4	822,2	0,06	4	753,5	0,01
LC204	4	954,9	0,02	4	854,9	0,02	3	591,2	0,00
LC205	4	792,0	0,00	4	688,9	0,01	3	592,4	0,00
LC206	4	867,9	0,09	4	841,9	0,07	4	618,3	0,00
LC207	4	709,3	0,00	4	684,5	0,01	3	588,3	0,00
LC208	4	761,5	0,00	4	719,9	0,00	3	629,4	0,00

Table B.15 Summary of results obtained by Lu and Dessouky (2006) testing three methods for solving the PDVRPTW

	Metaheuristic Li and Lim (2001)					Two-Stage Hybrid Algorithm Bent and Van Hentenryck (2006)			Grouping Genetic Algorithm Pankratz (2005)					Adaptive Large Neighbourhood Search Heuristic Ropke and D. Pisinger (2006)				
instant	best num. of r.	best travel cost	sched. dur.	wait. time	cpu [sec]	best num. of r.	travel cost	cpu [min]	best num. of r.	avg. num. of r.	best travel cost	avg. travel cost	avg cpu [sec]	best num. of r.	avg num. of r.	best travel cost	avg travel cost	avg cpu [sec]
LC101	10	828,94	9828,94	0,00	33	10	828,94	0,00	10	10,00	828,94	828,94	55,03	10	10	828,94	828,94	43
LC102	10	829,94	9828,94	0,00	71	10	828,94	0,00	10	10,00	828,94	828,94	68,67	10	10	828,94	828,94	44
LC103	10	827,86	10058,03	230,17	191	9	1035,35	0,02	10	10,00	827,86	827,86	85,33	9	9	1035,35	1037,77	49
LC104	9	861,95	10006,90	144,95	1254	9	860,01	0,33	10	10,00	818,60	818,67	139,90	9	9	860,01	860,15	63
LC105	10	828,94	9828,94	0,00	47	10	828,94	0,00	10	10,00	828,94	828,94	58,33	10	10	828,94	828,94	41
LC106	10	828,94	9828,94	0,00	43	10	828,94	0,00	10	10,00	828,94	828,94	63,60	10	10	828,94	828,94	42
LC107	10	828,94	9828,94	0,00	54	10	828,94	0,01	10	10,00	828,94	828,94	65,97	10	10	828,94	828,94	43
LC108	10	826,44	9826,94	0,00	82	10	826,44	0,00	10	10,00	826,44	826,44	81,00	10	10	826,44	826,44	46
LC109	10	827,82	9831,78	0,00	255	9	1000,60	42,57	10	10,00	827,82	827,82	118,10	9	9	1000,60	1000,60	35
LC201	3	591,56	9591,56	0,00	27	3	591,56	0,00	3	3,00	591,56	591,56	59,27	3	3	591,56	591,56	36
LC202	3	591,56	9591,56	0,00	94	3	591,56	0,00	3	3,00	591,56	591,56	115,50	3	3	591,56	591,56	59
LC203	3	585,56	9521,66	26,09	145	3	591,17	0,00	3	3,00	591,17	591,17	191,67	3	3	591,17	591,17	81
LC204	3	591,17	9591,17	0,00	746	3	590,60	4,47	3	3,00	590,60	620,38	346,13	3	3	590,60	590,60	141
LC205	3	588,88	9588,88	0,00	190	3	588,88	0,00	3	3,00	588,88	588,88	94,07	3	3	588,88	588,88	48
LC206	3	588,49	9588,49	0,00	88	3	588,49	0,00	3	3,00	588,49	588,49	124,20	3	3	588,49	588,49	60
LC207	3	588,29	9660,40	72,12	102	3	588,29	0,00	3	3,00	588,35	588,35	137,03	3	3	588,29	588,29	62
LC208	3	588,32	9744,23	155,91	178	3	588,32	0,00	3	3,00	588,75	588,75	141,93	3	3	588,32	588,32	69
LR101	19	1650,78	3599,45	948,65	87	19	1650,80	0,00	19	19,00	1650,80	1650,80	67,00	19	19	1650,80	1650,80	40
LR102	17	1487,57	3202,46	714,89	1168	17	1487,57	0,01	17	17,00	1488,74	1488,74	89,53	17	17	1487,57	1487,57	47
LR103	13	1292,68	2729,15	436,48	169	13	1292,68	0,01	13	13,00	1292,67	1292,67	82,87	13	13	1292,68	1292,68	45
LR104	9	1013,39	2050,85	37,46	459	9	1013,39	0,00	9	9,43	1037,16	1037,16	136,83	9	9	1013,39	1013,39	26
LR105	14	1377,11	2631,56	254,45	69	14	1377,11	0,00	14	14,00	1377,11	1377,11	70,97	14	14	1377,11	1377,11	40
LR106	12	1252,62	2412,11	159,49	87	12	1252,62	0,00	12	12,00	1252,63	1252,63	81,33	12	12	1252,62	1252,62	41
LR107	10	1111,31	2220,27	108,96	287	10	1111,31	0,00	10	10,03	1112,26	1112,26	95,67	10	10	1111,31	1111,31	44
LR108	9	968,97	2029,93	60,96	415	9	968,97	0,00	9	9,00	969,02	969,02	102,50	9	9	968,97	968,97	25
LR109	11	1239,96	2311,37	71,42	348	11	1208,96	0,00	11	12,00	1208,96	1233,99	103,80	11	11	1208,96	1208,96	41
LR110	10	1159,35	2222,99	63,64	547	10	1159,35	0,00	11	11,13	1176,20	1176,20	142,13	10	10	1159,35	1159,35	35
LR111	10	1108,90	2189,53	80,63	179	10	1108,90	0,00	10	10,20	1113,60	1113,60	105,53	10	10	1108,90	1108,90	44
LR112	9	1003,77	2013,17	9,41	638	9	1003,77	0,00	9	10,27	1040,34	1040,34	168,70	9	9	1003,77	1003,77	27
LR201	4	1263,84	3495,81	1231,97	193	4	1253,23	0,01	4	4,20	1253,23	1260,41	103,43	4	4	1253,23	1253,23	69
LR202	3	1197,67	2749,39	551,73	885	3	1197,67	0,01	3	4,03	1255,78	1255,78	234,50	3	3	1197,67	1197,67	60
LR203	3	949,40	2762,80	813,40	1950	3	949,40	0,13	3	3,00	962,82	962,82	381,50	3	3	949,40	949,40	98
LR204	2	849,05	1988,57	139,52	2655	2	849,05	0,53	2	2,27	879,01	879,01	486,50	2	2	849,05	849,05	181
LR205	3	1054,02	2550,13	496,11	585	3	1054,02	0,01	3	3,03	1078,84	1078,84	166,37	3	3	1054,02	1054,02	58
LR206	3	931,63	2502,46	570,84	747	3	931,63	0,78	3	3,00	941,67	941,67	259,03	3	3	931,63	931,63	86
LR207	2	903,06	1936,44	33,38	1594	2	903,06	0,01	2	2,43	927,58	927,58	418,77	2	2	903,06	903,06	187
LR208	2	734,85	1858,36	123,51	3572	2	734,85	0,01	2	2,03	760,95	760,95	531,07	2	2	734,85	734,85	285
LR209	3	937,05	2432,61	459,56	2773	3	930,59	12,97	3	3,07	932,43	955,96	236,90	3	3	930,59	930,59	73
LR210	3	964,22	2782,06	817,83	1482	3	964,22	0,04	3	3,00	972,34	972,34	286,13	3	3	964,22	964,22	77
LR211	2	927,80	1954,57	26,77	4204	2	913,84	1,23	3	3,07	888,15	897,03	478,53	2	2	911,52	911,52	126
LRC101	14	1708,80	2956,32	247,52	119	14	1708,70	0,00	15	15,00	1703,21	1704,05	76,07	14	14	1708,80	1708,80	38
LRC102	13	1563,55	2764,14	200,59	152	12	1558,07	0,00	12	12,17	1558,07	1559,65	95,53	12	12	1558,07	1558,07	41
LRC103	11	1258,74	2443,68	184,95	175	11	1258,74	0,00	11	11,00	1260,45	1260,45	92,80	11	11	1258,74	1258,74	43
LRC104	10	1128,40	2238,17	109,77	202	10	1128,40	0,01	10	10,00	1129,32	1129,32	108,23	10	10	1128,40	1128,40	52
LRC105	13	1637,62	2830,16	192,54	179	13	1637,62	0,00	13	13,10	1639,87	1639,87	88,17	13	13	1637,62	1637,62	42
LRC106	11	1425,53	2475,01	49,48	459	11	1424,73	0,00	11	11,77	1424,73	1441,82	95,63	11	11	1424,73	1424,73	42
LRC107	11	1230,15	2344,94	114,80	154	11	1230,14	0,00	11	11,07	1230,14	1237,91	97,73	11	11	1230,14	1230,14	43
LRC108	10	1147,97	2245,30	97,34	650	10	1147,43	0,00	10	10,40	1147,43	1159,82	111,67	10	10	1147,43	1147,43	25
LRC201	4	1468,96	3358,41	889,45	266	4	1406,94	0,01	4	4,77	1407,21	1438,12	101,47	4	4	1406,94	1406,94	38
LRC202	3	1374,27	2657,14	282,87	987	3	1374,27	0,01	4	3,97	1400,11	1400,11	161,70	3	4	1374,79	1387,74	82
LRC203	3	1089,07	2700,30	611,23	1605	3	1089,07	0,01	4	4,00	1114,40	1114,40	268,17	3	3	1089,07	1089,07	69
LRC204	3	827,78	2537,83	710,05	3634	3	818,66	0,18	3	3,00	818,66	838,55	457,30	3	3	818,66	818,66	173
LRC205	4	1302,20	3464,61	1162,41	639	4	1302,20	0,05	4	4,00	1305,37	1305,37	147,20	4	4	1302,20	1302,20	75
LRC206	3	1162,91	2444,87	281,96	445	3	1159,03	0,01	3	3,63	1159,03	1176,90	139,57	3	3	1159,03	1337,75	48
LRC207	3	1424,60	2461,42	36,82	607	3	1062,05	0,05	3	3,03	1062,05	1070,56	218,97	3	3	1062,05	1062,05	66
LRC208	3	852,76	2271,19	418,44	4106	3	852,76	0,11	3	3,20	882,78	882,78	322,13	3	3	852,76	852,76	88

Table B.16 Summary of results obtained by other authors proposing methods for solving the PDVRPTW

Appendix B2

Performance of Decission Support System

This appendix contains numerical results of the experiments conducted during the second application step of the present thesis project. The underlying study case is explained in details in Chapter 7.6. Chapter 7.7 provides description of all designed tesing scenarios. Each one of them is tagged with a number. The same number is used in the tables containing the results. However, to facilitate the identification of each scenario there is also provided its brief description regarding: TW, number of static customers, method used in DRSM and type of employed travel times' information.

The collection of results defines both initial and final solution. Initial solution is provided by IRSM. It constitutes a starting point in the process of frequent dynamic modifications of current routing plan, which objective is to optimize it taking into consideration the most recent changes in: traffic, new customers' requests and freight performance.

The description of initial routing plan regards: number of created routes, number of static customers to be served, total travel and waiting time. There is also provided the final cost of solution, which corresponds to the sum of total: waiting, serving and travel time that is to be performed by employed freight vehicles.

Similarly, the finaly performed routing and scheduling plan is defined by: number of performed routes, total performed travel and waiting time, final solution's cost. In addition there is specified service level, which corresponds to the percentage of served customers.

All the designed testing scenarios were divided in groups. Table B.17 and B.18 contain results from solving the first set using SPI and CSR procedure, respectively.

The next set of scenarios reckon with 20% of buffer time added to the forecasted values of travel time. Similarly as before, they are solved using two different methods: SPI and CSR. The result are displayed in individual Tables B.19 and B.20.

Subsequent listing presented in Table B.21 contains four scenarios, which include in their definition blocking of traffic for one hour on 10% of udnderlying road network. They were solved by both SPI and CSR method.

The last two Tables: B22 and B.23 provide the outcomes of solving scenarios considering deteriorated precision of calculation. Here, travel times data were recorded for 10 seconds long intervals (δ=10), unlike in the previous cases, were the considered value of time periods is equal to one secong (δ=1).

The analysis of all obtained result and final conclusions are provided in Chapter 7.8.

					Initial routing and scheduling plan					Final routing and scheduling plan				
Sce	TW	N° static customers	Method	Travel time data	N°r	N° customers to serve	Total Travel Time [sec]	Total Waiting Time [sec]	Solution Cost [sec]	N°r	Total Travel Time [sec]	Total Waiting Time [sec]	Solution Cost [sec]	Service Level
1	narrow	100	SPI	perfect	4	100	23564	17459	101023	4	23565	17458	101023	100
2	wide	100	SPI	perfect	4	100	13994	13564	87558	4	13992	13562	87554	100
3	narrow	100	SPI	AS	4	100	26477	16360	102837	4	30419	23247	101066	79
4	wide	100	SPI	AS	3	100	14561	10008	84569	3	24377	10078	87854	89
5	narrow	100	SPI	TD	4	100	26816	16511	103327	4	29747	20940	104687	90
6	wide	100	SPI	TD	4	100	15603	13858	89460	4	15542	14081	89022	99
7	narrow	80	SPI	TD	3	80	21399	15091	84490	6	48875	30040	137716	98
8	wide	80	SPI	TD	3	80	12020	10302	70322	4	19754	10253	87007	95
9	narrow	60	SPI	TD	3	60	18441	22697	77138	6	58942	28963	147905	100
10	wide	60	SPI	TD	2	60	9609	6643	52252	4	28437	6575	94412	99
11	narrow	50	SPI	TD	2	50	14231	14637	58868	7	78840	33050	167090	92
12	wide	50	SPI	TD	2	50	9318	6893	46211	4	28737	6826	95563	100
13	narrow	40	SPI	TD	2	40	12567	20324	56891	6	90788	19977	168365	96
14	wide	40	SPI	TD	2	40	7193	8406	39598	4	30073	7294	96167	98
15	narrow	20	SPI	TD	1	20	3740	15848	31588	7	109637	21918	190955	99
16	wide	20	SPI	TD	1	20	4869	5345	22214	4	37297	3803	101100	100

Figure B.17 Listing of results solving testing scenarios where δ=1 using SPI procedure

					Initial routing and scheduling plan					Final routing and scheduling plan				
Sce	TW	N° static customers	Method	Travel time data	N°r	N° customers to serve	Total Travel Time [sec]	Total Waiting Time [sec]	Solution Cost [sec]	N°r	Total Travel Time [sec]	Total Waiting Time [sec]	Solution Cost [sec]	Service Level
17	narrow	100	CSR	perfect	4	100	23564	17459	101023	4	23565	17458	101023	100
18	wide	100	CSR	perfect	4	100	13994	13564	87558	4	13992	13562	87554	100
19	narrow	100	CSR	AS	4	100	26477	16360	102837	8	78524	58772	181096	73
20	wide	100	CSR	AS	3	100	14561	10008	84569	4	45904	10100	115404	99
21	narrow	100	CSR	TD	4	100	26816	16511	103327	5	45367	28511	133278	99
22	wide	100	CSR	TD	4	100	15603	13858	89460	4	23248	14099	97347	100
23	narrow	80	CSR	TD	3	80	21399	15091	84490	6	62336	43333	164469	98
24	wide	80	CSR	TD	3	80	12020	10302	70322	4	24838	10256	95094	100
25	narrow	60	CSR	TD	3	60	18441	22697	77138	6	62008	11127	133135	100
26	wide	60	CSR	TD	2	60	9609	6643	52252	4	32114	6676	98789	100
27	narrow	50	CSR	TD	2	50	14231	14637	58868	6	68030	24897	152927	100
28	wide	50	CSR	TD	2	50	9318	6893	46211	4	33493	6820	100312	100
29	narrow	40	CSR	TD	2	40	12567	20324	56891	5	65097	12647	137744	100
30	wide	40	CSR	TD	2	40	7193	8406	39598	4	34956	7363	102319	100
31	narrow	20	CSR	TD	1	20	3740	15848	31588	6	93261	8034	160695	99
32	wide	20	CSR	TD	1	20	4869	5345	22214	4	38420	3668	102087	100

Figure B.18 Listing of results solving testing scenarios where δ=1 using CSR procedure

					Initial routing and scheduling plan					Final routing and scheduling plan				
Sce	TW	N° static customers	Method	Travel time data	N°r	N° customers to serve	Total Travel Time [sec]	Total Waiting Time [sec]	Solution Cost [sec]	N°r	Total Travel Time [sec]	Total Waiting Time [sec]	Solution Cost [sec]	Service Level
33	narrow	100	SPI	TD	4	100	26816	16511	103327	4	27791	17573	102365	95
34	wide	100	SPI	TD	4	100	15603	13858	89460	4	15258	13845	89103	100
35	narrow	80	SPI	TD	3	80	21399	15091	84490	6	46715	29149	134065	97
36	wide	80	SPI	TD	3	80	12020	10302	70322	4	23104	10376	93479	100
37	narrow	60	SPI	TD	3	60	18441	22697	77138	7	75166	36768	169534	96
38	wide	60	SPI	TD	2	60	9609	6643	52252	4	30163	6865	97028	100
39	narrow	50	SPI	TD	2	50	14231	14637	58868	8	88858	37330	183788	96
40	wide	50	SPI	TD	2	50	9318	6893	46211	4	27373	7080	93853	99
41	narrow	40	SPI	TD	2	40	12567	20324	56891	6	80117	26926	165243	97
42	wide	40	SPI	TD	2	40	7193	8406	39598	4	31542	6996	98537	100
43	narrow	20	SPI	TD	1	20	3740	15848	31588	6	87266	28075	169941	91
44	wide	20	SPI	TD	1	20	4869	5345	22214	4	38954	3803	102758	100

Figure B.19 Listing of results solving testing scenarios where δ=1, there is used 20% buffer time, using SPI procedure

					Initial routing and scheduling plan					Final routing and scheduling plan				
Sce	TW	Nº static customers	Method	Travel time data	Nºr	Nº customers to serve	Total Travel Time [sec]	Total Waiting Time [sec]	Solution Cost [sec]	Nºr	Total Travel Time [sec]	Total Waiting Time [sec]	Solution Cost [sec]	Service Level
45	narrow	100	CSR	TD	4	100	26816	16511	103327	6	57082	39997	157079	100
46	wide	100	CSR	TD	4	100	15603	13858	89460	4	23805	14228	98033	100
47	narrow	80	CSR	TD	3	80	21399	15091	84490	7	68122	68958	196480	99
48	wide	80	CSR	TD	3	80	12020	10302	70322	4	26452	10254	96706	100
49	narrow	60	CSR	TD	3	60	18441	22697	77138	7	77907	56340	193646	99
50	wide	60	CSR	TD	2	60	9609	6643	52252	4	32343	6801	99143	100
51	narrow	50	CSR	TD	2	50	14231	14637	58868	6	64248	14445	138693	100
52	wide	50	CSR	TD	2	50	9318	6893	46211	4	33942	6903	100844	100
53	narrow	40	CSR	TD	2	40	12567	20324	56891	5	71452	7807	139259	100
54	wide	40	CSR	TD	2	40	7193	8406	39598	4	35753	8379	104131	100
55	narrow	20	CSR	TD	1	20	3740	15848	31588	7	102213	26342	187955	99
56	wide	20	CSR	TD	1	20	4869	5345	22214	4	36996	3803	100800	100

Figure B.20 Listing of results solving testing scenarios where δ=1, there is used 20% buffer time, using CSR procedure

					Initial routing and scheduling plan					Final routing and scheduling plan				
Sce	TW	Nº static customers	Method	Travel time data	Nºr	Nº customers to serve	Total Travel Time [sec]	Total Waiting Time [sec]	Solution Cost [sec]	Nºr	Total Travel Time [sec]	Total Waiting Time [sec]	Solution Cost [sec]	Service Level
57	narrow	100	SPI	TD	4	100	26816	16511	103327	4	32952	24547	102498	75
58	wide	100	SPI	TD	4	100	15603	13858	89460	4	21901	13786	94487	98
59	narrow	100	CSR	TD	4	100	26816	16511	103327	8	98037	82709	231146	84
60	wide	100	CSR	TD	4	100	15603	13858	89460	4	29981	14074	104055	100

Figure B.21 Listing of results solving testing scenarios where δ=1, 10% of network is blocked, using SPI and CSR procedures

					Initial routing and scheduling plan					Final routing and scheduling plan				
Sce	TW	Nº static customers	Method	Travel time data	Nºr	Nº customers to serve	Total Travel Time [sec]	Total Waiting Time [sec]	Solution Cost [sec]	Nºr	Total Travel Time [sec]	Total Waiting Time [sec]	Solution Cost [sec]	Service Level
61	narrow	100	SPI	TD	4	100	25334	17246	102580	4	24860	17752	102611	100
62	wide	100	SPI	TD	5	100	17817	17320	95137	5	17915	16987	94902	100
63	narrow	80	SPI	TD	3	80	21638	14584	84222	6	55833	18092	133925	100
64	wide	80	SPI	TD	3	80	12428	10393	70820	4	22329	10281	92610	100
65	narrow	60	SPI	TD	3	60	16758	24381	77139	7	80667	38124	167391	81
66	wide	60	SPI	TD	2	60	9101	6841	51941	4	29609	6848	96457	100
67	narrow	50	SPI	TD	2	50	14987	13884	58870	7	83045	27471	166315	93
68	wide	50	SPI	TD	2	50	9256	6621	45877	4	28195	6577	94171	99
69	narrow	40	SPI	TD	2	40	12571	20321	56892	6	85883	21280	165362	97
70	wide	40	SPI	TD	2	40	7193	8406	39599	4	30594	6986	97580	100
71	narrow	20	SPI	TD	1	20	3740	15849	31589	8	140603	16563	213565	94
72	wide	20	SPI	TD	1	20	4871	5343	22214	4	38230	3803	102033	100

Figure B.22 Listing of results solving testing scenarios where δ=10 using SPI procedure

					Initial routing and scheduling plan					Final routing and scheduling plan				
Sce	TW	Nº static customers	Method	Travel time data	Nºr	Nº customers to serve	Total Travel Time [sec]	Total Waiting Time [sec]	Solution Cost [sec]	Nºr	Total Travel Time [sec]	Total Waiting Time [sec]	Solution Cost [sec]	Service Level
73	narrow	100	CSR	TD	4	100	25334	17246	102580	5	35525	21577	115902	98
74	wide	100	CSR	TD	5	100	17817	17320	95137	5	24158	17330	101488	100
75	narrow	80	CSR	TD	3	80	21638	14584	84222	6	50006	17608	127614	100
76	wide	80	CSR	TD	3	80	12428	10393	70820	4	30802	10261	101063	100
77	narrow	60	CSR	TD	3	60	16758	24381	77139	7	85993	18077	163469	99
78	wide	60	CSR	TD	2	60	9101	6841	51941	4	32966	7104	100070	100
79	narrow	50	CSR	TD	2	50	14987	13884	58870	6	67311	11387	138098	99
80	wide	50	CSR	TD	2	50	9256	6621	45877	4	32399	6754	99153	100
81	narrow	40	CSR	TD	2	40	12571	20321	56892	7	102307	23254	184961	99
82	wide	40	CSR	TD	2	40	7193	8406	39599	4	32596	6964	99560	100
83	narrow	20	CSR	TD	1	20	3740	15849	31589	7	106674	12866	178940	99
84	wide	20	CSR	TD	1	20	4871	5343	22214	4	38603	3710	102313	100

Figure B.23 Listing of results solving testing scenarios where δ=10 using CSR procedure

Subsequent tables contain information on cpu used to perform each iteration of the DRSM. There were also collected values of iterations kappa performed by PDP adapted PTS. The zero value of kappa indicates that PTS performed all initially established iteration without finding an improving move.

In the heather of each table there is presented a brief description of the tested scenario. Also all the tables cotain a summary including total and average values of both cpu and kappa.

VALUES OF CPU REQUIRED BY DRSM

Scenario	1		2		3		4		5		6	
TW	narrow		wide		Narrow		wide		narrow		wide	
No static customers	100		100		100		100		100		100	
Method	CSR		CSR		CSR		CSR		CSR		CSR	
Travel Times Data	perfect		perfect		AS		AS		TD		TD	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
1	523	328	525	322	267	303	273	352	354	309	353	286
2	523	331	799	175	254	254	273	355	335	259	349	263
3			725	314	241	204	272	280	327	225	344	184
4					248	198	263	252	305	222	289	189
5					239	156	233	234	278	171	290	240
6					243	157	221	185	273	173	358	287
7					221	137	232	177	273	170	329	173
8					216	136	227	136	261	133	299	192
9					216	137	215	140	256	134	265	164
10					212	136	214	130	256	134	264	167
11					204	126	208	124	257	135	267	152
12					196	93	201	105	241	105	266	131
13					191	85	202	105	239	101	249	107
14					187	56	195	92	237	94	243	97
15					189	76	192	82	224	70	244	94
16					188	79	189	79	221	71	246	100
17					184	73	188	79	222	70	232	69
18					173	52	185	81	222	70	226	65
19					171	50	181	62	206	49	215	63
20					169	48	176	57	207	48	210	59
21					170	50	176	58	206	49	211	53
22					164	42	176	58	200	41	210	55
23					158	38	176	60	194	40	206	48
24					158	38	163	47	194	37	194	38
25					157	35	163	47	183	23	193	43
26					148	27	162	44	180	28	191	35
27					145	28	158	44	167	14	191	33
28					145	26	153	35	170	16	180	31
29					137	19	149	37	169	14	176	29
30					136	20	150	36	166	13	177	30
31					132	16	144	28	154	11	176	30
32					131	17	141	25	153	11	165	26
33					126	12	138	25	152	11	161	22
34					123	12	138	25	148	10	162	21
35					122	12	134	22	138	6	163	21
36					121	12	131	22	137	6	153	17
37					118	11	128	19	134	6	150	14
38					112	8	128	19	131	5	150	15
39					113	8	125	16	129	4	157	12
40					110	9	121	14	121	4	141	12
41					107	6	117	13	121	3	140	11
42					101	7	199	12	120	4	139	11
43					101	6	115	11	118	3	133	9
44					98	4	112	8	115	3	127	6
45					94	4	106	7	105	3	127	6
46					90	4	103	7	156	4	124	6
47					93	4	104	6	105	3	118	5
48					90	4	99	5	95	2	115	5
49					83	4	96	4	91	2	115	5
50					82	3	93	4	86	3	109	4
51					79	4	116	3	86	2	112	3
52					70	5	90	2	86	3	105	3
53					69	5	88	2	78	2	117	3
54					65	5	87	2	77	2	99	3
55					65	4	85	2	77	1	96	3
56					59	3	81	2	67	1	93	3
57					59	4	77	2	66	1	90	3
58					58	3	76	3	64	1	86	2
59					53	3	73	2	64	1	83	2
60					53	2	71	2	57	1	83	2
61					53	3	67	2	54	1	82	2
62					47	2	67	2	54	1	74	2
63					86	2	62	2	50	1	72	2
64					46	1	62	2	44	1	72	2
65					42	1	58	1	41	1	72	1
66					41	1	56	2	36	1	65	0
67					39	0	55	2	32	1	62	1
68					36	1	53	2	31	1	60	1
69					35	1	50	1	27	1	58	1

Scenario	1		2		3		4		5		6	
TW	narrow		Wide		narrow		wide		narrow		wide	
No static customers	100		100		100		100		100		100	
Method	CSR		CSR		CSR		CSR		CSR		CSR	
Travel Times Data	perfect		Perfect		AS		AS		TD		TD	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
70					34	1	47	1	26	1	56	0
71					30	1	48	0	23	1	53	0
72					31	1	46	0	23	0	51	1
73					26	0	41	1	17	1	48	1
74					27	1	40	0	17	0	48	1
75					22	1	39	0	14	1	48	0
76					22	1	36	1	12	1	44	1
77					19	1	34	0	11	1	39	1
78					19	1	32	1	11	0	37	1
79					15	1	31	1	8	1	37	1
80					15	1	29	0	7	1	35	0
81					15	0	27	0	6	0	33	0
82					12	1	27	0	6	0	31	1
83					10	1	26	1	4	1	27	1
84					10	1	22	0	4	1	27	0
85					9	1	20	1	3	1	27	0
86					7	1	18	1	2	1	27	0
87					7	1	17	0			20	1
88					5	1	14	1			19	0
89					4	1	15	0			17	1
90					3	1	12	1			18	0
91					2	1	12	0			13	1
92					2	1	9	1			12	1
93							9	0			10	0
94							7	0			8	0
95							6	1			6	0
96							5	0			4	1
97							4	1			4	0
98							3	1			3	0
99							2	1				
TOTAL	**1046**	**659**	**2049**	**811**	**9275**	**3113**	**10490**	**3918**	**10817**	**3158**	**12675**	**3788**
AVERAGE	**523.0**	**329.5**	**683.0**	**270.3**	**100.8**	**33.8**	**106.0**	**39.6**	**125.8**	**36.7**	**129.3**	**38.7**

Scenario	7		8		9		10		11		12	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	80		80		60		60		50		50	
Method	CSR		CSR		CSR		CSR		CSR		CSR	
Travel Times Data	TD		TD		TD		TD		TD		TD	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
1	282	180	284	179	213	62	214	86	181	51	181	50
2	270	167	272	185	255	63	279	89	174	51	174	41
3	258	156	259	180	233	69	197	103	167	48	167	47
4	264	163	260	181	211	79	196	102	172	57	168	47
5	270	164	265	194	213	79	201	120	175	42	173	56
6	258	117	268	198	202	90	203	122	182	48	177	66
7	265	130	273	197	211	100	216	145	182	48	179	68
8	272	150	6433	247	220	102	222	127	181	55	192	92
9	278	162	428	253	219	106	221	97	186	64	197	107
10	278	165	365	245	214	94	228	116	193	69	205	109
11	278	164	359	196	222	91	233	123	192	78	205	125
12	283	172	337	193	221	92	238	141	193	69	211	111
13	270	142	295	175	221	90	239	137	197	69	215	113
14	273	134	278	151	216	67	244	147	199	58	225	109
15	267	137	279	158	211	91	245	154	206	67	226	118
16	281	136	277	176	206	77	243	150	201	65	227	120
17	263	111	268	142	213	77	246	152	197	60	231	135
18	262	98	260	125	213	75	253	162	202	57	230	113
19	261	95	256	130	216	80	251	154	201	49	233	112
20	249	85	252	107	211	71	255	171	199	54	238	124
21	239	79	250	107	216	76	261	172	197	53	244	137
22	244	80	285	182	218	73	262	179	203	59	244	134
23	236	63	258	115	218	71	260	148	205	58	243	138
24	224	57	231	111	216	76	263	135	205	58	260	152
25	221	49	224	97	222	77	269	145	208	58	248	154
26	222	50	220	94	217	75	259	138	205	59	251	152
27	209	42	218	85	216	59	260	129	200	55	254	152
28	211	43	216	82	214	66	256	106	201	58	260	167
29	210	42	208	66	267	58	252	113	202	46	266	174
30	210	41	206	66	206	59	259	123	202	51	263	167
31	192	22	201	64	205	62	250	103	200	48	260	142
32	194	21	201	68	208	60	247	88	199	47	267	134
33	194	21	194	46	205	64	242	77	226	54	264	130
34	191	16	192	44	200	57	240	73	253	59	262	131
35	175	13	189	40	200	56	233	75	185	45	260	116
36	172	12	186	39	206	96	232	75	195	53	260	131
37	171	12	178	31	205	53	233	75	193	51	257	106
38	168	12	177	34	204	89	224	54	191	40	246	98
39	169	12	175	31	198	43	217	51	196	43	242	79
40	168	12	168	26	194	39	217	51	192	44	238	78
41	162	9	166	25	188	36	216	51	189	43	238	78
42	155	9	161	25	183	35	214	48	189	42	231	66
43	156	8	159	23	180	29	201	40	182	34	227	62
44	185	9	155	20	179	29	203	39	180	31	223	57
45	152	8	152	18	178	51	202	39	180	30	223	57
46	140	5	151	19	179	27	199	36	176	31	215	50
47	139	5	148	17	172	47	186	28	173	26	213	53
48	139	5	147	16	167	20	187	29	163	18	207	44
49	131	4	140	16	167	20	187	29	167	20	208	42
50	131	4	139	16	168	20	183	26	168	20	200	39
51	127	3	135	14	167	20	173	20	172	21	198	36
52	119	3	134	13	167	20	179	20	173	22	195	35
53	119	3	129	10	159	16	166	19	166	20	188	33
54	115	3	126	9	158	17	166	20	160	20	183	28
55	111	3	121	7	151	14	200	16	154	14	180	27
56	107	3	118	7	148	12	159	16	155	15	180	26
57	109	2	115	6	148	12	207	16	148	12	177	21
58	104	2	115	6	145	12	155	14	148	12	169	21
59	101	3	111	5	143	10	225	9	144	10	167	21
60	95	2	106	5	139	10	141	10	142	10	165	19
61	94	2	105	4	139	10	140	9	140	9	161	17
62	92	1	104	4	132	10	139	9	137	8	156	18
63	92	1	98	3	132	10	133	8	133	8	151	12
64	79	1	96	3	127	10	130	7	153	7	154	11
65	75	2	95	3	124	11	129	7	129	7	149	11
66	75	2	92	3	123	8	126	7	126	7	144	9
67	75	1	87	3	121	6	120	6	121	5	140	8
68	67	1	84	2	117	7	117	4	118	5	136	7
69	66	1	82	2	115	4	116	5	124	6	136	7
70	60	1	81	3	112	5	111	4	115	5	132	6
71	54	1	78	2	118	5	110	4	113	5	128	7
72	55	0	75	1	106	4	104	3	113	4	123	4
73	54	0	73	1	100	3	104	3	108	4	122	5

Scenario	**7**		**8**		**9**		**10**		**11**		**12**	
TW	**narrow**		**wide**		**narrow**		**wide**		**narrow**		**wide**	
No static customers	**80**		**80**		**60**		**60**		**50**		**50**	
Method	**CSR**		**CSR**		**CSR**		**CSR**		**CSR**		**CSR**	
Travel Times Data	**TD**		**TD**		**TD**		**TD**		**TD**		**TD**	
Iteration	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**
74	48	1	69	1	100	2	99	3	107	3	117	4
75	46	1	65	1	119	3	96	2	105	4	114	3
76	43	1	62	1	97	2	93	3	142	3	113	3
77	44	1	60	1	98	2	90	2	98	3	110	3
78	38	0	59	1	87	2	87	2	100	3	106	3
79	35	1	54	1	86	2	84	2	93	2	104	3
80	30	0	54	1	87	2	81	2	91	3	103	3
81	26	1	53	1	85	2	78	2	85	3	95	3
82	22	1	46	1	85	2	77	2	84	3	91	3
83	22	0	47	0	75	2	73	1	82	3	92	2
84	20	1	47	1	75	2	69	1	82	2	89	2
85	17	0	40	0	71	2	67	1	79	3	86	2
86	14	1	39	1	71	2	67	0	72	1	81	1
87	11	1	40	1	64	1	62	0	71	2	78	2
88	9	1	33	1	64	1	58	1	69	2	75	2
89	8	1	34	0	63	1	58	0	69	2	75	2
90	6	1	32	1	61	1	56	0	61	2	72	2
91	6	0	29	1	61	1	50	1	58	1	70	1
92	4	1	27	1	52	1	50	1	58	1	67	2
93	3	0	24	0	52	1	47	1	57	1	64	2
94			21	1	53	1	43	1	54	1	65	2
95			21	1	50	1	43	0	49	2	57	1
96			18	0	44	0	39	0	48	1	55	1
97			17	0	44	1	37	1	45	1	53	1
98			14	0	44	1	36	1	39	1	53	1
99			15	0	43	1	32	1	38	1	48	1
100			11	1	36	0	31	1	34	2	46	1
101			11	0	35	0	30	0	34	1	43	1
102			8	1	33	0	26	0	34	2	43	1
103			8	0	29	1	25	0	28	2	39	1
104			5	1	28	1	23	0	28	1	37	1
105			6	0	25	0	22	0	25	1	36	1
106			4	1	23	1	20	0	22	1	32	1
107			2	1	22	1	17	1	22	2	31	1
108					19	0	17	0	19	2	27	1
109					19	0	14	0	17	2	27	1
110					15	1	12	0	16	1	22	1
111					14	0	11	0	14	1	22	1
112					12	1	10	1	9	2	18	1
113					11	0	8	0	7	1	18	1
114					11	1	8	0	5	1	17	1
115					8	1	6	0	4	2	17	2
116					7	0	4	1	3	1	14	2
117					6	1	3	0	3	1	13	2
118					5	0	2	1			11	1
119					4	1					11	0
120					3	0					8	1
121					2	0					8	0
122											6	0
123											4	0
124											3	0
125											2	0
126											1	0
TOTAL	**13389**	**3648**	**21098**	**5374**	**15626**	**3563**	**16849**	**5345**	**15057**	**2809**	**17651**	**5550**
AVERAGE	**133.9**	**36.5**	**197.2**	**50.2**	**129.1**	**29.4**	**142.8**	**45.3**	**128.7**	**24.0**	**140.1**	**44.0**

Scenario	13		14		15		16		17		18	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	40		40		20		20		100		100	
Method	CSR		CSR		CSR		CSR		SPI		SPI	
Travel Times Data	TD		TD		TD		TD		perfect		perfect	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
1	242	22	146	17	2	78	198	4	522	328	525	309
2	101	25	149	16	1	73	47	2	524	330	526	313
3	75	29	138	19	1	79	47	2				
4	82	34	136	19	1	89	47	3				
5	80	49	141	24	4	94	47	3				
6	91	62	146	28	6	97	50	3				
7	85	65	153	33	8	105	54	3				
8	91	57	147	20	8	111	57	8				
9	89	67	177	42	12	109	61	10				
10	97	65	160	48	11	116	64	12				
11	97	65	166	57	14	118	66	14				
12	105	74	172	66	16	132	67	15				
13	102	63	177	76	20	145	70	18				
14	97	69	182	79	14	128	73	22				
15	95	58	186	84	18	130	76	23				
16	91	48	191	94	19	125	79	25				
17	92	56	196	104	16	130	81	29				
18	96	53	201	80	16	127	84	35				
19	99	63	203	76	16	133	86	35				
20	170	63	202	72	20	134	87	37				
21	137	72	206	78	19	131	86	37				
22	103	58	204	74	20	136	87	38				
23	101	61	209	77	20	141	90	45				
24	99	58	208	74	23	140	93	53				
25	97	59	214	84	20	141	95	63				
26	98	64	221	94	16	135	95	63				
27	98	67	226	108	19	138	98	73				
28	116	70	226	107	22	144	100	71				
29	102	65	228	109	23	147	101	75				
30	101	55	229	110	24	150	104	88				
31	101	56	234	123	27	151	105	88				
32	102	61	240	135	28	161	109	105				
33	103	56	249	151	30	158	112	69				
34	104	58	237	94	30	157	118	91				
35	103	56	243	130	30	157	218	92				
36	96	55	248	107	32	156	119	82				
37	98	46	247	118	35	156	232	83				
38	99	39	255	151	32	146	121	83				
39	96	39	250	112	27	150	124	92				
40	96	39	245	93	24	151	135	111				
41	101	43	251	105	23	148	146	118				
42	99	43	252	105	24	142	131	115				
43	101	47	248	100	26	146	133	131				
44	104	46	247	94	26	152	135	129				
45	103	45	241	88	27	151	138	154				
46	102	45	239	89	28	147	138	151				
47	100	46	232	80	22	148	138	107				
48	104	44	233	82	22	153	141	128				
49	102	46	225	63	24	157	146	146				
50	105	43	225	70	29	161	148	124				
51	98	27	217	52	32	158	193	128				
52	97	27	216	52	30	163	178	132				
53	99	26	213	54	29	171	165	111				
54	99	24	210	50	28	170	149	106				
55	97	24	202	39	31	350	142	99				
56	93	21	202	40	31	159	145	101				
57	90	19	201	40	24	164	140	96				
58	90	18	201	40	27	164	153	90				
59	90	19	186	32	24	157	138	85				
60	94	16	183	31	24	155	138	84				
61	88	16	183	30	23	153	132	64				
62	88	16	183	31	19	146	131	61				
63	87	16	174	25	20	144	129	55				
64	87	15	171	20	21	144	126	58				
65	84	14	168	20	18	141	121	60				
66	81	11	168	21	16	146	118	53				
67	81	13	159	14	13	142	115	46				
68	81	13	157	12	14	134	116	43				
69	81	13	154	12	16	132	115	33				
70	81	11	155	12	13	129	113	31				
71	77	10	144	8	10	128	113	27				
72	79	8	142	7	10	132	112	27				
73	76	9	141	6	10	137	106	23				

Scenario	**13**		**14**		**15**		**16**		**17**		**18**	
TW	**narrow**		**wide**		**narrow**		**wide**		**narrow**		**wide**	
No static customers	**40**		**40**		**20**		**20**		**100**		**100**	
Method	**CSR**		**CSR**		**CSR**		**CSR**		**SPI**		**SPI**	
Travel Times Data	**TD**		**TD**		**TD**		**TD**		**perfect**		**perfect**	
Iteration	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**
74	73	8	139	5	11	137	108	23				
75	73	8	133	5	13	130	101	19				
76	70	6	132	5	11	123	103	19				
77	69	6	129	5	12	127	103	18				
78	65	6	127	4	7	130	98	13				
79	62	5	122	4	8	133	95	14				
80	60	5	119	4	7	125	93	13				
81	58	5	116	4	8	115	95	13				
82	61	4	110	3	8	117	89	11				
83	59	5	109	3	8	153	88	11				
84	52	3	181	19	4	114	88	11				
85	52	3	115	4	4	104	86	10				
86	50	3	96	4	4	103	82	7				
87	52	2	88	4	5	98	77	7				
88	52	3	86	3	4	98	77	6				
89	46	2	86	3	2	97	74	6				
90	46	2	83	3	2	92	71	5				
91	44	2	80	3	2	92	74	5				
92	41	2	77	3	2	91	69	5				
93	39	2	74	3	2	86	68	4				
94	40	1	73	3	1	84	65	4				
95	39	2	71	3	1	82	62	4				
96	38	1	69	2	1	78	60	5				
97	36	1	65	2	1	74	61	4				
98	32	2	64	2	2	74	58	4				
99	32	2	62	2	0	73	54	4				
100	32	1	61	2	1	68	54	3				
101	30	1	55	1	1	69	50	3				
102	30	1	55	1	0	67	50	3				
103	28	1	55	1	0	64	47	2				
104	27	1	52	1	1	61	47	3				
105	27	1	46	1	0	58	46	3				
106	23	1	47	1	0	55	44	2				
107	23	1	46	1	1	54	42	2				
108	22	1	44	1	1	54	39	2				
109	21	1	38	1	0	54	40	1				
110	19	1	37	1	0	54	37	2				
111	18	1	35	1	1	46	35	2				
112	17	1	33	1	1	46	34	1				
113	17	1	32	1	0	42	32	2				
114	16	1	30	0	0	40	32	2				
115	15	1	29	1	0	38	30	2				
116	14	1	25	1	0	38	28	2				
117	12	1	26	1	1	34	28	2				
118	13	1	22	1	0	32	27	1				
119	11	2	21	0	1	32	25	1				
120	9	1	19	1	0	32	25	1				
121	9	1	19	1	0	30	23	1				
122	9	1	17	0	0	25	44	2				
123	7	1	15	0	0	25	28	2				
124	7	1	12	1	0	22	18	2				
125	5	2	12	1	0	19	18	1				
126	4	1	10	0	0	20	16	1				
126	5	1	9	1	0	19	14	1				
127	4	1	9	1	0	19	15	1				
128	3	1	6	1	0	13	15	1				
129	2	2	4	1	0	13	13	1				
130			4	0	0	12	11	1				
131			2	1	1	10	11	1				
132					0	9	10	1				
133					0	8	8	2				
134					0	7	7	1				
135					0	5	6	1				
136					0	5	6	1				
137					0	3	5	1				
138					1	3	4	1				
139					1		4	1				
140					0		4	1				
TOTAL	**8986**	**3180**	**18044**	**4840**	**1600**	**14358**	**11436**	**5033**	**1046**	**658**	**1051**	**622**
AVERAGE	**69.1**	**24.5**	**136.7**	**36.7**	**11.3**	**103.3**	**81.1**	**35.7**	**523.0**	**329.0**	**525.5**	**311.0**

Scenario	19		20		21		22		23		24	
TW	narrow		wide		narrow		Wide		narrow		wide	
No static customers	100		100		100		100		80		80	
Method	SPI		SPI		SPI		SPI		SPI		SPI	
Travel Times Data	AS		AS		TD		TD		TD		TD	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
1	269	305	269	351	355	309	353	286	284	178	280	181
2	269	263	267	386	336	258	328	250	435	180	268	171
3	269	306	264	313	317	197	302	219	263	178	256	190
4	288	209	236	312	309	200	303	187	273	178	258	184
5	307	206	234	316	289	202	308	190	273	183	263	192
6	266	205	231	282	296	202	284	184	263	164	264	180
7	234	202	222	261	271	160	269	158	272	176	270	180
8	218	148	213	236	270	146	270	156	281	181	318	231
9	215	148	211	226	266	165	262	138	281	181	365	218
10	211	141	210	228	253	114	258	145	281	187	379	216
11	202	127	203	196	249	108	254	121	283	185	347	210
12	202	125	202	196	250	101	248	109	270	126	323	196
13	194	90	197	166	240	82	246	113	282	125	282	182
14	193	91	192	152	236	110	247	111	269	118	279	174
15	192	93	194	153	235	112	239	98	276	117	275	179
16	179	76	191	145	231	102	231	96	290	128	271	155
17	179	76	182	116	220	76	231	98	275	139	263	134
18	179	76	181	117	218	77	223	83	265	95	262	135
19	179	77	177	97	217	61	224	81	265	96	254	113
20	167	55	172	88	206	56	219	77	261	86	251	112
21	167	55	173	89	203	56	214	75	256	79	245	107
22	167	55	168	80	202	55	207	67	251	72	243	100
23	162	40	162	75	199	56	204	57	248	66	241	98
24	156	40	160	73	195	45	203	61	239	66	238	94
25	156	39	159	74	187	40	202	63	239	65	229	84
26	154	40	153	64	185	39	193	60	231	50	226	80
27	143	30	150	57	184	39	188	45	224	50	223	67
28	143	30	150	56	174	29	184	47	222	49	222	68
29	143	30	146	51	173	29	184	51	210	36	211	63
30	144	31	141	48	170	28	178	43	212	36	203	58
31	132	22	141	48	166	28	174	38	211	34	198	57
32	130	19	135	43	158	25	174	39	201	26	196	59
33	128	19	132	41	156	22	168	39	194	27	193	52
34	128	19	132	41	144	15	171	33	194	25	189	47
35	154	16	127	35	142	13	160	28	190	22	188	49
36	122	16	124	31	139	13	160	27	186	20	187	44
37	132	14	122	28	137	11	157	24	179	16	179	44
38	114	14	119	25	132	11	151	20	178	16	174	45
39	111	12	116	23	166	9	147	20	176	14	175	44
40	126	10	116	24	124	8	165	20	174	15	176	46
41	106	8	110	18	121	7	147	20	169	16	164	35
42	137	7	137	16	117	6	173	15	164	12	161	35
43	102	6	107	16	116	7	135	12	165	11	160	37
44	114	6	102	15	111	5	134	12	162	11	160	35
45	95	5	99	13	108	4	129	10	154	9	151	26
46	93	6	99	13	102	5	125	10	155	9	147	26
47	91	5	95	10	101	5	123	8	152	10	147	26
48	86	4	91	8	89	4	122	8	145	6	148	27
49	85	4	92	8	88	3	119	7	145	7	142	22
50	82	5	88	7	80	3	117	7	141	4	135	22
51	77	4	84	6	80	3	109	6	138	4	135	22
52	77	4	82	6	73	2	107	5	135	4	133	18
53	77	4	79	6	64	1	106	6	132	4	128	22
54	71	3	77	4	64	1	102	4	126	4	123	20
55	70	4	75	4	63	1	98	4	124	4	119	16
56	70	3	74	4	58	1	95	4	121	4	117	14
57	63	2	70	4	54	1	95	4	120	4	114	12
58	63	2	68	2	52	1	91	3	115	4	111	10
59	61	2	65	2	50	0	87	3	115	4	108	9
60	57	1	64	2	47	1	84	3	114	4	105	8
61	54	2	61	1	44	0	81	3	108	2	102	7
62	54	1	59	1	41	0	79	2	106	3	99	5
63	49	1	57	1	41	1	77	3	100	3	98	6
64	48	1	54	1	39	0	73	2	100	3	94	4
65	47	1	53	1	35	0	72	2	97	2	90	4
66	45	1	50	1	33	0	69	2	94	3	90	4
67	42	1	48	1	30	0	65	1	94	2	84	3
68	39	1	47	1	30	1	63	1	88	2	82	2
69	37	1	44	1	25	0	59	1	87	3	81	3
70	37	1	42	1	25	0	56	1	82	2	90	3
71	36	1	42	1	20	1	52	1	74	2	73	2
72	30	1	38	1	21	0	49	1	73	2	73	3
73	30	1	36	1	21	0	49	1	67	1	67	2

Scenario	19		20		21		22		23		24	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	100		100		100		100		80		80	
Method	SPI		SPI		SPI		SPI		SPI		SPI	
Travel Times Data	AS		AS		TD		TD		TD		TD	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
74	26	1	36	1	16	1	45	1	65	1	65	2
75	26	1	33	1	16	0	43	0	59	1	63	1
76	25	1	31	1	12	1	42	0	58	1	64	1
77	22	1	31	1	12	1	38	0	56	1	59	1
78	21	1	28	1	10	1	35	1	51	1	56	1
79	19	1	26	1	9	0	34	1	51	0	53	1
80	17	1	25	1	9	1	34	0	50	0	49	1
81	14	0	23	1	7	1	30	0	43	1	46	1
82	13	1	22	1	5	1	29	1	43	1	44	0
83	13	0	20	1	5	0	29	0	41	0	42	0
84	10	0	19	1	4	1	23	0	37	0	40	1
85	9	0	19	0	3	0	23	0	36	1	34	1
86	7	1	18	1	2	1	22	0	30	1	32	1
87	7	1	15	0			18	1	29	1	30	0
88	6	1	14	1			16	1	25	1	30	1
89	6	1	13	1			14	0	23	1	26	0
90	4	1	12	1			14	1	21	0	26	1
91	4	1	10	0			11	1	18	1	21	1
92	2	1	8	1			11	0	16	1	21	1
93	1	1	9	1			8	0	14	0	18	1
94			7	0			7	0	12	1	17	1
95			5	1			6	0	11	0	13	1
96			5	0			5	0	9	0	13	0
97			4	1			3	1	8	1	10	0
98			3	0					7	0	9	0
99			3	0					6	0	8	1
100									4	1	7	1
101									4	0	4	1
102									2	1	4	1
103									2	1	2	1
TOTAL	**9701**	**3685**	**9902**	**5539**	**10753**	**3482**	**12565**	**3938**	**14650**	**3969**	**14601**	**5353**
AVERAGE	**104.3**	**39.6**	**100.0**	**55.9**	**125.0**	**40.5**	**129.5**	**40.6**	**133.2**	**36.1**	**141.8**	**52.0**

Scenario	25		26		27		28		29		30	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	60		60		50		50		40		40	
Method	SPI		SPI		SPI		SPI		SPI		SPI	
Travel Times Data	TD		TD		TD		TD		TD		TD	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
1	221	66	214	86	185	45	180	43	194	23	148	19
2	265	68	278	90	211	52	205	40	98	25	153	16
3	201	76	195	105	169	61	165	48	75	29	139	18
4	207	85	197	104	178	63	165	47	81	34	137	17
5	210	83	201	122	178	63	172	56	79	40	143	21
6	209	96	204	118	187	70	178	65	83	46	147	26
7	216	104	214	141	184	69	180	68	88	55	153	31
8	224	119	221	135	192	73	191	92	88	53	160	37
9	223	109	221	126	199	80	197	108	90	61	161	45
10	219	94	227	125	199	79	199	111	95	49	170	53
11	220	91	233	134	204	86	204	124	97	50	177	66
12	227	90	238	137	199	72	210	119	99	56	148	18
13	224	88	239	135	231	83	216	112	98	67	196	77
14	227	88	241	150	261	91	224	127	93	51	178	79
15	215	79	241	145	260	96	225	109	92	44	184	92
16	215	72	246	161	229	76	227	120	91	42	189	90
17	221	77	245	159	226	84	227	123	100	59	195	75
18	220	70	253	175	245	71	226	114	96	60	202	76
19	217	63	249	160	238	96	231	119	98	68	202	78
20	223	72	253	180	230	67	236	134	109	65	204	81
21	223	76	252	166	244	91	236	133	100	74	202	77
22	216	44	257	182	266	82	242	143	99	63	206	77
23	221	53	258	183	220	63	242	144	295	52	208	78
24	224	52	262	203	211	62	239	133	100	58	208	79
25	223	52	268	221	210	62	245	151	99	62	212	89
26	218	49	265	182	214	63	247	147	98	71	213	85
27	213	49	263	187	211	65	254	165	101	59	218	98
28	215	40	256	170	204	52	255	168	104	63	221	103
29	212	40	260	175	196	41	261	145	101	48	224	108
30	213	48	264	176	200	46	259	127	104	53	225	100
31	213	45	255	153	200	47	260	141	100	46	229	111
32	218	50	247	145	200	44	263	143	103	53	235	121
33	208	67	247	145	205	53	261	123	103	53	239	137
34	219	75	244	139	205	50	263	123	99	49	264	153
35	218	69	238	110	209	52	262	122	99	43	316	162
36	214	63	234	112	199	49	262	110	98	41	305	181
37	207	54	229	114	210	50	255	101	98	42	285	167
38	208	55	228	113	203	27	251	99	165	42	265	173
39	202	55	222	100	210	30	244	87	98	42	279	150
40	191	42	216	91	212	36	241	82	101	42	284	172
41	190	45	217	91	200	24	240	80	100	44	268	174
42	189	55	210	85	200	25	237	75	102	45	281	155
43	184	35	203	78	196	20	228	64	101	41	294	119
44	183	38	204	77	193	19	225	58	100	41	247	96
45	179	32	197	64	189	19	224	61	103	42	238	86
46	179	32	191	58	181	18	224	57	102	41	239	90
47	180	35	188	52	598	13	211	47	101	41	234	85
48	171	21	185	47	170	13	208	39	101	40	231	84
49	167	22	182	42	174	13	208	43	103	43	222	77
50	167	23	179	43	174	14	208	42	174	35	221	67
51	166	23	172	36	178	14	197	38	95	25	222	65
52	165	19	169	34	181	16	192	36	97	25	217	51
53	162	19	165	31	174	16	192	37	123	25	206	56
54	151	14	160	27	161	9	192	35	92	21	206	57
55	151	14	160	27	161	8	184	34	95	17	203	49
56	151	13	155	25	161	9	195	29	96	18	200	46
57	148	12	150	18	946	9	178	29	137	17	192	31
58	148	11	145	17	151	8	179	28	92	17	192	32
59	148	12	141	17	149	6	171	24	153	10	191	30
60	132	6	136	15	147	6	165	20	87	11	186	28
61	133	5	134	14	147	7	161	19	87	11	178	24
62	131	6	130	12	136	4	156	18	87	11	175	26
63	128	6	129	10	136	4	154	17	84	8	175	24
64	125	6	127	8	135	4	151	13	82	9	172	20
65	125	5	122	8	135	5	148	11	81	9	165	18
66	116	5	119	8	131	4	144	10	78	8	162	17
67	116	4	116	6	123	3	226	10	76	8	162	16
68	116	4	112	6	119	3	140	10	75	8	160	14
69	108	3	110	6	113	3	135	9	73	8	152	12
70	108	3	108	5	109	2	132	7	79	7	148	11
71	105	3	102	5	109	2	128	6	79	8	151	12
72	100	3	99	4	105	3	128	7	79	7	145	11
73	95	2	99	4	100	2	123	5	74	7	139	9

Scenario	25		26		27		28		29		30	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	60		60		50		50		40		40	
Method	SPI		SPI		SPI		SPI		SPI		SPI	
Travel Times Data	TD		TD		TD		TD		TD		TD	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
74	94	2	92	4	101	2	122	6	69	7	135	9
75	94	2	89	3	97	2	119	5	70	6	132	8
76	94	2	89	3	92	1	115	5	69	6	133	7
77	91	2	83	2	89	2	109	4	65	4	127	8
78	85	2	82	2	87	1	106	3	65	5	123	6
79	79	2	82	2	81	1	106	4	62	4	120	5
80	79	1	74	2	82	2	100	3	64	4	117	6
81	75	2	74	2	74	1	99	3	61	4	118	5
82	75	2	73	2	74	1	94	2	61	4	111	4
83	70	2	66	1	71	1	94	2	55	4	110	4
84	70	2	64	1	69	1	89	1	57	3	107	3
85	66	1	64	1	68	2	89	1	54	4	104	2
86	63	2	58	2	61	1	83	2	52	3	97	3
87	61	1	55	2	59	1	82	2	48	2	95	2
88	57	1	55	1	58	2	77	1	47	3	92	2
89	57	1	51	1	54	1	77	1	47	2	92	3
90	53	1	49	1	54	1	72	1	47	2	87	2
91	54	1	48	1	48	1	72	1	42	2	85	2
92	47	1	45	0	46	1	67	1	43	2	82	2
93	45	1	41	1	44	1	66	1	42	2	79	2
94	44	1	41	1	44	1	66	1	42	2	78	1
95	43	1	38	1	40	0	66	1	36	2	73	2
96	39	0	35	1	37	1	56	1	36	2	70	2
97	37	0	34	0	37	1	55	1	36	2	70	2
98	36	0	34	1	32	1	56	1	36	2	65	1
99	36	0	29	1	31	1	48	1	29	1	63	1
100	35	1	28	1	28	1	48	0	29	1	62	1
101	29	1	27	1	26	1	45	1	29	1	60	1
102	28	0	26	0	23	1	41	1	29	1	54	1
103	28	0	22	1	22	1	41	0	23	1	54	2
104	27	1	22	0	22	1	36	1	22	2	52	1
105	26	1	21	1	18	1	35	0	23	2	46	1
106	20	1	16	1	17	1	33	1	22	1	43	1
107	19	1	16	1	15	0	31	0	23	1	44	1
108	16	1	16	1	12	1	28	1	17	1	39	1
109	13	0	12	1	10	0	28	1	16	1	39	1
110	10	1	12	1	7	1	24	0	17	2	39	1
111	10	1	12	0	6	1	23	0	15	1	32	1
112	7	1	8	1	5	1	21	0	14	1	31	1
113	8	1	7	1	4	1	21	0	13	1	29	1
114	5	1	7	1	3	1	16	1	17	1	27	0
115	4	0	5	1	3	0	16	1	11	1	26	1
116	3	1	5	0			13	1	11	1	25	1
117	2	1	3	0			11	1	9	1	23	1
118			2	0			10	1	12	1	21	1
119							8	1	9	1	16	1
120							7	1	16	1	16	1
121							6	0	7	2	14	0
122							5	1	5	1	12	0
123							3	1	5	1	10	1
124							2	1	4	1	9	1
125									3	1	9	1
126									2	1	7	1
126											6	0
127											5	1
128											5	1
TOTAL	**15431**	**3351**	**16403**	**6787**	**16567**	**2911**	**17821**	**5555**	**9135**	**2856**	**18218**	**5249**
AVERAGE	**131.9**	**28.6**	**139.0**	**57.5**	**144.1**	**25.3**	**143.7**	**44.8**	**72.5**	**22.7**	**141.2**	**40.7**

Scenario	31		32		33		34		35		36	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	20		20		100		100		80		80	
Method	SPI		SPI		CSR		CSR		CSR		CSR	
Travel Times Data	TD		TD		TD		TD		TD		TD	
Buffer	0%		0%		20%		20%		20%		20%	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
1	78	1	204	1	356	311	352	286	286	181	284	180
2	73	2	124	0	345	239	328	228	274	142	270	158
3	79	1	44	0	334	180	305	215	261	143	257	176
4	89	3	47	0	338	183	333	225	267	149	259	176
5	94	5	47	0	309	180	348	215	266	155	264	196
6	97	6	50	0	280	170	312	214	266	147	266	191
7	105	8	53	1	275	159	270	146	266	150	271	205
8	111	11	56	0	271	150	267	129	273	154	283	179
9	109	12	60	6	258	119	268	149	277	156	350	193
10	116	11	63	9	257	120	263	156	277	159	391	193
11	118	13	65	11	257	119	250	119	282	153	400	211
12	132	18	69	14	257	116	246	117	266	133	360	192
13	145	18	71	17	237	98	245	91	270	119	286	146
14	128	24	75	21	242	106	239	115	295	121	278	142
15	130	21	75	19	243	106	233	69	275	121	279	147
16	125	17	79	23	219	76	228	85	275	131	277	144
17	130	14	82	28	219	76	227	82	289	128	260	109
18	127	12	85	33	220	82	217	75	263	100	260	100
19	133	17	84	34	206	53	213	65	265	103	262	110
20	134	12	86	40	204	53	209	66	261	94	254	102
21	131	12	87	40	200	52	209	64	252	80	244	82
22	136	16	89	42	184	38	203	71	248	77	244	76
23	141	16	89	44	184	40	196	49	242	73	245	82
24	140	16	92	51	180	33	196	56	247	73	244	77
25	141	15	95	60	172	25	193	55	237	68	227	61
26	135	17	98	71	174	25	193	55	229	54	226	60
27	138	22	98	72	171	25	183	33	221	52	223	61
28	144	21	101	84	166	20	181	42	221	52	224	56
29	147	28	101	84	158	19	177	45	224	52	211	47
30	150	29	105	98	158	19	184	47	213	41	209	46
31	151	30	190	52	154	16	208	49	205	40	284	183
32	161	30	110	61	153	17	225	40	204	39	239	45
33	158	24	123	67	144	9	217	51	202	39	194	42
34	157	23	117	73	144	9	220	33	191	21	186	32
35	157	23	121	87	143	8	171	28	196	16	182	32
36	156	25	118	77	145	9	170	20	197	24	182	34
37	156	22	118	83	135	7	165	293	194	22	179	31
38	146	16	117	70	128	5	159	24	192	18	172	28
39	150	18	120	79	128	5	156	22	175	11	170	26
40	151	18	123	89	125	3	141	21	172	10	165	26
41	148	18	126	99	130	3	142	21	173	10	162	23
42	142	13	126	102	116	2	145	16	702	10	159	21
43	146	17	130	117	115	3	175	22	171	10	157	21
44	152	18	134	168	114	2	140	15	167	10	153	19
45	151	18	136	144	110	2	130	15	161	5	149	17
46	147	20	135	96	110	2	152	17	157	6	145	15
47	148	19	136	81	101	2	146	13	158	6	145	15
48	153	23	140	93	101	1	124	13	148	6	143	13
49	157	23	139	115	92	1	113	11	153	6	140	12
50	161	25	141	91	82	1	121	8	147	6	133	9
51	158	25	173	144	76	1	134	10	141	5	133	9
52	163	29	190	137	77	1	130	6	138	4	130	8
53	171	29	171	93	65	1	126	7	135	4	130	8
54	170	27	157	87	66	0	101	4	136	3	122	6
55	350	27	162	89	64	0	84	3	128	2	119	6
56	159	24	148	79	57	0	83	3	124	2	119	5
57	164	27	133	106	57	0	79	3	122	2	118	6
58	164	18	133	66	56	0	76	1	122	2	116	5
59	157	17	129	54	54	0	75	2	122	2	108	4
60	155	15	129	54	49	0	86	2	110	2	105	4
61	153	16	127	62	45	1	68	2	107	1	106	3
62	146	11	126	45	41	1	67	2	107	2	100	4
63	144	10	194	58	35	0	64	1	107	1	99	3
64	144	10	122	39	33	0	62	1	98	0	103	3
65	141	10	118	46	30	0	63	1	99	1	91	3
66	146	10	116	54	30	0	55	1	100	1	90	2
67	142	10	114	52	26	0	59	1	92	1	88	2
68	134	9	113	50	25	0	56	1	83	1	86	2
69	132	8	111	45	21	1	49	0	82	1	80	2
70	129	8	108	40	14	1	52	1	78	1	79	2
71	128	7	105	41	14	0	46	0	75	1	77	2
72	132	9	103	35	12	0	43	0	73	1	77	2

Scenario	**31**		**32**		**33**		**34**		**35**		**36**	
TW	**narrow**		**wide**		**narrow**		**wide**		**narrow**		**wide**	
No static customers	**20**		**20**		**100**		**100**		**80**		**80**	
Method	**SPI**		**SPI**		**CSR**		**CSR**		**CSR**		**CSR**	
Travel Times Data	**TD**		**TD**		**TD**		**TD**		**TD**		**TD**	
Buffer	**0%**		**0%**		**20%**		**20%**		**20%**		**20%**	
Iteration	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**
	137	9	102	31	11	1	41	1	67	0	69	1
74	137	10	100	31	11	0	42	1	66	1	66	1
75	130	8	97	23	8	0	35	1	56	1	64	2
76	123	6	94	20	8	0	36	0	56	0	62	1
77	127	8	94	20	6	0	35	0	56	0	59	1
78	130	8	91	14	6	0	30	0	54	0	56	1
79	133	8	87	12	4	1	30	0	48	0	58	0
80	125	8	88	12	3	0	29	0	47	0	57	0
81	115	6	84	10	2	0	24	0	46	0	49	1
82	117	6	81	10			25	0	36	1	48	0
83	153	6	85	9			23	0	26	0	48	1
84	114	4	80	7			20	0	22	0	43	0
85	104	4	78	5			20	0	20	0	42	0
86	103	3	73	6			17	0	13	0	41	1
87	98	4	70	3			15	0	11	0	36	0
88	98	3	69	3			15	0	10	0	36	0
89	97	2	67	3			13	0	12	0	36	0
90	92	3	65	2			13	0	4	0	30	0
91	92	2	62	2			11	0	2	1	29	0
92	91	2	61	2			9	0			28	0
93	86	3	58	1			8	0			26	0
94	84	3	58	1			7	0			22	1
95	82	2	59	1			5	1			20	0
96	78	2	53	1			4	0			20	1
97	74	2	53	1			3	0			16	0
98	74	1	52	1			3	0			17	0
99	73	2	48	0							13	1
100	68	2	49	1							13	0
101	69	2	46	1							11	0
102	67	2	45	0							10	0
103	64	1	43	1							8	0
104	61	1	43	0							7	0
105	58	1	40	1							5	0
106	55	2	40	0							5	0
107	54	2	40	0							3	0
108	54	1	34	1								
109	54	1	34	0								
110	54	1	34	0								
111	46	2	31	1								
112	46	1	28	0								
113	42	1	28	0								
114	40	1	26	0								
115	38	1	24	0								
116	38	1	25	0								
117	34	2	25	0								
118	32	2	21	0								
119	32	1	22	0								
120	32	1	20	0								
121	30	2	19	0								
122	25	1	18	0								
123	25	1	16	1								
124	22	1	16	0								
125	19	1	14	0								
126	20	1	15	0								
126	19	2	12	0								
127	19	1	13	0								
128	13	1	12	0								
129	13	1	10	0								
130	12	1	10	0								
131	10	1	9	0								
132	9	2	7	0								
133	8	1	6	1								
134	7	1	5	0								
135	5	1	5	1								
136	5	1	4	0								
137	3	1	4	0								
138	3	1	3	0								
139			3	0								
140			2	0								
TOTAL	**14358**	**1373**	**10966**	**4463**	**10550**	**3108**	**12659**	**4152**	**14884**	**3720**	**14976**	**4646**
AVERAGE	**103.3**	**9.9**	**77.8**	**31.7**	**130.2**	**38.4**	**129.2**	**42.4**	**163.6**	**40.9**	**140.0**	**43.4**

Scenario	**37**		**38**		**39**		**40**		**41**		**42**	
TW	**narrow**		**wide**		**narrow**		**wide**		**narrow**		**wide**	
No static customers	**60**		**60**		**50**		**50**		**40**		**40**	
Method	**CSR**		**CSR**		**CSR**		**CSR**		**CSR**		**CSR**	
Travel Times Data	**TD**		**TD**		**TD**		**TD**		**TD**		**TD**	
Buffer	**20%**		**20%**		**20%**		**20%**		**20%**		**20%**	
Iteration	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**
1	216	62	216	84	180	49	179	49	147	17	147	17
2	208	61	279	91	173	51	173	40	150	22	267	134
3	201	122	198	101	167	48	166	47	138	29	284	142
4	211	131	198	102	175	39	168	47	147	30	243	112
5	209	135	203	120	176	39	173	57	149	38	236	103
6	202	133	206	122	183	47	178	66	155	50	236	101
7	214	147	217	107	180	47	180	69	159	58	231	92
8	221	99	227	114	177	55	192	92	163	42	226	87
9	218	84	223	105	189	61	196	108	167	42	221	75
10	230	89	230	111	195	76	200	76	176	45	221	74
11	216	71	236	122	196	78	208	79	176	54	218	66
12	219	70	242	135	195	99	214	90	178	51	212	70
13	219	71	242	137	194	99	219	101	182	58	210	54
14	219	69	247	147	198	121	227	113	177	50	209	52
15	221	76	246	152	201	64	226	110	169	45	202	48
16	207	71	246	143	201	64	223	96	166	45	196	46
17	216	64	246	143	206	70	228	107	171	41	193	44
18	272	65	252	150	194	59	226	100	179	47	194	46
19	210	65	253	159	199	53	234	110	179	54	188	39
20	206	59	252	150	203	54	238	123	185	60	183	36
21	206	59	254	152	203	51	238	126	185	61	182	36
22	212	62	259	167	203	55	243	133	185	65	180	32
23	211	63	264	183	204	58	240	123	179	49	177	29
24	212	60	264	180	204	56	241	123	173	44	170	25
25	217	58	269	134	209	61	246	137	178	47	169	26
26	220	57	272	145	208	60	252	152	182	55	166	22
27	209	57	263	109	209	59	253	159	185	53	168	23
28	209	56	263	117	207	55	259	176	182	56	156	19
29	202	47	262	119	198	42	263	175	185	54	156	18
30	204	47	263	109	199	41	262	139	183	54	156	16
31	205	48	261	143	201	49	262	178	185	55	151	15
32	201	46	254	88	186	45	264	131	186	53	144	11
33	213	53	249	82	190	49	266	135	186	46	144	12
34	212	54	244	73	194	49	261	118	186	47	142	10
35	198	45	242	69	194	48	260	118	183	45	141	10
36	210	49	236	67	197	44	255	111	179	46	132	8
37	205	53	231	63	189	42	256	102	181	44	129	7
38	203	50	231	83	199	45	256	113	179	41	130	7
39	197	24	229	59	199	45	245	88	173	28	123	7
40	203	31	220	64	194	38	240	91	177	37	123	7
41	202	31	216	85	193	38	235	85	177	37	117	5
42	191	19	288	66	189	35	235	81	180	37	116	6
43	180	20	204	73	189	35	228	59	178	38	111	4
44	180	21	200	53	177	27	222	54	179	32	111	4
45	180	21	191	55	175	26	219	51	177	33	104	4
46	176	16	190	66	176	25	218	50	181	38	103	3
47	176	16	184	56	175	26	207	37	175	34	99	2
48	168	18	179	52	176	26	204	32	178	35	99	3
49	173	17	180	47	162	15	198	29	183	38	96	1
50	172	13	176	45	161	15	198	29	182	38	92	2
51	162	12	168	35	166	17	192	24	178	33	113	2
52	158	12	165	31	167	17	187	23	168	25	88	1
53	159	11	161	29	169	18	183	23	167	24	83	1
54	158	12	158	27	166	18	182	23	161	21	80	1
55	158	12	155	24	161	17	182	22	161	20	81	1
56	147	8	152	24	154	13	173	18	155	16	77	1
57	145	7	147	22	152	13	168	17	154	17	77	1
58	145	8	147	21	154	13	178	18	151	15	70	1
59	145	7	142	18	154	11	180	44	147	14	67	1
60	133	4	136	17	148	10	195	17	148	14	67	0
61	132	5	133	16	139	6	146	15	144	12	67	0
62	132	4	128	13	139	6	157	15	149	14	60	1
63	130	3	123	11	137	5	143	13	145	12	60	0
64	128	3	123	11	131	5	143	13	143	11	55	1
65	118	2	116	10	131	6	134	12	134	6	52	1
66	119	2	114	8	131	5	131	11	134	7	52	1
67	117	2	113	8	126	5	131	11	130	8	49	1
68	118	2	110	7	123	3	126	10	134	8	45	1
69	118	2	106	6	121	3	123	9	132	8	43	0
70	119	2	104	7	117	4	120	9	129	8	43	1
71	105	1	100	5	115	3	119	9	128	7	39	0
72	103	1	124	5	112	3	116	10	121	7	37	1

Scenario	**37**		**38**		**39**		**40**		**41**		**42**	
TW	**narrow**		**wide**		**narrow**		**wide**		**narrow**		**wide**	
No static customers	**60**		**60**		**50**		**50**		**40**		**40**	
Method	**CSR**		**CSR**		**CSR**		**CSR**		**CSR**		**CSR**	
Travel Times Data	**TD**		**TD**		**TD**		**TD**		**TD**		**TD**	
Buffer	**20%**		**20%**		**20%**		**20%**		**20%**		**20%**	
Iteration	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**
73	103	1	99	4	109	2	110	8	153	7	37	0
74	104	1	90	3	105	1	108	7	120	6	33	0
75	104	1	86	3	104	1	106	7	119	6	30	1
76	100	1	87	3	103	1	107	6	110	4	30	0
77	86	1	81	2	99	2	101	7	106	4	27	0
78	86	1	78	2	97	1	97	6	103	4	25	0
79	86	1	76	2	97	1	96	6	104	4	25	0
80	84	0	74	1	90	1	99	6	101	3	23	0
81	83	1	70	1	87	1	92	5	98	3	21	0
82	74	1	69	1	86	1	87	4	93	3	19	0
83	74	0	66	1	86	1	86	4	93	2	18	0
84	74	1	63	1	84	1	87	4	90	2	14	1
85	71	1	61	1	77	1	80	4	88	2	13	0
86	72	0	58	1	73	1	90	3	82	1	12	0
87	69	1	58	1	73	1	76	3	83	1	10	0
88	60	1	53	1	73	1	86	2	82	1	9	0
89	59	1	51	0	73	0	68	2	78	1	7	0
90	59	1	51	1	62	0	69	1	73	0	8	0
91	57	1	47	0	61	1	66	1	72	0	6	0
92	55	0	46	1	61	0	62	1	72	1	5	1
93	50	1	42	1	58	0	97	1	68	1	3	1
94	49	0	39	0	58	1	61	1	65	0	3	0
95	47	0	40	0	51	0	59	1	61	1		
96	45	0	38	0	51	0	51	0	61	0		
97	43	1	34	0	50	1	52	0	59	0		
98	40	1	31	1	49	1	47	0	58	1		
99	36	0	31	1	48	0	46	1	54	0		
100	37	0	28	0	40	0	44	0	54	0		
101	36	0	28	0	40	0	42	1	49	0		
102	36	0	28	0	37	0	38	0	48	1		
103	28	1	23	0	34	0	37	1	43	1		
104	28	0	22	1	33	0	34	0	43	1		
105	27	0	20	1	33	0	32	0	42	0		
106	23	0	18	0	28	0	31	1	40	0		
107	21	0	16	0	25	1	29	0	38	0		
108	19	1	16	0	23	1	26	1	36	0		
109	16	1	16	0	21	1	24	0	34	1		
110	13	1	12	0	21	0	24	0	30	1		
111	10	0	11	1	19	0	23	0	28	1		
112	8	0	10	1	17	0	19	0	28	0		
113	7	1	8	0	15	0	18	0	28	1		
114	4	0	9	0	14	0	18	0	25	0		
115	2	1	8	1	12	0	13	1	22	1		
116			5	0	11	0	13	0	22	0		
117			5	1	9	0	13	1	22	0		
118			3	1	9	0	9	0	17	1		
119			2	1	7	0	8	0	17	0		
120					6	0	7	0	16	0		
121					5	0	6	1	15	0		
122					4	0	4	1	13	1		
123					3	0	4	0	11	0		
124							3	0	10	0		
125									10	0		
126									9	1		
126									6	1		
127									6	0		
128									5	0		
129									4	0		
130									3	0		
TOTAL	**15416**	**3102**	**16529**	**5695**	**15186**	**2759**	**17388**	**5280**	**15068**	**2595**	**10187**	**1834**
AVERAGE	**134.1**	**27.0**	**138.9**	**47.9**	**123.5**	**22.4**	**140.2**	**42.6**	**109.2**	**18.8**	**108.4**	**19.5**

Scenario	**43**		**44**		**45**		**46**		**47**		**48**	
TW	**narrow**		**wide**		**narrow**		**wide**		**narrow**		**wide**	
No static customers	**20**		**20**		**100**		**100**		**80**		**80**	
Method	**CSR**		**CSR**		**SPI**		**SPI**		**SPI**		**SPI**	
Travel Times Data	**TD**		**TD**		**TD**		**TD**		**TD**		**TD**	
Buffer	**20%**		**20%**		**20%**		**20%**		**20%**		**20%**	
Iteration	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**
1	78	0	77	1	355	309	270	285	284	179	284	182
2	73	0	73	1	323	241	276	242	273	152	270	166
3	78	0	114	0	290	199	281	188	261	160	257	180
4	93	1	190	0	311	199	242	185	270	167	283	182
5	94	4	84	0	331	198	268	184	271	170	272	175
6	94	5	89	1	277	148	228	174	262	144	261	191
7	103	6	95	4	274	141	221	150	270	154	260	177
8	111	8	103	5	273	139	214	152	279	166	268	158
9	111	10	109	7	256	109	210	131	271	162	350	179
10	115	9	115	9	254	109	210	131	272	161	318	195
11	120	12	118	10	257	104	207	118	284	164	347	198
12	125	15	125	13	247	97	198	113	272	123	316	199
13	125	15	130	17	237	113	198	116	279	126	357	202
14	125	15	137	21	234	114	194	107	281	102	295	179
15	127	19	138	19	231	89	190	96	278	102	275	168
16	146	15	143	24	232	93	190	82	295	114	273	160
17	127	15	149	29	219	58	182	82	273	108	270	169
18	120	9	154	34	216	86	178	72	263	87	262	134
19	126	11	154	34	217	69	179	73	263	85	257	119
20	132	15	159	41	218	85	174	72	260	108	256	128
21	131	14	158	41	202	40	169	75	257	71	252	108
22	135	16	164	47	202	52	167	63	256	94	249	114
23	134	16	167	49	202	49	166	63	250	57	240	103
24	142	20	169	52	203	49	161	58	240	53	240	104
25	141	19	175	41	186	40	158	56	241	53	231	92
26	137	18	184	44	184	39	155	51	240	71	232	90
27	136	18	187	47	182	39	151	46	237	81	225	83
28	139	21	187	50	173	31	147	42	223	61	222	79
29	147	22	193	59	171	31	146	40	221	42	216	79
30	152	22	187	46	168	31	144	36	208	44	216	79
31	150	27	193	50	166	31	138	41	208	44	209	69
32	154	27	195	54	162	24	137	35	208	27	204	73
33	147	23	201	60	157	25	133	38	202	25	200	59
34	155	26	206	70	154	21	129	31	192	22	197	59
35	153	24	212	74	146	17	129	27	192	22	193	47
36	152	23	210	76	141	13	190	27	193	22	193	47
37	156	27	211	76	139	13	120	21	192	21	188	44
38	154	23	207	68	139	13	120	18	191	28	183	44
39	154	23	213	77	136	11	152	18	200	18	178	43
40	153	24	218	86	126	9	132	18	173	17	178	42
41	144	18	224	97	127	8	111	15	174	17	177	46
42	148	20	229	103	122	6	109	14	172	18	172	39
43	147	21	229	103	117	6	106	11	172	18	173	29
44	144	19	234	114	116	6	103	11	166	16	164	30
45	141	10	242	130	114	4	100	11	160	10	164	31
46	149	13	240	128	110	4	98	11	154	11	187	25
47	147	14	242	127	106	4	94	10	158	8	150	22
48	145	13	242	96	102	4	92	8	151	12	147	21
49	149	16	244	97	111	3	88	7	168	9	144	19
50	149	17	248	96	93	2	87	7	142	5	148	19
51	156	30	253	100	99	3	97	6	146	5	137	14
52	160	24	253	96	88	3	81	5	140	4	134	14
53	163	25	251	97	85	3	80	5	139	8	132	13
54	167	25	246	93	83	3	79	5	129	3	131	13
55	166	24	244	93	77	2	75	3	125	6	125	10
56	166	23	244	85	73	2	71	3	125	5	123	11
57	165	24	235	78	69	1	71	4	123	4	119	9
58	161	24	235	78	67	0	67	4	120	6	116	9
59	162	23	228	69	67	1	65	2	112	2	116	9
60	166	31	223	64	57	1	63	2	111	2	115	9
61	156	25	220	52	57	1	60	3	106	3	108	7
62	157	25	216	53	56	1	58	3	105	3	104	7
63	151	25	212	44	49	1	58	2	100	3	101	6
64	144	9	289	40	49	0	54	2	98	3	100	6
65	147	9	203	36	49	1	52	2	97	3	95	4
66	196	9	203	36	42	0	52	1	96	3	92	4
67	144	9	196	31	40	1	48	1	93	2	92	4
68	144	9	192	30	36	1	45	1	87	3	85	4
69	137	6	188	26	36	1	46	1	85	2	83	3
70	136	6	190	25	32	0	42	1	84	3	80	2
71	78	0	191	21	30	0	40	0	76	2	77	2
72	73	0	180	21	28	0	40	1	76	2	77	2

Scenario	43		44		45		46		47		48	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	20		20		100		100		80		80	
Method	CSR		CSR		SPI		SPI		SPI		SPI	
Travel Times Data	TD		TD		TD		TD		TD		TD	
B33uffer	20%		20%		20%		20%		20%		20%	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
73	133	4	175	18	24	0	36	1	70	1	72	1
74	132	6	173	18	25	0	35	0	69	1	69	1
75	131	5	166	14	22	0	33	0	67	1	67	1
76	131	5	165	14	19	1	31	0	63	1	63	1
77	128	5	407	14	19	0	29	1	58	1	62	1
78	134	5	158	13	17	1	29	0	58	1	58	0
79	587	5	150	12	14	0	26	1	51	1	55	1
80	123	5	149	10	13	0	25	1	47	1	54	1
81	123	4	147	10	13	0	25	1	47	0	49	1
82	122	4	143	8	11	0	22	0	46	1	47	1
83	128	6	140	7	11	0	20	0	40	0	47	0
84	194	6	137	6	9	1	20	0	38	0	42	1
85	115	4	134	5	7	0	17	0	35	0	40	0
86	116	4	133	6	7	1	16	0	35	0	40	1
87	117	3	126	4	7	0	16	0	29	0	36	0
88	113	3	124	3	4	1	14	0	27	1	34	0
89	109	3	121	3	4	0	13	1	24	1	34	0
90	104	2	117	3	2	1	12	1	23	0	32	0
91	98	4	118	3			11	0	21	0	28	0
92	101	3	114	2			10	1	18	0	26	0
93	99	3	113	3			8	1	16	0	26	0
94	99	3	104	2			8	0	14	1	22	0
95	87	2	103	1			6	0	14	0	20	1
96	87	2	101	2			5	0	11	1	20	0
97	89	2	98	1			5	1	11	0	20	0
98	87	2	92	1			3	0	8	0	15	0
99	85	2	92	1			2	0	8	0	14	0
100	76	0	86	1					7	0	12	1
101	76	1	86	1					6	1	10	0
102	71	1	81	1					4	1	9	1
103	71	1	78	1					3	0	7	1
104	69	1	77	1					2	1	6	0
105	64	1	73	1							6	0
106	64	0	73	1							4	1
107	63	0	68	0							3	0
108	60	0	67	1								
109	60	0	63	1								
110	53	1	60	1								
111	52	1	60	0								
112	53	0	60	1								
113	51	0	56	0								
114	49	0	51	0								
115	44	0	50	1								
116	45	0	48	1								
117	43	0	43	1								
118	39	0	41	1								
119	38	0	41	0								
120	37	0	38	0								
121	35	0	35	1								
122	32	0	34	0								
123	32	0	31	0								
124	28	1	29	0								
125	26	1	29	0								
126	24	0	26	1								
126	23	0	23	0								
127	20	0	22	0								
128	19	1	20	0								
129	16	1	18	0								
130	15	0	17	1								
131	15	0	16	0								
132	12	1	13	1								
133	12	0	13	0								
134	10	0	13	0								
135	8	1	10	0								
136	8	0	9	0								
137	8	0	9	0								
138	5	1	5	1								
139	5	0	4	0								
140	4	0	4	0								
141	3	0										
142	133	4										
TOTAL	**14862**	**1279**	**19039**	**4000**	**11206**	**3357**	**10063**	**3729**	**14745**	**3824**	**15094**	**5358**
AVERAGE	**106.2**	**9.1**	**135.0**	**28.4**	**124.5**	**37.3**	**94.9**	**35.5**	**141.8**	**36.8**	**141.1**	**50.1**

Scenario	49		50		51		52		53		54	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	60		60		50		50		40		40	
Method	SPI		SPI		SPI		SPI		SPI		SPI	
Travel Times Data	TD		TD		TD		TD		TD		TD	
Buffer	20%		20%		20%		20%		20%		20%	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
1	216	62	215	85	182	44	49	185	296	16	147	18
2	257	63	280	90	177	45	40	177	150	21	152	15
3	201	70	198	104	172	42	47	168	141	26	140	18
4	210	78	198	101	180	48	47	167	146	31	138	19
5	210	77	203	122	180	48	57	174	150	37	143	24
6	205	87	205	124	188	54	66	179	159	44	148	29
7	217	92	218	118	184	54	69	182	159	51	153	33
8	225	95	226	122	191	60	92	193	161	34	160	40
9	225	93	226	103	197	66	108	199	168	38	165	46
10	220	78	234	117	196	65	76	202	174	42	171	55
11	221	73	239	131	194	73	79	206	173	42	177	64
12	223	73	244	144	195	61	90	212	173	43	183	76
13	220	73	244	145	199	62	101	220	174	48	185	78
14	222	73	246	158	201	60	113	223	180	48	193	92
15	224	81	247	162	206	58	110	226	176	47	192	94
16	205	62	248	147	201	58	96	182	167	43	198	77
17	211	66	252	150	198	57	107	268	173	48	206	84
18	217	66	255	166	194	46	100	225	176	48	206	77
19	212	58	256	167	216	44	110	225	175	48	209	71
20	215	61	255	167	237	57	123	231	180	54	210	74
21	215	61	262	186	190	49	126	235	182	45	206	81
22	221	65	261	187	194	51	133	236	187	54	211	79
23	222	58	269	207	195	51	123	241	185	49	211	81
24	221	59	264	183	199	55	123	241	177	48	218	91
25	217	58	269	203	199	58	137	235	178	45	224	109
26	217	57	265	196	201	58	152	240	179	53	219	97
27	211	47	271	149	197	54	159	247	184	53	226	107
28	205	47	269	147	200	55	176	251	184	52	232	116
29	208	48	262	123	189	50	175	257	180	55	231	113
30	212	51	258	106	192	48	139	262	186	55	233	114
31	216	51	254	97	190	50	178	259	191	59	239	125
32	218	49	254	96	194	46	131	256	186	49	245	98
33	210	51	250	99	199	44	135	257	182	47	242	16
34	211	51	242	89	201	43	118	257	183	48	250	139
35	213	44	238	88	187	40	118	258	182	47	232	125
36	207	43	234	74	194	44	111	259	175	44	238	140
37	206	43	236	90	201	45	102	254	182	48	237	142
38	209	45	227	74	201	40	113	250	178	42	237	133
39	202	37	222	63	202	39	88	246	181	41	236	133
40	188	27	219	62	192	34	91	242	182	37	240	99
41	187	27	215	58	183	27	85	243	180	39	236	93
42	186	27	210	56	181	28	81	235	178	37	241	98
43	184	16	210	51	179	25	59	230	179	37	242	110
44	184	15	204	50	176	25	54	229	182	41	243	90
45	175	21	198	43	176	25	51	229	175	31	241	83
46	169	17	195	42	166	18	50	219	559	32	237	78
47	174	17	194	47	165	18	37	215	182	32	232	78
48	173	18	191	46	167	20	32	214	174	29	228	66
49	549	18	184	36	164	20	29	210	178	30	225	62
50	184	18	179	36	168	20	29	205	176	34	219	60
51	164	8	181	34	164	13	24	198	173	30	219	65
52	157	8	179	37	168	13	23	198	165	22	220	59
53	159	9	171	26	167	10	23	192	163	17	215	47
54	158	8	166	23	163	12	23	193	162	19	205	43
55	157	9	165	24	144	5	22	188	170	15	206	45
56	145	5	165	24	145	6	18	183	155	15	206	44
57	240	5	155	16	146	6	17	184	149	13	205	44
58	146	4	151	16	145	6	18	177	149	13	191	28
59	145	5	152	15	138	4	44	169	147	10	191	28
60	146	5	149	12	135	4	17	169	148	10	188	28
61	130	3	141	10	127	3	15	163	148	10	184	26
62	130	3	138	10	127	3	15	160	145	10	178	25
63	130	3	138	10	127	3	13	156	145	9	175	22
64	127	2	134	10	124	4	13	156	142	8	175	22
65	127	2	131	8	120	2	12	153	139	7	175	23
66	126	2	127	7	116	2	11	150	132	7	164	19
67	113	1	126	7	112	2	11	143	136	7	162	16
68	109	1	123	6	112	2	10	197	132	7	162	17
69	110	1	120	6	112	2	9	139	133	7	161	17
70	110	1	115	5	105	2	9	133	131	6	152	15
71	107	1	111	4	107	2	9	134	134	5	150	13
72	103	1	110	4	97	1	10	128	119	5	148	13

Scenario	**49**		**50**		**51**		**52**		**53**		**54**	
TW	**narrow**		**wide**		**narrow**		**wide**		**narrow**		**wide**	
No static customers	**60**		**60**		**50**		**50**		**40**		**40**	
Method	**SPI**		**SPI**		**SPI**		**SPI**		**SPI**		**SPI**	
Travel Times Data	**TD**		**TD**		**TD**		**TD**		**TD**		**TD**	
Buffer	**20%**		**20%**		**20%**		**20%**		**20%**		**20%**	
Iteration	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**
73	102	1	110	4	97	1	8	128	133	5	148	13
74	99	1	104	2	97	1	7	121	116	5	139	9
75	91	0	99	2	97	1	7	116	119	4	137	8
76	93	0	98	2	93	2	6	117	110	3	135	7
77	90	1	98	3	92	2	7	116	106	3	129	5
78	89	1	90	2	83	1	6	107	102	3	127	5
79	84	1	87	2	83	1	6	104	102	3	122	5
80	77	0	87	1	80	1	6	104	99	2	123	4
81	75	0	85	1	79	1	5	98	97	2	118	3
82	73	1	80	1	75	1	4	94	91	2	114	3
83	72	1	77	1	70	1	4	91	91	1	110	2
84	70	1	76	2	70	1	4	89	91	1	109	3
85	66	0	72	0	70	0	4	85	88	1	105	2
86	61	1	69	1	67	1	3	82	87	1	103	2
87	60	1	66	1	63	1	3	82	80	1	99	2
88	57	0	66	1	63	1	2	76	77	1	99	2
89	57	1	65	1	60	1	2	85	75	1	94	2
90	47	0	62	0	58	0	1	95	73	0	94	1
91	46	0	57	0	51	1	1	94	69	0	88	2
92	42	0	53	1	48	0	1	93	65	0	85	2
93	42	0	53	1	46	0	1	86	66	0	83	1
94	42	0	49	0	45	1	1	81	66	0	83	1
95	39	0	46	1	41	1	1	65	65	0	77	1
96	38	0	46	0	41	0	0	62	58	0	76	1
97	32	0	43	0	38	0	0	62	57	0	74	1
98	30	0	39	0	37	0	0	60	55	0	74	1
99	28	0	37	0	34	0	1	57	54	1	67	0
100	26	0	38	0	30	1	0	55	53	1	65	0
101	24	0	33	1	28	0	1	53	45	1	65	0
102	24	0	30	1	25	1	0	47	42	0	65	0
103	21	0	30	1	25	1	1	49	42	0	59	0
104	17	0	28	1	22	0	0	55	41	1	55	1
105	13	0	24	1	20	1	0	55	39	0	55	0
106	10	0	23	0	20	0	1	48	36	0	55	0
107	8	0	23	0	17	0	0	43	35	0	48	0
108	7	0	19	0	14	1	1	38	33	1	46	0
109	6	0	18	0	12	1	0	38	29	1	46	1
110	4	1	18	0	9	1	0	32	29	1	46	0
111	3	1	16	0	9	0	0	35	29	0	42	0
112	2	1	13	0	7	1	0	27	28	0	37	1
113			13	0	6	0	0	20	26	0	37	0
114			10	0	5	0	0	18	23	0	34	1
115			10	0	4	0	1	16	20	0	30	1
116			7	0	3	0	0	15	19	0	28	1
117			7	0			1	14	19	0	28	0
118			5	0			0	13	18	0	24	0
119			4	1			0	10	14	0	24	0
120							0	10	13	0	20	0
121							1	7	13	0	20	0
122							1	8	13	0	16	0
123							0	6	10	0	16	1
124							0	4	7	0	13	0
125								3	7	0	11	1
127									6	1	9	1
128									4	1	8	1
129									3	1	8	0
130									3	0	6	1
131											5	1
132											4	0
133											3	0
TOTAL	**15656**	**2768**	**17126**	**5957**	**14465**	**2418**	**5280**	**18088**	**15466**	**2423**	**18299**	**4799**
AVERAGE	**139.8**	**24.7**	**143.9**	**50.1**	**124.7**	**20.8**	**42.6**	**144.7**	**113.7**	**17.8**	**138.6**	**36.4**

Scenario	55		56		57		58		59		60	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	20		20		100		100		100		100	
Method	SPI		SPI		CSR		CSR		SPI		SPI	
Travel Times Data	TD		TD		TD		TD		TD		TD	
Buffer/Traffic	20%buffer		20%buffer		10%traffic blocked		10%traffic blocked		10%traffic blocked		10%traffic blocked	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
1	70	0	78	1	352	308	355	287	358	313	363	290
2	73	0	73	0	332	256	635	246	690	266	697	257
3	80	2	78	0	312	210	310	183	310	218	319	201
4	90	2	83	0	304	195	302	210	341	222	335	195
5	95	4	83	0	306	197	305	191	325	206	329	190
6	97	5	89	0	273	173	293	202	281	171	285	185
7	105	7	94	0	272	171	270	148	275	164	273	172
8	110	9	102	5	272	169	262	127	275	171	273	164
9	111	11	109	6	254	134	261	138	273	164	264	149
10	115	10	115	9	257	133	255	126	255	106	262	128
11	119	12	116	12	362	317	251	104	258	117	260	129
12	125	16	122	14	300	133	250	101	257	115	256	115
13	125	16	128	17	239	98	249	125	242	81	255	118
14	129	24	135	21	238	99	241	96	236	74	242	100
15	128	19	142	22	237	99	232	79	236	76	240	93
16	127	14	142	24	221	67	227	82	236	75	238	92
17	120	10	155	28	222	65	227	76	227	80	237	106
18	127	12	153	34	217	59	215	54	218	64	227	82
19	133	16	158	41	215	53	211	51	218	72	225	80
20	132	16	158	41	210	48	213	52	219	78	225	80
21	138	18	158	41	205	47	211	53	208	39	221	84
22	141	22	163	48	201	40	200	42	203	41	209	64
23	143	21	162	44	202	40	198	44	202	43	209	63
24	134	19	168	53	193	37	197	42	201	52	208	65
25	140	21	173	61	194	29	195	40	198	47	208	62
26	143	21	179	73	194	30	184	36	193	42	193	57
27	146	22	183	81	186	22	185	36	188	40	195	58
28	151	23	183	54	178	11	183	36	186	40	193	57
29	147	24	192	55	177	14	179	35	175	35	193	55
30	154	26	189	52	155	7	171	31	176	35	179	40
31	152	26	193	55	155	7	169	31	151	21	179	39
32	146	23	200	64	153	5	167	25	146	19	179	37
33	156	26	202	63	150	6	160	21	141	19	179	39
34	154	23	208	72	149	7	159	21	102	4	167	31
35	153	23	213	84	145	5	153	19	92	4	167	28
36	163	24	212	82	144	6	150	17	92	3	165	26
37	155	24	211	80	117	2	149	17	86	3	157	23
38	155	22	217	88	109	2	148	15	79	2	175	24
39	146	16	221	99	99	1	138	14	78	2	154	20
40	146	15	221	97	98	1	134	13	76	2	146	17
41	143	14	228	120	98	1	132	14	71	2	146	17
42	140	13	230	127	98	1	121	8	67	2	145	17
43	141	14	237	147	97	2	121	9	68	1	138	16
44	142	13	242	102	85	1	121	8	60	1	137	16
45	145	16	237	1	83	1	118	8	53	1	128	12
46	139	15	232	99	81	1	109	7	53	0	126	12
47	139	18	229	91	70	1	109	7	53	0	121	9
48	144	19	235	97	69	1	108	7	45	1	119	8
49	147	23	236	108	65	0	109	8	45	0	117	8
50	157	23	235	120	54	1	98	5	45	1	107	6
51	154	22	241	95	54	0	98	5	38	1	104	5
52	158	25	246	103	48	0	98	5	37	1	101	4
53	157	41	242	99	48	0	96	4	37	1	101	4
54	158	36	241	97	40	1	88	3	31	0	96	4
55	158	36	241	98	38	0	87	3	32	0	93	3
56	155	31	233	88	35	1	85	2	25	0	93	2
57	160	39	226	73	32	0	82	2	20	0	91	3
58	157	30	224	66	27	0	78	1	20	1	85	2
59	153	30	220	66	21	0	74	2	16	1	83	2
60	153	17	215	60	18	1	72	1	16	0	82	3
61	144	15	212	55	18	0	69	1	12	1	76	2
62	139	11	207	48	13	0	69	1	10	1	74	2
63	136	11	204	45	14	0	68	1	9	0	73	2
64	137	11	205	45	11	0	64	1	8	0	66	2
65	136	11	198	39	9	1	59	1	6	0	63	2
66	135	12	192	38	5	0	57	0	4	1	61	1
67	133	10	193	37	2	0	57	1	4	0	59	1
68	135	11	193	38			57	0	2	1	55	1
69	127	6	185	27			51	0			54	0
70	126	7	179	26			48	0			51	1
71	124	6	179	26			48	0			48	1
72	124	7	176	23			46	0			46	1

Scenario	55		56		57		58		59		60	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	20		20		100		100		100		100	
Method	SPI		SPI		CSR		CSR		SPI		SPI	
Travel Times Data	TD		TD		TD		TD		TD		TD	
Buffer/Traffic	20%buffer		20%buffer		10%traffic blocked		10%traffic blocked		10%traffic blocked		10%traffic blocked	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
O	121	6	172	20			41	0			44	0
74	125	7	166	18			40	0			41	1
75	125	8	166	17			40	0			40	0
76	125	10	163	16			39	1			38	0
77	124	11	161	16			34	0			35	1
78	121	11	154	14			32	0			33	0
79	116	9	153	14			31	1			31	1
80	123	10	150	9			31	0			29	0
81	116	10	146	11			27	1			27	0
82	115	10	143	9			24	0			26	0
83	113	9	184	9			22	0			25	0
84	107	7	134	7			22	0			22	0
85	105	7	130	6			22	0			19	1
86	103	6	130	6			17	1			18	0
87	95	4	130	6			17	0			18	0
88	99	3	152	5			18	0			15	0
89	89	3	173	3			13	0			15	0
90	88	2	118	3			13	0			12	0
91	88	2	117	4			12	0			11	0
92	88	2	112	3			9	0			8	0
93	87	3	106	2			8	0			6	1
94	82	2	131	2			7	0			5	0
95	75	1	100	1			5	0			4	1
96	75	1	98	2			3	0			3	0
97	72	1	96	1			2	0				
98	72	1	95	2								
99	69	0	95	1								
100	63	1	93	1								
101	62	1	85	1								
102	59	0	81	1								
103	55	0	81	1								
104	53	0	79	1								
105	53	1	74	1								
106	53	0	71	1								
107	52	1	69	0								
108	45	0	69	1								
109	44	1	67	1								
110	44	0	65	1								
111	43	0	58	0								
112	38	1	57	1								
113	37	1	58	0								
114	30	0	58	0								
115	30	0	50	1								
116	30	0	49	0								
117	25	1	49	0								
118	24	1	49	0								
119	24	0	41	0								
120	24	1	40	0								
121	19	0	40	0								
122	17	1	39	0								
123	17	0	32	0								
124	16	0	33	0								
125	13	0	31	0								
127	13	0	27	0								
128	13	0	27	0								
129	9	0	25	0								
130	8	0	21	1								
131	6	0	20	1								
132	5	0	20	1								
133	5	0	16	0								
134	3	0	15	0								
135			14	1								
136			11	1								
137			10	0								
138			10	1								
139			9	1								
140			8	0								
141			6	0								
142			4	0								
143			3	1								
TOTAL	**13520**	**1394**	**18593**	**4152**	**9832**	**3317**	**12220**	**3385**	**9590**	**3344**	**12945**	**3990**
AVERAGE	**101.7**	**10.5**	**130.9**	**29.2**	**146.7**	**49.5**	**126.0**	**34.9**	**141.0**	**49.2**	**134.8**	**41.6**

Scenario	61		62		63		64		65		66	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	100		100		80		80		60		60	
Method	CSR		CSR		CSR		CSR		CSR		CSR	
Travel Times Data	TD		TD		TD		TD		TD		TD	
Data Precision	δ=10		δ=10		δ=10		δ=10		δ=10		δ=10	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
1	250	288	248	261	200	162	199	184	151	56	151	82
2	223	243	222	281	188	131	188	152	190	58	143	83
3	196	184	196	151	176	142	176	166	136	59	135	97
4	196	184	197	169	184	150	178	165	143	66	135	96
5	196	183	195	169	184	150	180	181	143	66	138	109
6	194	177	185	171	176	131	178	160	141	74	140	114
7	182	143	177	125	182	141	185	196	141	74	149	137
8	182	137	177	128	185	150	192	226	145	84	153	111
9	181	140	175	122	183	150	201	270	154	90	152	96
10	174	105	165	103	179	151	201	279	153	99	155	111
11	170	107	164	104	183	162	201	275	147	78	159	125
12	170	107	163	103	181	127	201	270	151	77	163	139
13	168	87	161	102	183	127	187	219	149	78	163	137
14	159	84	152	72	183	122	186	216	152	81	162	135
15	157	77	151	78	186	132	187	205	143	68	165	146
16	148	61	148	75	171	95	179	179	147	68	165	133
17	147	60	140	60	177	98	174	162	151	72	165	133
18	145	60	137	64	177	97	175	161	150	72	169	142
19	136	39	137	54	167	101	166	136	141	60	169	140
20	135	40	136	61	163	79	166	144	147	67	168	144
21	134	40	130	58	159	73	165	145	147	63	172	157
22	125	32	125	54	159	74	157	121	152	67	172	158
23	124	32	125	54	149	52	156	97	152	68	173	161
24	124	33	121	49	146	49	155	82	152	68	175	162
25	116	23	118	48	142	48	146	60	144	69	175	156
26	113	22	118	43	136	40	145	65	140	54	178	135
27	106	16	118	49	137	42	144	61	138	50	173	128
28	105	16	114	41	136	41	144	60	141	51	173	128
29	104	16	109	34	134	41	133	41	133	47	167	101
30	101	15	104	29	124	31	133	41	139	51	170	116
31	97	14	104	28	123	32	132	39	139	51	169	93
32	95	12	100	24	124	31	128	33	137	47	165	82
33	95	12	99	25	112	18	123	29	142	50	163	78
34	95	12	96	21	111	18	122	29	137	46	158	78
35	90	10	94	18	112	17	122	29	140	47	156	73
36	86	6	91	16	112	17	118	23	132	33	156	83
37	85	6	90	16	108	15	113	22	131	33	152	78
38	85	7	86	11	103	13	113	23	129	32	147	56
39	77	4	84	9	99	13	111	20	126	29	146	63
40	76	4	83	10	98	12	107	16	123	24	142	58
41	76	4	81	8	99	12	104	14	123	23	141	56
42	68	3	76	8	99	12	103	14	121	25	136	42
43	68	3	76	8	94	9	103	14	119	22	132	42
44	68	3	72	7	89	7	97	10	117	23	131	37
45	68	4	71	6	89	7	96	10	113	21	130	33
46	60	2	72	5	86	6	96	10	110	19	126	29
47	59	2	66	5	85	6	91	7	109	19	123	28
48	54	2	66	5	84	6	88	7	111	19	120	26
49	55	1	66	5	78	4	87	7	110	18	121	27
50	54	2	60	3	77	5	87	7	105	16	116	25
51	49	1	59	4	76	5	84	6	105	15	112	19
52	48	1	58	4	76	5	80	5	102	15	111	19
53	45	1	54	3	74	4	79	6	102	14	110	19
54	43	1	51	2	69	3	79	5	98	14	106	16
55	43	0	52	2	69	3	79	5	94	12	103	13
56	40	0	50	2	66	3	72	3	93	12	102	13
57	38	0	47	1	65	3	71	4	92	11	100	13
58	37	1	45	1	66	3	71	4	92	10	96	10
59	37	0	44	1	59	2	69	3	90	10	95	10
60	34	0	41	1	58	2	64	2	85	6	92	7
61	34	0	40	1	58	2	63	3	83	6	90	7
62	33	0	40	1	52	1	63	2	81	6	87	7
63	28	0	37	1	49	2	63	3	81	7	85	6
64	28	0	35	0	50	1	56	1	80	4	84	6
65	27	0	34	0	50	1	57	1	77	4	81	5
66	25	0	31	1	47	2	55	2	72	2	80	6
67	24	1	31	0	42	1	53	1	75	2	79	5
68	22	0	31	0	43	1	49	1	75	1	77	5
69	19	0	27	0	41	1	50	1	72	1	73	4
70	19	0	26	1	37	1	48	1	71	1	74	4
71	16	1	27	0	37	1	47	1	65	1	72	4
72	15	0	23	0	37	1	43	1	63	1	68	3

Scenario	61		62		63		64		65		66	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	100		100		80		80		60		60	
Method	CSR		CSR		CSR		CSR		CSR		CSR	
Travel Times Data	TD		TD		TD		TD		TD		TD	
Buffer	δ=10		δ=10		δ=10		δ=10		δ=10		δ=10	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
73	13	0	22	1	33	0	43	0	60	1	65	2
74	14	0	22	0	33	0	43	0	59	1	65	2
75	14	0	19	0	31	1	39	1	60	1	65	1
76	11	1	19	0	28	0	37	0	55	1	62	2
77	11	0	16	0	27	1	37	0	58	1	57	2
78	9	0	15	1	24	0	35	1	51	1	57	1
79	8	0	13	0	24	1	34	1	51	1	56	1
80	7	0	12	1	23	0	31	0	48	1	54	1
81	6	1	10	1	21	0	31	0	46	1	51	1
82	6	0	10	0	21	0	30	0	46	1	50	1
83	5	0	9	0	18	0	29	1	44	0	50	1
84	4	0	8	1	16	0	24	1	43	0	49	1
85	4	0	6	1	16	0	23	1	40	0	44	1
86	3	0	6	0	16	0	23	0	38	1	43	1
87	3	0	5	0	13	0	21	0	37	0	43	0
88	2	0	4	1	12	0	19	0	35	1	43	1
89	1	0	3	0	11	0	19	0	35	0	37	0
90	1	0	4	0	9	0	17	0	35	0	37	1
91			3	0	7	1	16	0	33	0	36	1
92			2	1	7	0	16	0	30	0	36	1
93			1	0	6	0	14	0	29	0	31	0
94			1	0	5	0	12	0	28	0	30	1
95					4	0	12	0	27	1	27	0
96					4	0	9	1	27	1	27	0
97					3	0	9	0	25	1	24	0
98					3	0	7	0	22	1	23	0
99					2	0	7	1	20	0	20	0
100					2	0	5	0	20	0	20	0
101					1	0	6	0	20	0	20	0
102							4	0	20	0	20	0
103							4	0	16	0	18	0
104							2	0	15	0	17	0
105							2	0	15	1	16	0
106							1	0	12	1	14	0
107									12	0	14	0
108									10	0	11	1
109									9	0	11	0
110									8	0	9	1
111									6	0	9	0
112									7	0	7	0
113									5	0	6	0
114									4	0	5	0
115									3	0	5	0
116									3	0	4	0
117									2	0	3	1
118									2	0	2	0
119									1	0	2	0
120											2	0
121											1	0
TOTAL	**6998**	**2873**	**7334**	**3184**	**8653**	**3401**	**9375**	**5151**	**10007**	**2805**	**11032**	**5126**
AVERAGE	**77.8**	**31.9**	**1833.5**	**796.0**	**85.7**	**33.7**	**88.4**	**48.6**	**84.1**	**23.6**	**91.2**	**42.4**

Scenario	**67**		**68**		**69**		**70**		**71**		**72**	
TW	**narrow**		**wide**		**narrow**		**wide**		**narrow**		**wide**	
No static customers	**50**		**50**		**40**		**40**		**20**		**20**	
Method	**CSR**		**CSR**		**CSR**		**CSR**		**CSR**		**CSR**	
Travel Times Data	**TD**		**TD**		**TD**		**TD**		**TD**		**TD**	
Buffer	**δ=10**		**δ=10**		**δ=10**		**δ=10**		**δ=10**		**δ=10**	
Iteration	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**	**cpu[sec]**	**kappa**
1	127	38	127	38	104	14	104	14	56	0	56	0
2	152	43	152	36	108	18	107	13	51	0	51	0
3	116	52	114	43	95	23	97	16	53	0	55	0
4	121	57	115	43	103	28	95	17	58	0	58	0
5	123	41	119	51	101	33	99	19	63	3	59	0
6	127	47	122	61	108	40	102	24	66	4	62	0
7	126	50	124	63	107	48	106	30	70	6	66	0
8	128	57	132	88	113	52	109	36	76	7	71	4
9	133	63	136	97	116	42	111	42	76	9	75	6
10	132	64	139	105	120	46	116	50	78	10	79	8
11	135	71	143	129	120	47	121	58	81	13	81	9
12	131	57	146	143	123	47	125	68	87	15	83	11
13	131	57	148	139	123	46	127	71	86	13	86	13
14	131	60	154	116	120	47	127	74	87	17	91	16
15	133	56	154	121	120	47	131	89	90	18	94	17
16	134	58	154	112	112	38	134	96	93	18	98	21
17	132	51	156	100	111	38	137	115	82	13	102	25
18	131	48	160	114	115	41	137	105	82	13	105	31
19	130	50	162	136	122	47	137	72	85	15	105	31
20	136	54	162	125	121	47	140	66	93	17	105	32
21	134	53	162	127	123	53	140	72	92	19	105	32
22	138	60	161	119	126	59	143	76	91	17	106	34
23	137	57	160	119	122	58	142	74	94	18	110	40
24	140	61	164	132	115	52	145	78	94	19	113	48
25	141	62	167	142	121	57	148	88	92	18	118	57
26	127	42	169	153	119	59	152	103	92	19	116	58
27	131	44	172	154	121	52	151	100	94	21	121	66
28	131	45	176	153	120	47	154	112	97	24	120	46
29	130	46	176	173	123	53	153	106	99	26	125	49
30	129	44	175	170	122	54	158	120	98	27	127	52
31	133	47	173	168	121	53	160	126	98	24	128	46
32	134	49	172	170	120	50	162	129	100	27	131	49
33	132	42	174	125	122	55	162	130	100	26	133	58
34	136	43	174	128	121	54	166	144	105	30	138	65
35	135	43	174	121	122	53	163	134	104	27	141	70
36	135	45	167	94	121	53	160	123	102	25	140	82
37	133	42	162	87	114	44	161	79	103	24	140	74
38	131	36	162	92	113	40	166	94	102	25	137	69
39	130	37	162	86	116	45	162	90	98	24	138	75
40	126	33	157	82	116	46	163	84	98	24	141	65
41	120	29	151	64	115	43	166	93	96	21	143	80
42	117	25	150	66	118	46	165	94	95	20	148	88
43	117	26	146	52	115	42	158	109	93	17	150	99
44	117	25	144	54	115	41	157	81	93	17	155	110
45	116	25	141	48	115	41	153	72	95	19	158	122
46	114	25	139	55	115	40	153	63	97	19	157	123
47	114	24	137	45	112	42	146	54	97	20	154	106
48	107	18	132	49	111	37	146	52	96	21	155	110
49	111	18	132	46	113	31	142	49	96	22	158	116
50	110	19	127	45	115	30	141	50	99	25	161	134
51	111	18	127	40	112	26	136	41	102	27	162	130
52	107	16	121	28	107	26	135	43	102	26	164	113
53	107	17	121	28	103	19	131	33	102	28	163	118
54	98	11	116	23	103	19	130	35	105	32	157	96
55	98	11	115	22	103	16	125	27	104	25	158	93
56	96	10	110	20	100	17	126	28	103	27	152	72
57	94	9	110	18	99	17	129	26	102	20	152	79
58	94	9	110	19	91	12	125	25	104	18	147	85
59	88	7	106	16	91	14	119	19	104	17	147	76
60	86	7	102	14	91	13	114	19	108	21	141	64
61	84	5	101	13	90	11	112	19	100	16	141	61
62	84	5	101	12	90	14	112	19	96	14	136	56
63	83	5	97	11	86	7	106	13	95	15	135	56
64	78	4	93	8	85	8	103	13	95	15	131	50
65	78	4	92	7	84	6	101	13	92	12	130	43
66	76	3	89	5	84	7	101	13	87	7	126	38
67	76	3	89	5	84	7	97	9	86	9	125	39
68	75	3	84	4	83	7	94	8	84	7	121	31
69	71	2	83	4	77	5	92	7	86	9	118	28
70	66	2	83	4	76	4	89	6	88	10	117	27
71	66	1	82	4	79	5	88	5	81	5	116	23
72	67	1	74	3	69	3	87	5	78	5	111	20

Scenario	67		68		69		70		71		72	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	50		50		40		40		20		20	
Method	CSR		CSR		CSR		CSR		CSR		CSR	
Travel Times Data	TD		TD		TD		TD		TD		TD	
Buffer	δ=10		δ=10		δ=10		δ=10		δ=10		δ=10	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
73	63	1	74	3	71	3	84	3	78	6	109	18
74	63	1	74	3	70	3	83	4	77	5	108	18
75	59	1	73	3	67	3	79	3	80	6	105	16
76	59	1	68	2	62	2	77	2	79	6	101	11
77	56	1	67	2	61	2	75	2	81	7	99	11
78	56	0	66	3	62	1	73	2	77	5	99	11
79	56	1	66	2	62	1	72	2	72	6	95	10
80	50	1	60	2	62	1	72	2	75	5	92	8
81	49	0	59	2	60	2	67	2	75	6	91	8
82	49	1	58	2	52	1	65	1	77	6	91	8
83	46	1	58	2	50	1	64	1	69	6	89	6
84	46	1	53	1	50	1	62	1	69	4	84	7
85	44	0	52	2	50	1	61	1	66	4	84	7
86	43	1	52	1	49	1	57	1	65	4	80	5
87	42	0	50	1	44	1	58	0	64	3	80	4
88	40	0	46	1	44	1	56	1	64	3	76	4
89	38	1	46	1	43	1	54	0	59	2	75	3
90	35	0	45	1	41	1	53	0	59	2	75	3
91	35	1	43	0	41	0	50	1	59	1	74	3
92	35	1	40	1	41	0	49	1	57	2	67	3
93	33	0	40	1	37	1	46	0	57	2	66	2
94	33	0	40	0	36	0	44	0	55	2	64	2
95	27	1	36	1	35	1	43	0	50	1	63	2
96	27	1	34	0	35	0	42	1	48	1	62	1
97	27	0	33	1	33	1	40	1	48	1	59	1
98	27	0	33	0	31	0	37	1	48	1	57	0
99	22	1	30	0	30	0	36	0	48	1	55	1
100	22	0	29	1	27	0	36	0	44	1	53	0
101	22	0	29	0	28	0	36	0	41	1	52	1
102	22	0	25	0	28	0	31	1	41	1	50	1
103	20	1	24	1	26	0	31	0	39	1	49	1
104	17	0	24	0	23	0	31	1	37	0	46	0
105	16	0	22	0	21	0	30	0	37	1	44	0
106	15	0	19	1	21	0	26	1	35	1	43	0
107	14	0	19	0	21	0	26	0	34	0	42	1
108	12	1	17	0	21	0	26	0	34	0	38	1
109	11	1	17	0	21	0	24	0	33	0	36	1
110	10	0	16	0	17	0	21	0	30	1	36	1
111	9	1	13	0	16	0	21	0	30	0	34	0
112	8	0	14	0	16	0	21	0	26	1	32	0
113	6	0	13	0	16	0	19	0	26	0	32	0
114	5	1	10	0	16	1	16	0	26	0	30	0
115	4	0	10	0	11	0	16	1	23	1	29	0
116	4	0	10	0	11	0	14	0	23	0	27	0
117	3	0	8	0	12	0	12	0	22	0	26	1
118	3	0	7	0	9	0	12	0	21	0	26	0
119	2	0	5	0	8	1	11	0	19	1	23	0
120	2	0	6	0	8	0	10	0	17	0	21	0
121	0	1	4	0	6	1	8	0	16	1	21	0
122			3	0	5	0	8	0	16	0	19	0
123			3	0	4	0	6	1	16	0	18	0
124			1	0	4	0	6	0	12	0	17	0
125					3	0	4	0	13	0	16	0
127					2	1	3	0	13	0	14	0
128					1	1	2	0	12	1	14	0
129					2	0	3	0	9	0	13	0
130					1	0	1	0	9	0	10	0
131									8	1	11	0
132									7	0	10	0
133									5	1	9	0
134									5	0	7	0
135									5	0	6	0
136									4	0	6	0
137									3	1	5	0
138									3	0	5	0
139									2	0	4	0
140									2	0	2	0
141									1	0	2	0
142											1	0
TOTAL	**9685**	**2415**	**11527**	**5328**	**9515**	**2517**	**11562**	**4318**	**9082**	**1334**	**11878**	**4026**
AVERAGE	**80.0**	**20.0**	**93.0**	**43.0**	**73.8**	**19.5**	**89.6**	**33.5**	**64.9**	**9.5**	**84.2**	**28.6**

Scenario	73		74		75		76		77		78	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	100		100		80		80		60		60	
Method	SPI		SPI		SPI		SPI		SPI		SPI	
Travel Times Data	TD		TD		TD		TD		TD		TD	
Buffer	δ=10		δ=10		δ=10		δ=10		δ=10		δ=10	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
1	250	286	249	260	199	162	199	184	152	56	152	82
2	224	246	222	228	189	164	188	158	191	60	144	83
3	197	201	194	171	179	149	176	173	136	67	135	96
4	197	200	194	159	183	155	177	177	143	75	135	97
5	195	199	194	165	183	156	181	183	143	74	139	110
6	185	151	192	152	177	147	181	182	141	84	140	114
7	184	152	188	149	185	161	187	212	150	92	149	127
8	184	153	181	135	189	166	191	241	152	99	153	134
9	178	125	180	132	198	167	195	269	151	105	156	113
10	173	118	175	123	189	157	199	203	147	81	155	116
11	173	118	174	123	180	124	195	179	151	84	159	126
12	167	117	174	123	183	121	194	192	151	84	163	132
13	162	86	168	101	182	121	187	158	149	76	163	132
14	159	85	163	88	183	120	187	158	148	71	162	131
15	148	70	158	81	180	121	182	165	141	69	165	137
16	147	69	157	81	180	128	182	172	144	64	168	150
17	147	70	157	77	181	127	175	134	147	69	168	160
18	137	47	156	79	173	97	171	133	145	60	169	151
19	137	48	152	78	174	100	171	127	145	61	167	143
20	136	51	146	63	167	86	170	125	148	67	170	154
21	126	33	145	62	166	87	164	101	146	70	170	155
22	124	32	144	62	157	70	162	100	149	70	169	158
23	123	33	141	63	152	69	162	109	152	74	173	171
24	123	33	140	65	154	68	162	108	141	57	175	175
25	116	24	130	49	144	48	150	70	140	56	176	174
26	113	27	130	47	143	49	149	75	143	57	175	174
27	111	22	129	48	142	49	148	78	138	49	174	172
28	110	22	129	48	142	49	144	75	136	49	173	177
29	106	20	129	47	131	41	138	55	139	35	168	145
30	105	20	119	41	135	41	138	56	142	36	172	115
31	101	17	119	40	123	23	137	58	142	35	168	145
32	101	17	119	39	124	24	134	57	136	34	168	148
33	96	15	115	37	124	23	128	46	133	41	162	90
34	95	15	109	30	123	26	127	42	136	53	162	95
35	91	15	108	29	123	23	128	42	137	44	157	87
36	91	14	108	30	110	17	127	45	131	39	156	92
37	90	12	100	24	111	16	117	40	131	38	150	79
38	87	10	99	24	110	17	117	32	133	37	150	60
39	85	10	98	24	107	16	114	30	125	21	145	66
40	82	7	98	23	109	16	114	24	121	20	141	53
41	77	6	95	20	102	8	108	20	129	22	139	46
42	77	6	89	18	102	7	108	21	121	21	137	47
43	74	5	90	17	97	6	104	17	121	24	135	44
44	72	5	90	17	97	7	104	17	114	16	131	37
45	72	4	89	18	97	6	99	15	109	16	128	37
46	69	3	81	14	92	5	99	15	108	17	127	40
47	64	3	81	13	90	5	95	12	111	16	127	38
48	64	3	78	11	88	4	94	13	108	15	120	34
49	64	3	72	9	88	5	90	10	106	12	116	31
50	59	3	72	7	88	5	87	8	98	8	117	31
51	59	3	69	6	81	3	86	8	98	8	117	29
52	58	3	68	5	78	3	86	8	97	9	110	25
53	52	2	68	5	78	3	82	6	96	7	107	22
54	53	2	65	4	77	2	79	4	94	5	107	21
55	51	2	60	4	77	3	77	4	90	5	108	20
56	47	1	60	3	77	3	77	5	90	4	101	19
57	46	1	58	2	73	2	74	4	88	5	98	18
58	48	1	56	3	70	2	70	4	86	5	98	19
59	41	0	53	2	67	2	69	4	79	4	97	19
60	42	0	53	3	67	2	70	3	79	4	92	13
61	41	1	49	2	63	2	66	4	79	4	89	10
62	37	0	49	2	63	2	66	3	79	4	87	9
63	37	0	49	2	62	2	62	3	77	3	88	9
64	35	0	45	1	58	3	59	3	73	2	84	7
65	34	0	42	1	58	3	58	2	68	1	83	8
66	31	0	42	1	52	1	55	2	68	1	79	7
67	28	1	38	1	53	1	54	1	66	1	79	6
68	27	0	39	1	52	1	54	1	66	1	76	4
69	26	0	35	1	49	2	50	1	64	1	75	5
70	24	1	35	0	45	2	46	2	61	1	72	4

Scenario	73		74		75		76		77		78	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	100		100		80		80		60		60	
Method	SPI		SPI		SPI		SPI		SPI		SPI	
Travel Times Data	TD		TD		TD		TD		TD		TD	
Buffer	δ=10		δ=10		δ=10		δ=10		δ=10		δ=10	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
71	24	0	35	1	45	1	47	1	60	1	72	4
72	22	0	31	1	42	1	46	2	57	1	68	3
73	20	0	29	1	41	1	42	1	56	1	68	3
74	19	0	28	1	40	1	42	1	55	0	65	2
75	19	0	26	1	37	0	40	1	56	0	64	2
76	15	0	25	1	36	0	37	1	52	1	59	2
77	15	0	23	0	34	1	36	1	46	1	58	2
78	15	0	23	0	31	0	34	0	46	1	57	1
79	12	0	20	0	31	0	33	1	46	0	57	1
80	13	0	20	0	30	1	31	0	45	0	54	1
81	12	0	17	1	27	0	30	1	43	0	53	1
82	9	0	16	0	27	0	27	1	39	0	49	0
83	9	0	17	0	24	1	28	0	39	0	48	1
84	9	0	14	0	21	1	25	0	39	0	46	1
85	7	0	13	1	21	0	25	0	38	1	46	0
86	7	0	11	0	19	0	22	1	33	1	42	1
87	5	0	12	0	17	0	21	1	30	1	42	1
88	5	0	9	0	16	0	21	0	30	1	42	1
89	4	0	9	1	14	0	21	0	28	0	38	0
90	4	0	7	0	14	0	17	0	28	0	36	1
91	3	0	7	0	12	0	17	0	29	0	35	1
92	2	0	6	0	11	1	15	0	24	0	33	0
93	2	0	6	0	9	1	13	1	21	1	31	0
94	1	0	4	0	9	0	12	0	21	0	30	0
95			3	0	7	1	11	0	17	1	29	1
96			2	1	7	0	9	0	16	1	27	0
97			2	0	6	0	9	1	14	1	25	1
98					6	0	7	0	12	0	25	0
99					4	0	7	0	12	0	23	0
100					3	1	6	0	10	0	21	0
101					4	0	5	0	9	1	21	0
102					3	0	4	0	7	0	18	0
103					3	0	4	0	5	1	18	0
104					2	0	3	0	3	1	17	0
105					1	0	2	1	3	0	15	0
106							1	0	2	1	14	0
107									1	1	13	1
108									1	0	12	0
109											10	0
110											10	0
111											9	0
112											7	1
113											6	0
114											7	0
115											5	0
116											5	0
117											4	1
118											2	1
119											1	0
TOTAL	**7318**	**3049**	**8268**	**3603**	**9179**	**3615**	**9526**	**5004**	**9522**	**2674**	**11057**	**5713**
AVERAGE	**77.9**	**32.4**	**85.2**	**37.1**	**87.4**	**34.4**	**89.9**	**47.2**	**88.2**	**24.8**	**92.9**	**48.0**

Scenario	79		80		81		82		83		84	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	50		50		40		40		20		20	
Method	SPI		SPI		SPI		SPI		SPI		SPI	
Travel Times Data	TD		TD		TD		TD		TD		TD	
Buffer	δ=10		δ=10		δ=10		δ=10		δ=10		δ=10	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
1	127	38	127	39	105	14	105	14	73	0	71	1
2	152	44	152	37	108	18	108	13	51	0	52	0
3	115	52	115	43	96	23	97	16	55	1	55	0
4	121	61	115	43	104	27	96	16	63	2	59	0
5	123	63	119	51	101	33	99	20	67	3	59	0
6	124	55	122	61	109	39	103	24	66	4	62	0
7	125	54	124	63	110	48	106	30	74	6	67	0
8	128	60	132	85	109	46	110	35	77	8	70	1
9	134	65	137	99	113	38	111	42	76	9	74	6
10	134	65	139	115	119	41	118	50	80	9	79	8
11	135	73	141	124	119	41	121	59	82	11	81	10
12	132	58	145	105	122	48	125	68	85	14	85	12
13	131	58	151	108	125	53	125	72	86	13	89	15
14	131	56	155	115	116	42	130	84	89	17	93	18
15	134	60	154	125	114	37	131	87	89	19	95	17
16	133	63	157	118	112	37	134	100	86	16	98	21
17	130	57	153	116	116	42	138	70	83	13	101	26
18	137	61	185	126	118	41	140	66	80	10	104	31
19	135	50	161	130	121	47	143	114	83	14	104	31
20	133	56	164	147	123	52	148	70	88	14	107	37
21	133	49	166	147	122	53	144	79	91	19	107	36
22	133	49	166	148	126	59	143	74	90	16	110	44
23	133	50	165	149	115	48	146	76	94	19	111	40
24	136	54	168	149	120	43	145	77	95	19	113	47
25	138	51	170	165	120	52	149	88	92	19	118	36
26	136	55	174	148	122	56	152	100	92	19	124	60
27	139	57	175	143	120	53	154	102	92	21	120	37
28	134	53	179	153	122	56	154	101	99	23	127	44
29	128	38	176	189	126	56	156	111	101	23	126	49
30	135	42	174	188	120	38	161	122	97	27	130	54
31	133	41	174	199	122	39	163	136	101	26	131	55
32	129	42	172	141	121	43	164	136	97	23	133	55
33	130	42	175	187	122	43	159	115	102	26	133	53
34	133	42	171	140	122	42	161	130	103	27	138	68
35	126	28	168	123	120	41	164	107	103	24	141	78
36	130	38	167	124	114	40	163	94	104	28	140	67
37	133	38	161	105	116	38	167	119	105	27	139	73
38	132	33	160	89	116	33	166	130	104	27	138	63
39	132	32	155	93	116	33	163	103	98	23	141	72
40	132	32	155	93	113	35	168	114	97	20	145	78
41	130	34	150	72	116	36	168	103	97	21	148	91
42	130	33	150	72	117	36	162	92	97	22	151	101
43	130	31	145	63	117	36	162	91	99	25	151	95
44	116	20	145	64	117	38	157	80	99	23	154	106
45	117	18	144	56	115	34	153	75	98	24	157	118
46	116	22	139	56	114	38	150	60	100	24	156	118
47	115	20	135	49	111	26	156	60	103	27	157	122
48	111	14	134	50	115	29	146	49	102	26	156	121
49	111	15	129	41	115	30	142	45	103	28	155	110
50	116	20	129	43	111	31	139	41	108	30	158	125
51	122	20	123	39	108	28	139	41	107	33	162	92
52	116	10	124	39	104	23	135	33	107	28	164	98
53	108	7	119	34	105	23	132	32	111	32	161	85
54	107	8	119	33	102	18	129	32	110	31	160	98
55	106	12	114	25	102	18	129	31	104	26	156	68
56	101	6	110	26	95	11	128	32	105	24	153	67
57	99	5	109	23	93	12	121	27	104	25	150	57
58	92	5	105	21	93	13	118	23	105	25	149	57
59	91	5	104	18	92	12	117	23	104	25	145	51
60	91	4	101	18	92	9	118	23	97	18	143	53
61	91	4	100	15	91	11	111	20	95	19	138	44
62	84	3	96	13	86	9	109	18	95	18	138	44
63	83	3	96	11	86	9	108	19	92	16	133	37
64	80	2	92	11	85	8	102	16	93	16	133	35
65	80	2	91	9	85	8	100	16	84	11	128	29
66	79	2	89	8	83	8	97	15	84	11	127	31
67	79	3	87	7	82	10	97	15	86	12	121	26
68	76	1	87	8	82	7	92	11	86	13	122	26
69	76	2	83	8	78	6	92	12	82	9	117	23
70	72	2	82	7	78	6	89	8	78	8	115	18
71	69	1	78	7	78	6	89	9	78	8	112	20
72	69	1	78	7	72	6	85	6	78	6	109	19

Scenario	79		80		81		82		83		84	
TW	narrow		wide		narrow		wide		narrow		wide	
No static customers	50		50		40		40		20		20	
Method	SPI		SPI		SPI		SPI		SPI		SPI	
Travel Times Data	TD		TD		TD		TD		TD		TD	
Buffer	δ=10		δ=10		δ=10		δ=10		δ=10		δ=10	
Iteration	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa	cpu[sec]	kappa
73	66	1	74	6	71	5	84	7	78	5	109	18
74	63	1	74	6	68	5	81	6	82	7	107	17
75	63	1	70	4	67	5	80	6	82	6	102	16
76	57	1	70	4	68	4	77	4	76	4	101	14
77	57	1	66	3	64	3	77	4	76	4	98	12
78	57	1	66	2	61	3	73	3	77	4	98	12
79	55	1	63	2	60	3	73	4	75	5	94	10
80	55	1	62	2	60	3	69	3	74	5	93	10
81	52	1	60	1	56	2	70	2	74	5	89	8
82	47	1	58	2	55	2	66	2	73	5	89	9
83	46	1	55	1	52	1	65	2	68	6	85	7
84	45	1	56	1	52	1	63	2	64	2	85	7
85	45	1	52	1	49	1	63	2	66	3	81	5
86	44	0	51	1	47	0	59	1	66	2	81	5
87	44	0	49	1	47	1	56	2	63	2	77	4
88	41	1	49	1	46	1	55	2	62	2	77	5
89	41	0	45	1	45	1	53	1	57	2	73	4
90	35	0	60	1	41	1	52	1	58	2	73	3
91	34	0	76	1	41	0	51	1	53	1	70	2
92	34	0	44	1	38	1	49	1	51	1	69	3
93	33	1	43	0	38	0	46	1	50	1	66	2
94	29	1	39	0	38	1	45	1	50	1	66	3
95	29	0	39	0	35	1	45	1	46	1	62	2
96	27	0	37	0	35	0	44	1	43	0	60	2
97	25	0	34	0	33	0	41	1	43	1	60	2
98	23	0	34	0	32	1	38	1	40	0	57	2
99	22	0	33	0	31	1	38	1	40	1	56	2
100	22	0	29	1	30	0	36	0	38	1	53	1
101	22	0	29	0	26	0	35	1	37	0	53	1
102	17	0	29	0	25	1	32	0	37	0	50	1
103	16	1	26	1	23	1	30	1	34	0	48	1
104	16	0	26	0	23	0	29	1	33	0	46	1
105	14	0	26	0	24	0	29	1	34	0	47	0
106	14	0	22	0	23	0	26	1	30	0	44	1
107	13	0	21	0	23	0	24	1	30	0	43	0
108	10	0	18	0	23	0	24	1	29	1	42	0
109	9	0	19	0	16	1	22	0	26	0	40	0
110	7	0	16	1	15	0	22	0	25	0	38	1
111	7	0	16	0	15	1	22	0	22	0	37	0
112	5	0	14	0	15	0	19	1	19	1	34	0
113	4	0	14	0	13	0	17	0	19	0	33	1
114	3	0	12	0	11	0	17	0	18	0	33	1
115	3	0	11	0	12	0	17	1	17	0	29	0
116	1	1	9	0	11	0	14	0	15	0	28	0
117	1	1	9	0	11	1	14	0	15	0	27	0
118	1	0	7	0	7	1	12	0	13	1	25	0
119			7	1	7	0	10	0	13	0	25	0
120			5	0	8	0	11	0	11	1	23	0
121			6	0	7	1	8	0	9	1	20	1
122			3	1	4	1	8	0	9	0	21	0
123			3	0	4	0	6	1	9	0	18	0
124			3	0	3	1	6	0	8	0	18	0
125			1	0	2	0	4	0	7	0	16	0
127					2	0	4	0	6	0	15	0
128					1	0	3	0	5	0	14	0
129							3	0	4	0	13	0
130							1	0	4	0	10	1
131									3	0	11	0
132									2	0	10	0
133									1	0	9	1
134									1	0	7	0
135											7	0
136											7	0
137											5	0
138											5	0
139											5	0
140											2	0
141											3	0
142											1	1
TOTAL	**9786**	**2369**	**11646**	**5723**	**9489**	**2319**	**11620**	**4395**	**8851**	**1387**	**11942**	**3727**
AVERAGE	**82.9**	**20.1**	**93.2**	**45.8**	**74.7**	**18.3**	**90.1**	**34.1**	**66.5**	**10.4**	**84.7**	**26.4**

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"If I have seen further it is by standing on the shoulders of giants."

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