Chapter 5
Routing & Scheduling

COUrier Routing through Innovative Emulation Learning program
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5.1. Introduction

Definition of Routing & Scheduling

- Private firms that undertake the distribution of their goods to customer locations, and public transportation authorities responsible for the provision of transportation services to users both rely upon a fleet of vehicles and associated crews.

- The effective management of these vehicles and crews gives rise to a variety of problems generally subsumed under the heading of “routing and scheduling problems”.

(L. Bodin, B. Golden, A. Assad and M. Ball, "Routing and scheduling of vehicles and crews: The state of the art", Computers and Operations Research, 10(2), 63-211, 1983)
# Main Entities in a Routing & Scheduling System (1/2)

## Resource Characteristics

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fleet</strong></td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>Number of available vehicles (fixed or variable)</td>
</tr>
<tr>
<td>Types</td>
<td>Homogeneous, Heterogeneous, Special Vehicle Types (Compartmentalized, refrigerator trucks, etc.), outsourced fleet</td>
</tr>
<tr>
<td>Capacity</td>
<td>Available space for carrying products (related to the type and kind of the products), weight or volume limitations, compatibility with product types (perishable goods, dangerous materials, etc.)</td>
</tr>
<tr>
<td><strong>Crew</strong></td>
<td></td>
</tr>
<tr>
<td>Maximum Shift Time</td>
<td>Maximum allowed time for driving</td>
</tr>
<tr>
<td>Other Driving Restrictions</td>
<td>Drivers’ Break (usually in the middle of the shift), maximum continuous driving, etc.</td>
</tr>
<tr>
<td><strong>Depots</strong></td>
<td></td>
</tr>
<tr>
<td>Capacity</td>
<td>Number of vehicles that can be housed in a depot</td>
</tr>
<tr>
<td>Single / Multiple</td>
<td>Number of available depots to house vehicles</td>
</tr>
<tr>
<td>Service Area</td>
<td>The assigned geographical area serviced by each depot</td>
</tr>
</tbody>
</table>

## Main Entities in a Routing & Scheduling System (2/2)

### Demand Characteristics

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customers</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>Address, Geographical location of the customers</td>
</tr>
<tr>
<td>Nature of Demands</td>
<td>Deterministic, stochastic, partial satisfaction of demand allowed</td>
</tr>
<tr>
<td>Type of Demand</td>
<td>Pick-ups, deliveries, mixed, split deliveries</td>
</tr>
<tr>
<td>Special Requirements</td>
<td>Time Windows, Load / Unload (Service) Times</td>
</tr>
</tbody>
</table>

### Road Network Characteristics

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network</td>
<td></td>
</tr>
<tr>
<td>Type of Network</td>
<td>Directed, undirected, mixed, Euclidean</td>
</tr>
<tr>
<td>Travel Times</td>
<td>Deterministic, stochastic, based on traffic conditions</td>
</tr>
<tr>
<td>Vehicle Restrictions</td>
<td>Areas that some specific types of vehicles are forbidden, etc.</td>
</tr>
</tbody>
</table>

5.1. Introduction

Costs related with Routing & Scheduling

Various cost factors have to be taken under consideration in order to generate the cost associated with routing and scheduling. Costs are generally separated in fixed and variable costs.

<table>
<thead>
<tr>
<th>Fixed Costs</th>
<th>Personnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Acquisition &amp; Annual Depreciation</td>
<td>Drivers’ (and/ or co-drivers’) Salaries</td>
</tr>
<tr>
<td>Vehicle Equipment (GPS, routing software)</td>
<td>Dispatcher’s Salaries</td>
</tr>
<tr>
<td>Annual Expenses (taxes, insurance, etc.)</td>
<td>Drivers’ Equipment (mobile phones, handheld devices, etc.)</td>
</tr>
<tr>
<td>Service Expenses</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable Costs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Costs</td>
<td>Overtime compensation</td>
</tr>
<tr>
<td>Spare parts (tires, lubrication, etc.)</td>
<td></td>
</tr>
<tr>
<td>Unforeseen events (damages, etc.)</td>
<td></td>
</tr>
</tbody>
</table>

- Fixed costs are calculated on an annual basis.
- Variable costs are calculated based on Kilometers.
- Other costs may include the utilization of third-party (hired) fleets.
Scope of the Routing & Scheduling procedures is to produce an efficient plan of routes, taking under consideration all the aforementioned parameters, that minimizes a given objective function. This can be:

<table>
<thead>
<tr>
<th>Objective Function</th>
<th>Examples of conflicting obj functions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimization of the total distance travelled</td>
<td>Increase of total duration, overtimes</td>
</tr>
<tr>
<td>Minimization of the total duration of the routes</td>
<td>Increase of vehicles, other costs (i.e. tolls)</td>
</tr>
<tr>
<td>Minimization of the number of vehicles needed</td>
<td>Increase of total distance and duration</td>
</tr>
<tr>
<td>Maximization of the utilization (both in capacity and time) of the vehicles</td>
<td>Increase of overtimes</td>
</tr>
<tr>
<td>Maximization of the profit gained from the customers</td>
<td></td>
</tr>
<tr>
<td>Combinations of the aforementioned objective functions.</td>
<td></td>
</tr>
</tbody>
</table>

Scope of the routing procedures is depended largely on each company’s operations, the underlying operating network, the personnel payment schemes, and it is almost unique for each organization.
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5.2. Route Networks

Routes Topology (1/3)

Routes, generally, are characterized by:

- The geographical coverage (long, short)
- The demand characteristics (high/low volumes, service times, etc.)
- The degree of dynamism (different/same customers every day, etc.)
- The underlying road network.

There are three (3) main types of routing networks.

<table>
<thead>
<tr>
<th>Routes Topology</th>
<th>Description</th>
<th>Characteristics</th>
<th>Examples</th>
</tr>
</thead>
</table>
| Petal (Bow)     | ☐ Each vehicle serves specific customers.                                   | ☐ Low / Medium Demand Volume  
☐ Low / Medium Service Times  
☐ Urban / Semi-Urban Areas  
☐ Both, different and same customers every day, routing | ☐ Postal  
☐ Courier  
☐ Newspapers  
☐ School Buses  
☐ Waste Collection |
| Radial          | ☐ Each vehicle serves one or a limited number of customers.                 | ☐ Medium / High Demand Volume  
☐ Medium / High Service Times  
☐ Usually Semi-Urban / Rural Areas  
☐ Same customers every day, routing | ☐ Container Transportation  
☐ Truck Routing |
| Peripheral      | ☐ Each vehicle serves a specific dispersed geographical regions (line-haul) with high density of demand (commercial areas, hubs, etc) | ☐ Low / Medium Demand Volume  
☐ Low / Medium Service Times  
☐ Urban (High Density) Areas  
☐ Usually same customers every day, routing | ☐ Line-haul / Backbone Routing  
☐ Freight Rail Transportation |
Routing policies are based on geographical, demand and scheduling characteristics, which are specific for each company and customer.

<table>
<thead>
<tr>
<th>Policies</th>
<th>Main Characteristics</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fixed</strong></td>
<td>The vehicles visit specific areas (and so customers) in specific days. Customer demands are adapted to the scheduled routes.</td>
<td>High Quality of Service (Customers may know the time and day of service)</td>
<td>Routes cannot react to unforeseen demand changes or to additional customer requests (i.e. service for another day). Vehicles may not be fully loaded (customers demand is less than expected) Vehicles may fail to satisfy increased demand</td>
<td>Postmen Suppliers of mini-markets in rural areas Newspapers</td>
</tr>
<tr>
<td><strong>Variable</strong></td>
<td>Routes are designed based on the known demands</td>
<td>Good response to demand variations Minimization of routing costs Minimization of needed vehicles Minimization of distances travelled</td>
<td>Actual service time may vary Customers do not know the actual service time Everyday workload to design the routes</td>
<td>Courier services Taxi services Parcel deliveries (e-commerce, etc.)</td>
</tr>
<tr>
<td><strong>Mixed</strong></td>
<td>Both routing policies are followed by a fleet of vehicles</td>
<td>The best policy is applied wherever applicable Each area or customer is treated based on its specific characteristics High utilization of vehicles</td>
<td>More difficult to organize and manage Complicated routes network</td>
<td></td>
</tr>
</tbody>
</table>

Source: G. Giannatos, S. Andrianopoulos, Logistics: Transportation – Distribution (in Greek)
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5.3. Routing & Scheduling Problems

The Most Known Categories of Routing & Scheduling Problems

- Shortest Path Problem
- Traveling Salesman Problem
- Vehicle Routing Problem
- Arc Routing Problem
- Vehicle Scheduling Problem
Shortest Path Problem (SPP)

**Description - Scope**

- Finding the shortest path in order to travel from point A to point B by traveling through a set of intermediate points (cities)
- Not all points (cities) have to be visited
- The cost is, usually, the traveling distance (kms) or the travel time.

The shortest path from node 1 to node 5 is [1,3,2,4,5] with cost 20.
Shortest Path Problem (SPP) Example

How can we find the shortest path?

- Values represent distances in km.

<table>
<thead>
<tr>
<th>Step</th>
<th>Solved Nodes</th>
<th>Directly Connected Unsolved Nodes</th>
<th>Distance</th>
<th>Shortest Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>C, D</td>
<td>30</td>
<td>30 (A, C)</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>D</td>
<td>40</td>
<td>40 (A, D)</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>E, B</td>
<td>30+20=50</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30+20=50</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>E, B</td>
<td>30+20=50</td>
<td>50 (C, E)</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>E, F</td>
<td>40+20=60</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40+30=70</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>B</td>
<td>30+40=70</td>
<td>60 (E, B)</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>E, F</td>
<td>40+20=60</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40+30=70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>B</td>
<td>50+10=60</td>
<td></td>
</tr>
</tbody>
</table>

The Shortest Path is [A, C, E, B] with cost 60.

Traveling Salesman Problem (TSP)

Description - Scope

- One Salesman has to visit a given set of customers (towns) and return to its starting location.
- Each customer should be visited once.
- The Salesman should use the less expensive (shorter) route.
- The cost, usually, is the traveling distance (kms) or the travel time.

An optimal TSP tour through Germany's 15 largest cities. It is the shortest among 43,589,145,600 possible tours visiting each city exactly once.

Traveling Salesman Problem (TSP)

George Dantzig, Ray Fulkerson, and Selmer Johnson (1954) were the first to solve a 49-city problem.

TSP Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Cities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1954</td>
<td>n=49</td>
</tr>
<tr>
<td>1962</td>
<td>n=33</td>
</tr>
<tr>
<td>1977</td>
<td>n=120</td>
</tr>
<tr>
<td>1987</td>
<td>n=532</td>
</tr>
<tr>
<td>1987</td>
<td>n=666</td>
</tr>
<tr>
<td>1987</td>
<td>n=2392</td>
</tr>
<tr>
<td>1994</td>
<td>n=7397</td>
</tr>
<tr>
<td>1998</td>
<td>n=13509</td>
</tr>
<tr>
<td>2001</td>
<td>n=15112</td>
</tr>
<tr>
<td>2004</td>
<td>n=24978</td>
</tr>
</tbody>
</table>

Source: http://www.tsp.gatech.edu/index.html
Traveling Salesman Problem (TSP)

Applegate, Bixby, Chvátal, Cook, and Helsgaun (2004) found the optimal tour of 24,978 cities in Sweden (approximately 72,500 kilometers).

The authors proved that no shorter route exists.

Previous record on the TSP was solved by Applegate, Bixby, Chvátal, and Cook (2001) for 15,112 cities in Germany.

Source http://www.tsp.gatech.edu/index.html
Traveling Salesman Problem (TSP)

Researchers at Bell Labs in the mid-1980s developed a technique for the quick production of customized computer chips. The TSP in this application is to minimize the total travel time of the laser, as it moves between the interconnections to be cut. The cities correspond to the locations of the interconnections, and the travel cost between two cities is the time to move from one interconnection point to the other interconnection point. The solution provides the order in which the laser cuts the necessary interconnections.

- Consists of a tour through 85,900 cities
- Solved in 2005/2006

http://www.tsp.gatech.edu/index.html
Arc Routing Problem (ARP)

Description - Scope

- One Postman has to visit all roads of a city and return to its starting location.
- Each road should be visited once.
- The Postman should use the less expensive (shorter) route.
- The cost, usually, is the traveling distance (kms) or the travel time.

Garbage Collection in Valencia

Source: Corberan, NETOPT 2009
Arc Routing Problem (ARP)

Origin of the ARP is the “Seven Bridges of Königsberg” Problem.

The city of Königsberg in Prussia (now Kaliningrad, Russia) was set on both sides of the Pregel River, and included two large islands which were connected to each other and the mainland by seven bridges.

The problem was to find a walk through the city that would cross each bridge once and only once.

Its negative resolution by Leonhard Euler in 1735 laid the foundations of graph theory and presaged the idea of topology.

Source: http://en.wikipedia.org/wiki/Seven_Bridges_of_K%C3%B6nigsberg
The first published work on ARP came from Kwan Mei-Ko (1962), a Chinese mathematician. “Based on this Alan J. Goldman suggested the name "Chinese Postman problem" to Jack Edmonds when Edmonds was in Goldman's Operations Research group at the U.S. National Bureau of Standards (now NIST). Edmonds appreciated its "catchiness" and adopted it” (Alan J. Goldman, personal communication, 14 December 2003)

The problem was to find the shortest route that traverses all roads and returns to its starting position.

(3) http://web.mit.edu/urban_or_book/
Other related practical problems to the ARP are:

- Street Cleaning
- Garbage Collection
- Meter Reading
- Snow & Ice Control
- Inspection of 3D structures (by automated robots)

The problem has also many variations:

- Chinese postman problem for mixed graphs: Some roads are directed (one-way).
- k-Chinese postman problem: There are k postmen and all roads should be traversed by one postman only.
- Rural postman problem: The postman has to visit a certain subset of the roads.
- General Routing problem: The postman has to visit a certain subset of the roads.

Vehicle Routing Problem (VRP)

**Description - Scope**

- Vehicle Routing Problems (VRP) deal with the management of pickup and/or delivery activities.

- Critical problems, in particular in short distance transportation.

- **Operational decisions:**
  How the available fleet of vehicles (resources) can be efficiently used to satisfy a given service demand according to a set of operational requirements?

- **Scope of Vehicle Routing:**
  *Define the routes and possibly the schedule for the available vehicles.*

- A route is a tour that begins at the depot, traverses a subset of the customers in a specified sequence and returns to the depot.

Source: http://neo.lcc.uma.es/cEA-web/VRP.htm
Vehicle Routing Problem (VRP)

Description - Scope

- A set of vehicles should visit a given number of customers (towns). All vehicles should return to its starting location.
- Each customer should be visited once.
- The cumulative cost of all vehicles should be minimized.
- The cost, usually, is the traveling distance (kms) or the travel time.

Source: http://neo.lcc.uma.es/cEA-web/VRP.htm
Vehicle Routing Problem (VRP)

- Proposed by Dantzig and Ramser in 1959. (1)
- Consists of one of the hardest routing problems. Its complexity increases exponentially to the number of the customers. (Reimann et al., 2003).
- Several variations of the VRP exist in order to adapt to various practical characteristics and constraints:
  - Capacitated VRP (CVRP)
  - Multiple Depot VRP (MDVRP)
  - Split Delivery VRP (SDVRP)
  - VRP with Backhauls (VRPB)
  - VRP with Pickups and Deliveries (VRPPD)
  - VRP with Satellite facilities (VRPS)
  - VRP with time windows (VRPTW)
  - Dynamic VRP (DVRP)

Vehicle Routing Problem (VRP)

Model Formulation

**minimize:**  global transportation cost (travel time OR distance)
number of vehicles and/or drivers

**subject to:** all customers are served exactly once
all vehicles start and end at the depot
travel time of each vehicle <= available time horizon (shift)
total load for service customers of each vehicle <= vehicle capacity

**additional constraints:**
each customer must be serviced within its specified time windows
the pickup of a customer must be performed before the delivery (for related loads)
customers with specific items could be served only by the related type of vehicle
vehicles used <= (OR ==) vehicles available
Vehicle Scheduling Problem (VSP)

- **Description - Scope**
  - The VSP arises when certain tasks should be implemented within specific time periods (i.e. Public bus departures, deliveries with specific start and end time).
  - A set of vehicles should serve a given number of tasks in specific time periods.
  - Each task should be served once.
  - The cumulative cost of all vehicles should be minimized.
  - The cost, usually, is the:
    - traveling distance (kms) or the travel time.
    - Deadhead Times (waiting times at the depot)

Vehicle Scheduling Problem (VSP)

Scope

Minimization of Vehicles

- Finding the minimum number of paths, servicing all tasks, gives us also the minimum number of required vehicles.

Minimization of Deadhead Times

- Since tasks must be served in specific time periods, there are periods where the vehicles are inactive, i.e. waiting for the task’s start time to begin (deadhead times).
- Finding the connections where the deadhead times are minimized gives also the overall minimum travel time of all vehicles.

5.3. Routing & Scheduling Problems

Vehicle Scheduling Problem (VSP) Example

Consider the following public bus trips.

<table>
<thead>
<tr>
<th>#</th>
<th>Trips - Sequence</th>
<th>Deadhead Times (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1, 6, 7, 10</td>
<td>15 + 30 + 60 = 105</td>
</tr>
<tr>
<td>B</td>
<td>3, 4, 9</td>
<td>10 + 50 = 60</td>
</tr>
<tr>
<td>C</td>
<td>2, 5, 8</td>
<td>0 + 30 = 30</td>
</tr>
</tbody>
</table>

These trips should start from the depot (terminal) travel a given bus route and return to the depot afterwards. We need to minimize the deadhead times.

A feasible solution is given by using 3 vehicles:

- A
- B
- C

195 minutes

If we are not allowed to have a vehicle travelling from 8.00 to 01.15, what should we do?

Are there any alternative solutions?

# Vehicle Scheduling Problem (VSP)

<table>
<thead>
<tr>
<th>Variations</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Depot VSP (SDVSP)</td>
<td>- The simplest case of VSP&lt;br&gt;- All vehicles start and end at the same depot&lt;br&gt;- They visit a terminal (where their schedule starts) and return to the depot (when schedule ends)</td>
</tr>
<tr>
<td>VSP with Length of Path Restrictions (VSPLRP)</td>
<td>- Same as above&lt;br&gt;- One additional constraint of the maximum allowed time a vehicle may be away from depot or the maximum km that a vehicle may traverse (Due to maintenance or fuel restrictions).</td>
</tr>
<tr>
<td>VSP with Multiple Vehicle Types (VSPMVT)</td>
<td>- All vehicles start and end at the same depot&lt;br&gt;- There are a number of different vehicle types (different capacities and operational characteristics)&lt;br&gt;- Tasks can be assigned either only to a specific vehicle type or to a number of vehicle types</td>
</tr>
<tr>
<td>Multiple Depot VSP (MDVSP)</td>
<td>- There exists a number of different depots (different capacities and operational characteristics)&lt;br&gt;- Usually, every vehicle should return to the starting depot&lt;br&gt;- Vehicles should be assigned to a specific depot and tasks should be assigned to vehicles</td>
</tr>
</tbody>
</table>

**Vehicle Scheduling Problem (VSP)**

- Scheduling problems are characterized by delivery-time restrictions.
- The starting and ending times for a service may be specified in advance → **"Time windows"**
- A one-sided time window either specifies that a service precede a given time or follow a given time. (e.g., most newspapers attempt to have papers delivered before 7:00 A.M.)
- Two-sided time window:
  - In the Meals-for-ME program, meals had to be delivered between 11:30 A.M. and 1:00 P.M.
  - Furniture delivery is usually scheduled after 9:00 A.M. and before 4:30 P.M.
Vehicle Scheduling Problem (VSP)

- An arc may join node i to node j if the start time of task j is greater than the end time of task i and the start time of task j must include a user-specified period of time ("deadhead time") longer than the end time of task i.
- In this example, the deadhead time is 45 minutes.
- This is the nonproductive time required for the vehicle to travel from one task location to another or return to the depot empty.
- The paths are not restricted in length.
- Each vehicle must start and end at the depot.
Vehicle Scheduling Problem (VSP)

Basic Steps:

- Order all tasks by starting times. Assign the first task to vehicle 1.
- For the remaining number of tasks, do the following. If it is feasible to assign the next task to an existing vehicle, assign it to the vehicle that has the minimum deadhead time to that task. Otherwise, create a new vehicle and assign the task to the new vehicle.

Example:

- Initially, vehicle 1 is assigned to task 1.
- Because task 2 begins before vehicle 1 is available, a second vehicle is assigned to this task.
- Vehicle 2 finishes task 2 in time to take care of task 3 also.
- In the meantime, vehicle 1 completes task 1 and is available for task 4.
- A third vehicle is not required until task 5, when vehicles 1 and 2 are busy with tasks 4 and 3, respectively.
- Continuing in a similar fashion, the schedule for vehicle 1 is 1-4-7-10-12, for vehicle 2 the schedule is 2-3-6-9, and for vehicle 3 the schedule is 5-8-11.
Vehicle Scheduling Problem (VSP)

Examples of the Vehicle Scheduling Problem are:
- Public Transportation (Bus) Scheduling Problem
- Aircraft Fleet Scheduling Problem
- Line-haul Transportation Problem

In many cases, these problems should be solved in compliance with other problems in order to take under consideration personnel availability and restrictions:
- Vehicle and Crew Scheduling
- Air Crew Scheduling
- Crew Rostering
- Combined Routing and Scheduling
As mentioned earlier, the parameters that characterize a routing / scheduling problem are:

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Description</th>
<th>Characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Size</td>
<td>Single Vehicle</td>
<td>Demand</td>
<td>Deterministic</td>
</tr>
<tr>
<td></td>
<td>Multiple Vehicles</td>
<td></td>
<td>Dynamic</td>
</tr>
<tr>
<td>Fleet Capacity</td>
<td>Uncapacitated</td>
<td>Demand Location</td>
<td>On Arcs</td>
</tr>
<tr>
<td></td>
<td>Capacitated (same for all vehicles)</td>
<td></td>
<td>On Nodes</td>
</tr>
<tr>
<td></td>
<td>Capacitated (different)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shift Duration</td>
<td>Without Limitations</td>
<td>Demand Type</td>
<td>Delivery / Split Deliveries</td>
</tr>
<tr>
<td></td>
<td>Maximum Route Length</td>
<td></td>
<td>Pick-up / Split Pick-up</td>
</tr>
<tr>
<td>Homogeneity</td>
<td>Homogeneous Fleet</td>
<td></td>
<td>Both</td>
</tr>
<tr>
<td></td>
<td>Heterogeneous Fleet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depot</td>
<td>Single</td>
<td>Time Windows</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Multiple</td>
<td></td>
<td>Single Time Windows</td>
</tr>
<tr>
<td>Objective</td>
<td>Single</td>
<td></td>
<td>Multiple Time Windows</td>
</tr>
<tr>
<td></td>
<td>Multiple</td>
<td></td>
<td>Tight Time Windows (scheduling)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Costs / Travel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Times / Distances</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Deterministic</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dynamic (Traffic Related)</td>
</tr>
</tbody>
</table>

Can you match the characteristics with some of the problem categories or their variations?
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5.7. Principles for Efficient Routing & Scheduling
Definition of Networks and Optimization

**Networks**
- A Graph is a set of Nodes and Arcs.
- Each arc connects two nodes.
- A network is a graph with flow through the arcs. For example a road network has a flow of vehicles, a pipeline network has a flow of liquids.

*(F.S. Hiller – G.J. Lieberman)*

**Optimization**
- As optimization is considered the selection of the most efficient solution among a set of solutions (i.e. the best route for a courier).
- This solution can be found through mathematical modeling and specialized software.
Node

- Nodes, usually, represent physical locations:
  - The location of a customer
  - The hub of a Hub-And-Spoke Network
  - A Distribution Center
- In order to model special characteristics of a customer, a node may be separated in two or more nodes (i.e. a warehouse with two storage areas that facilitate different materials).
- Nodes also are used to represent connections / intersections of roads.
- Additionally, long road segments with change of characteristics (i.e. a 2-lane motorway changes to a 3-lane motorway. An additional node is entered where the change begins.

5.4. Modeling the Routing & Scheduling Problems

Nodes

Source: V. Zeimpekis Lecture Notes

Source: http://neo.lcc.uma.es/cEA-web/VRP.htm
Arcs

- Arcs, usually, represent:
  - road segments,
  - motorways,
  - railroads,
  - Pipelines,
  - etc.
- Arcs connect two adjacent nodes.
- Arcs may have a certain capacity of “flow” (i.e. Number of vehicles per hour, number of passengers per hour, m³ per hour, etc.)
- Flow may be directional (one-way roads, water sewering) or bi-directional.
- In most cases each arc is attributed with a certain cost (representing travel time, distance, etc.)
5.4. Modeling the Routing & Scheduling Problems

Arcs

Representation of the “Seven Bridges of Königsberg” Problem on Nodes and Arcs

Source: http://en.wikipedia.org/wiki/Seven_Bridges_of_K%C3%B6nigsberg
Mathematical Interpretation of a Routing Network

- **Nodes:** \{A, B, C, D, E\}
- **Arcs:** (A, B), (B, C), (B, E), (E, A), (E, C), (C, E), (D, C), (E, D), (A, D).
- Arcs may be directed (i.e. arc 1) representing one-way roads or undirected (i.e. arc 6-7).
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5.7. Principles for Efficient Routing & Scheduling
The case of Courier Operations

**Courier**: Is a company who is responsible to carry messages, letter or parcels. Its business differs from the conventional postal service companies in speed, safety, expertise, “personalization” of pickup/delivery and the strict time of delivery.

Routing procedure in a courier company consists of two (2) main stages during a working day:

1. **Backbone Routing (Line-Haul)**
   - Internal process of goods from the pickup DC to the delivery DC
   - Multimodal transportation (air, road, train, sea)
   - Mostly emphasis on scheduling (importance on time of arrival in DCs)

2. **Delivery Routing**
   - From DCs to customer service points (delivery & pickup)
   - Road transportation – 2 type of vehicles (vans & scooters)
   - Emphasis on routing

SEE FIGURE NEXT SLIDE
Routing Types in Courier Operations

Delivery Routing

Backbone Routing

Delivery Routing

Customer Service Points

Internal Process of Goods

Customer Service Points

Routing Types in Courier Operations

Pick-up/Delivery Route

L.S.P.

HUB

National Transport (Road/Air/Sea) Picking Sorting

Transit Hub

L.S.P.

Pick-up/Delivery Route

DELIVERY

Delivery

Delivery

PICK-UP

Delivery

Time Horizon

08 00-16 00
16 00-20 00
17 00-06 00
05 00-08 00
08 00-19 00

5.5. The Case of Courier Routing
Backbone Routing for Process of Internal Goods

The backbone routing in courier companies is used for the distribution of internal goods. This process is mainly seen as a Vehicle Scheduling Problem due to several restrictions:

1. All items should leave from the origin at the end of the day and arrive to various delivery destinations before the shift of the next day begins
2. Road transportation consumes a lot of time for the delivery of the items and, thus, many modes of transportation are in need (such as air transportation which is faster)
3. All transportation modes have their own time windows, which are usually very strict
4. Several adjustments need to be done in order to fully cover the need in transportation modes and meet the requirements in time.

All of the above restrictions and limitations force the courier companies to see this process as a VSP and try to:

- Optimize the departure time of items from their origin
- Optimize the arrival time of the items in the destination
- Minimize the vehicles needed to perform the process within the day
- Minimize the deadhead times
- Minimize the use of other modes of transport
- Minimize distance covered by all vehicles

SEE REAL-LIFE EXAMPLE NEXT SLIDE
Backbone Routing for Process of Internal Goods

Example of ELTA Courier - GREECE

1. Η παραγγελία λαμβάνεται στο αντίστοιχο ΣΕ και προωθείται στο Κ∆ στο οποίο υπάγεται γεωγραφικά το ΣΕ

2. Η παραγγελία από το Κ∆ προώθησης, προκειμένου να μεταφερθεί στο Κ∆ προορισµού, ενδέχεται να περάσει από ενδιάµεσα Κ∆ (transit hubs). Το transit hub ενδέχεται να είναι Κ∆, αποθηκευτικός χώρος (αεροδρόµια), ή σπίτι φύλαξης των διαµεταφορέων (handlers)

3. Η παραγγελία προωθείται τελικά στο αντίστοιχο Κ∆ προορισµού και από το σηµείο αυτό στον προορισµό του αντικειµένου.
Delivery Routing in Customer Service Points

Delivery routing in courier companies implies the routing from distribution centers to the customers service points, i.e. to the delivery/pickup locations. Courier delivery routing problems fall into the category of the well-known VRPs, with various objectives and constraints that depend on several parameters of each courier company.

Several unique characteristics arise in the courier routing problems:

- Large number of customers to be routed every day
- Customers change from day to day (no similar patterns – few exceptions)
- New customers ask for service (pickup) during the execution of the planned routes

Thus, better allocation of the customers between the routes may yield to:

- Decreased operation times
- Lower distance travelled
- Less vehicles used
- Increased number of serviced customers
- Better service quality to customers
- Better management by the dispatchers
Several parameters that affect the process of delivery routing in a courier company are:

- **Distribution area of the vehicle, due to:**
  - Range and mapping of the area
  - Dispersion of the service points (customers)
  - Traffic conditions of the area

- **Vehicle type:**
  - Vans have larger capacity but they can move in urban environment with less speed and flexibility
  - Scooters have better flexibility on streets, but they can only be used to carry letters and very small parcels

- **Parcels/Letter’s volume for pickup/delivery:**
  - It affects the type of vehicle used for its service

- **Work type:**
  - Pickup (it is believed that is more time consuming).
  - Delivery
Delivery Routing in Customer Service Points

- **Completion times of the service:**
  - They change dynamically and concern mostly the service times of the customers

- **Unforeseen delay events:**
  - A number of unforeseen events may occur during the day leading to an increased complexity of the urban routing problems. These events may be:
    - Weather conditions
    - Lack of parking space
    - Vehicle breakdown
    - Delays on deliveries
    - Lack of human resources (e.g. due to holidays)
    - Increased traffic on streets, or road works on progress
  - These events may be efficiently handled by specific methods and systems for the real-time fleet management
Dynamic Vehicle Routing (DVRP) in Courier Operations

What is it?
Various dynamic events may occur during the execution of planned routes and service of already known customers. Usually, these events concern:
- Unexpected traffic congestion
- Vehicle breakdown
- Blocked Road(s)
- New customers ask for service during the execution of planned routes

These events may cause the disruption of the scheduled routes and service of already planned customers and need to be addressed in an appropriate way.

Dynamism in courier operations is commonly implied by arrival of new requests

Why use it?
- To effectively add and drop stops during the day as needed
- To adjust to changing traffic and weather conditions
- To minimize operating costs

Should we re-optimize OR Reject/Lose customers?
Dynamic Vehicle Routing (DVRP) in Courier Operations

While executing a delivery plan in courier companies, a fleet of vehicles is in movement to service customer requests known in advance, while new requests may arise dynamically over time and demand for service as the working plan unfolds.

These customers are usually called **dynamic requests** and need to be serviced by the current vehicles en-route. Many different factors must be considered when a decision about the allocation and scheduling of a new dynamic request is taken:

- Current location of each vehicle
- Current planned routes
- Characteristics of the new request
- Travel Times between the service points
- Characteristics of the underlying road network
Currently, most of the courier companies deal with these customers empirically. The dispatcher guesses the current location of each vehicle and assigns the vehicle to service the request that falls into the geographic region of a specific vehicle.

What if after a while another dynamic request occurs, and another, and another, etc…?

What if the vehicle assigned by the dispatcher left the area of the appearance of the request?

Since the number of dynamic requests may reach a large amount of the total serviced customers (for the ELTA courier they may consist of a 15-20% of the total customers, i.e. up to 200 (!!!) requests from a total of 1000 customers per day), it implies that there should be an automated and better handling of dynamic requests.

The results of the pilot testing of the research project MADREL done in ELTA courier during the period 2006 – 2008 showed that there is a potential improvement of 28% on average on the cost of handling the dynamic requests.
### Dynamic Vehicle Routing (DVRP) in Courier Operations

<table>
<thead>
<tr>
<th>Most common solution approach:</th>
<th>Methodology selection parameters:</th>
</tr>
</thead>
<tbody>
<tr>
<td>DVRP is often approached sequentially by continuously updating the current routes</td>
<td>Problem size (# of static &amp; dynamic requests)</td>
</tr>
<tr>
<td>Often, the dynamic problem is decomposed into a series of static sub-problems which are solved by a static algorithm/method in a rolling horizon framework (e.g. every 1 hour).</td>
<td>Calculating time needed for the solution</td>
</tr>
<tr>
<td>Four (4) major solution approaches of the static sub-problems exist:</td>
<td></td>
</tr>
<tr>
<td>- <em>Optimal solution algorithms,</em></td>
<td></td>
</tr>
<tr>
<td>- <em>Simple strategy techniques</em></td>
<td></td>
</tr>
<tr>
<td>- <em>Problem-specific heuristic algorithms</em></td>
<td></td>
</tr>
<tr>
<td>- <em>More advanced heuristics</em></td>
<td></td>
</tr>
</tbody>
</table>

#### Solution Evaluation

- Route cost
- Profit (of serviced customers)
- Penalty imposed by exceeding the time windows of customers
- Number of rejected customers
- Response time
## Approaches for dealing with newly occurred requests

<table>
<thead>
<tr>
<th>Approach</th>
<th>Description</th>
</tr>
</thead>
</table>
| Local Update of Current Solution | - Simple incorporation of new request  
- Usually done by simple insertion methods                                  |
| Re-optimization of the complete solution | - A new problem is solved from scratch  
- May change the sequence of scheduled customers   |
| Advanced Approaches              | - Waiting strategies  
- Diversion  
- Anticipation of future requests |
| Waiting Strategies                | - Let vehicles wait on specific regions/points when they finish service or for restricted time during the service of customers |
| Diversion                        | - Consider the possibility of changing the destination of a moving vehicle to go service a newly arrived request. |
| Anticipation of future requests   | - Take into account general knowledge about demand patterns by using statistical (historical) information  
- Keep the vehicle on an area that there is high possibility on the arrival of new requests |
Typical Solution of Dynamic Vehicle Routing

Dynamic Request Handling Algorithm

- ‘Good’ solution quality:
  - # of serviced dynamic requests (or rejected)
  - Total travel cost (time or length - kms)
  - Time to calculate final solution

Algorithm

1. Define desired number of requests
2. Request allocation
3. Re-routing
4. Inform fleet for the new solution
An Illustrative Example on Dynamic Vehicle Routing

5.5. The Case of Courier Routing

<table>
<thead>
<tr>
<th>time = 0</th>
<th>time = 15 mins</th>
<th>time = 30 mins</th>
<th>time = 1 hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routes begin their service</td>
<td>Appearance of one dyn. req (5)</td>
<td>Appearance of two dyn. reqs (6, 7)</td>
<td>Appearance of two dyn. reqs (5, 8)</td>
</tr>
</tbody>
</table>

Source: Angelelli E., Mansini R., Speranza G., A Real-time Vehicle Routing Model for a Courier Service Problem
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Providing a solution to a Routing / Scheduling Problem

- Before the advent of Informational Technology, routing / scheduling was performed by experienced personnel (even now, in cases which can be handled by a experienced employee)

- Advantage of the experienced personnel were:
  - The good knowledge of the road network
  - The knowledge on traffic issues on the road network.

- Solutions provided are considered of high quality but… can only be provided for low-scale problems. So, large-scale problems, usually, are decomposed into smaller routing problems (i.e. Geographical areas separation).

- A large-scale problem enables a series of interfering parameters that are hard to be simultaneously taken under consideration by a person.

- Some examples:
  - Public Bus Scheduling: More that 1000 routes (in a medium bus network) to be scheduled along with a crew with >1000 members.
  - Postman Routing Problem: in a high density urban area.
### Algorithms

- **Heuristics**
  Are simple procedures, very fast and efficient. Their scope is to achieve a good solution (not the optimal one) very quickly. Many of these algorithms have been based upon the empirical routing and scheduling methods of experienced personnel.

- **Mathematical Programming**
  Are methods that are based on mathematical theory and networks theory. Their scope is to provide the optimal solution to the problems. For moderate large problems, most of the times they are computational expensive.
Nearest Neighbor Algorithm

- The nearest neighbor procedure (NNP) builds a tour based only on the cost or distance of traveling from the last-visited node to the closest node in the network.
- The heuristic is simple, but it has the disadvantage of being rather shortsighted.
- The procedure is outlined as follows:
  1. Start with the depot node.
  2. Find the node, not already in the path, which is closest to the last node added to the tour. Add it to the path.
  3. Go back to step 2 until all nodes have been added.
  4. Connect the first and the last nodes to form a complete tour.
Route Construction Algorithms

Nearest Neighbor Algorithm – EXAMPLE

A

B

Depot

1

2

3

4

5

6

1

2

3

4

5

6

Depot

5.4 Miles

2.8 Miles

4.1 Miles

10.5 Miles

5.6. Solution Procedures
Route Construction Algorithms

Nearest Neighbor Algorithm – EXAMPLE

C

D

5.6. Solution Procedures
Route Construction Algorithms

Nearest Neighbor Algorithm – EXAMPLE

\[ \text{2.8} + \text{3.6} + \text{8.5} + \text{5.0} + \text{5.0} + \text{10.5} = \text{35.4 miles} \]
Route Construction Algorithms

Nearest Neighbor Algorithm – EXAMPLE

Unfortunately, there is a “much” better and improved solution

5.4 + 5.0 + 5.0 + 7.8 + 3.6 + 4.1 = 30.9 miles

In case of VRP (many vehicles), this is performed until capacity and/or time limit constraints has been reached. Then, another vehicle performs the same procedure.
### Insertion Algorithm

- Insertion algorithms start from a partial route (e.g. Depot – Customer – Depot) and try to insert all unassigned customers into the best feasible position in this partial route.

- The selection of the next customer to be inserted could be: a) the nearest, b) the farthest, c) the cheapest insertion, d) random.

- The procedure is outlined as follows (for the case of nearest insertion):
  1. Start from the depot, find the nearest node and create a partial route with node i.
  2. Find the node, not already in the path, which is closest to any node of the already generated tour.
  3. Add it in the best position of the tour (position that minimizes the cost to insert this customer to the arc).
  4. Go back to step 3 until all nodes have been added.
Route Construction Algorithms

Nearest Insertion Algorithm – EXAMPLE

A  B  C
Nearest Insertion Algorithm – EXAMPLE

In case of VRP (many vehicles), this is performed until capacity and/or time limit constraints has been reached. Then, another vehicle performs the same procedure.
The Clarke & Wright savings heuristic (C&W) is one of the most well-known techniques for solving VRP.

The heuristic begins by assuming that one vehicle travels from the depot directly to a node and returns to the depot.

- The distance from node 2 to node 3 is 5 miles.
- The total distance covered by the two vehicles is 36 miles.
- The key to the C&W heuristic is the computation of savings.
- Savings is a measure of how much the trip length or cost can be reduced by “merging” a pair of nodes (e.g. nodes 2 & 3) and creating the tour which can then be assigned to a single vehicle.
- By linking nodes 2 & 3, we add 5 miles (the distance from node 2 to node 3), but we save 10 miles for the trip from node 2 to node 1 and 8 miles from the trip from 3 to 1.
- The total tour length for the complete tour, 1 → 2 → 3 → 1, is 23 miles.
- The savings obtained = (10+10+8+8) – (10+5+8) = 36 – 23 = 13 miles.
Route Construction Algorithms

Clark & Wright Savings Heuristic – STEPS

- Select any node as the depot node (node 1).
- Compute the savings, $S_{ij}$ for linking nodes i and j:
  \[ S_{ij} = c_{1i} + c_{1j} - c_{ij} \]
  e.g. $S_{23} = 10 + 8 - 5 = 13$ miles
  for i and j = all nodes and $c_{ij}$ = the cost of traveling from node i to node j (e.g. $c_{23} = 5$ miles)
- Rank the savings from largest to smallest.
- Starting at the top of the list, form larger subtours by linking appropriate nodes i and j.
- Stop when a complete tour is formed.
Route Construction Algorithms

Clark & Wright Savings – EXAMPLE

- The initial tours (with solid lines) are shown in the figure.
- The dashed lines show arcs that may be used but are not in use currently.

### Nodes (i – j) | Savings | $S_{ij}$ | Ranking

| i = 2 | j = 3 | $10 + 8 - 5 = 13$ miles | $S_{23} = 13$ | 1 |
| i = 2 | j = 4 | $5 + 10 - 3 = 12$ miles | $S_{24} = 12$ | 3 |
| i = 3 | j = 4 | $5 + 8 - 7 = 6$ miles | $S_{34} = 6$ | 2 |

- The first step in specifying a tour is to link the nodes with the highest savings; nodes 2 and 3.

- $5 + 5 + 10 + 10 + 8 + 8 = 46$ miles
- $5 + 5 + 10 + 5 + 8 = 33$ miles
Route Construction Algorithms

Clark & Wright Savings – EXAMPLE 1

- Proceeding to the next highest savings, nodes 2 and 4 are linked.
- The complete tour is $1 \rightarrow 4 \rightarrow 2 \rightarrow 3 \rightarrow 1$, which has a total tour length of 21 miles.
- The total savings obtained over the “one vehicle per node” configuration is 25 miles.

<table>
<thead>
<tr>
<th>Nodes (i – j)</th>
<th>Savings</th>
<th>$S_{ij}$</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i = 2 \mid j = 4$</td>
<td>$10 + 5 - 3 = 12$ miles</td>
<td>$S_{24} = 12$</td>
<td>1</td>
</tr>
</tbody>
</table>

$5 + 5 + 10 + 10 + 8 + 8 = 46$ miles

$5 + 3 + 5 + 8 = 21$ miles
Clark & Wright Savings – EXAMPLE 2

\[ S_{35}: \text{link 3&5} \]

\[ S_{34}: \text{link 3&4 (keep 3-5)} \]

0-3-5-0

0-4-3-5-0
Route Construction Algorithms

Clark & Wright Savings – EXAMPLE 2

\[ S_{45} \]: skip

\[ S_{36} \]: skip

\[ S_{56} \]: link 5&6
Route Construction Algorithms

Clark & Wright Savings – EXAMPLE 2

\( S_{23}: \text{skip} \)

\( S_{26}: \text{skip} \)

\( S_{24}: \text{link 2&4} \)
Route Construction Algorithms

Clark & Wright Savings – EXAMPLE 2

\[ S_{25}: \text{skip} \]

Final route: 0-1-2-4-3-5-6-0
Route Construction Algorithms

Cluster First – Route Second Techniques

THE SWEEP ALGORITHM

**Step 1**: Locate all stops including the depot on a map or grid.

**Step 2**: Extend a straight line from the depot in any direction. Rotate the line clockwise or counterclockwise, until it intersects a node (customer).

- The customer is included on a specific vehicle, if the vehicle capacity is not exceeded.
- If the vehicle’s capacity has reached its maximum, a *cluster* has been created.
- Assign another vehicle and continue until all points are assigned to vehicles.

**Step 3**: Within each “*cluster*”, sequence the customers to minimize distance (May be used anyone of techniques described previously – Nearest Neighbor, Nearest Insertion, etc.)

**Sweep Method (1/2)**

**Sweep Algorithm – EXAMPLE**

- A company uses vans in order to deliver heating oil to customer locations
- Each vehicle can carry only 10 tons of heating oil
- The company wants to determine how many vehicles are needed and which customers should be on which route and in which sequence.

**Cluster 1**

\[ 4 + 1 + 3 + 2 = 10 \]

**Cluster 2**

\[ 2 + 2 + 1 + 2 + 2 = 9 \]

**Cluster 3**

\[ 2 + 3 + 3 = 8 \]

Route Construction Algorithms

SWEEP Algorithm – EXAMPLE

Route 1
\[ 4 + 1 + 3 + 2 = 10 \]

Route 2
\[ 2 + 2 + 1 + 2 + 2 = 9 \]

Route 3
\[ 2 + 3 + 3 = 8 \]

You can use any heuristic learned previously in order to solve the TSP on each cluster.

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Most common & logical approach for VRPs

- When points are spatially related, good solutions can be found by using the pattern recognition capabilities of the human mind.
  - Good stop sequences are formed when the paths of the route do not cross.
  - The route shape will usually bulge, or form a flower shape, where possible.

- An analyst may be able to quickly sketch out a route plan that might require a computer many hours to find.

(a) Poor routing – paths cross
(b) Good routing – no paths cross

Some Empirical Rules for an Efficient Routing of Vehicles

- Allocate requests to specific days, by grouping neighboring requests (both in space and time).
- Allocate to a vehicle a certain amount of items (based on an average maximum capability) based on type of items, traffic conditions and gained experience.
- Try to visit customers such as to minimize the crossing arcs of the route. (See Figure).
- Pickups and Deliveries should be blended and not serviced after the end of deliveries (if possible).
- Routes should start servicing the most distant (from the distribution center) customers.
- Delivery Items should be loaded on track such as (1) the items for the initial stops should be closer to the vehicle door and vice versa, and (2) neighbor customers’ items should be close to each other.

Do you know any other empirical rules? What would you do?

5.7. Principles for Efficient Routing & Scheduling

**Principles for Good Routing & Scheduling**

**A** Form truck routes around clusters of stops that are nearest to each other in order to minimize the inter-stop travel between them.

**B** Build routes beginning with the farthest stop from the depot and then working back toward the depot.

1. Identify the farthest stop.
2. Select the volume from the tightest cluster of stops around that stop to fill out the assigned truck capacity.
3. After the stop volumes have been assigned to the vehicle, select another vehicle and identify the farthest stop from the depot among the remaining stops not yet routed.
4. Proceed until all stops have been assigned to the vehicles.

5.7. Principles for Efficient Routing & Scheduling

Principles for Good Routing & Scheduling

C The sequence of stops on a truck route should form a teardrop pattern.
- No routes paths cross.
- The route appears to have a teardrop shape.
- However, time window restrictions and the forcing of stop pickups after deliveries may cause route paths to cross.

D The most efficient routes are built using the largest vehicles available.
- Ideally, using a vehicle large enough to handle all stops in one route will minimize total distance or time traveled to serve the stops.
- Therefore, the largest vehicles should be allocated first, providing that good utilizations for them can be utilized.

E Narrow stop time window restrictions should be avoided.
- Time window restrictions on stops, where they are narrow, can force stop sequencing away from ideal patterns.
- Any stop(s) forced to be served in a less-than-desired routing pattern should have its time window limits renegotiated and hopefully widened.