Problems in Transport and Logistics

- Technical Report -

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Introduction

The transportation industry facilitates the movement of goods for the purposes of trade, production and consumption.

Good transportation systems are often described as satisfying several quality factors, such as cost, time and length.

There are many issues that affect the efficient transportation of goods and this document describes in detail a range of these problems as well as a discussion of some methods used in creating strategies and solutions for these problems.

Nomenclature

The terminology that exists in transportation and operations research is often abused and for some readers can often prove misleading. This section aims to summarise the most popular terminology found in the references utilised and present a unified interpretation of what the author believes these terms actually mean.

Variables

Vertex

A vertex (node, city) is a point of reference often specified by a set of geographical coordinates. Vertices are the cities, junctions, depots in a transportation problem. A set of vertices can be defined and then further broken down into smaller subsets such as a subset of houses, road junctions and distribution centres. From this specialisation more specific information can be applied to each vertex.

Edge

An edge (road, arc) is the entity which joins two or more vertices together. In transportation it can often refer to a physical link such as a road or train track, or a non-physical link such as a shipping channel or airlane. In most cases there is some cost, length or time (or combinations of) associated with an edge which will be specific to that edge.

Graph

In the operations research field it is more commonly referred to as a 'transportation network' or simply a 'network'. The usage of 'graph' to describe a transportation network stems from the usage of the words 'vertex' and 'edge' which are most prevalent in Graph Theory which stems from the work of Euler[1].

Vehicle

A vehicle refers to any entity capable of transporting freight, be it a truck, train, boat, plane, bike etc.

Goods

Commonly referred to as freight, goods encompass any raw materials or finished product that is able to be transported from one vertex to another. They usually have a monetary value associated with them, and can often require a specific vehicle for transportation.

Weight

Weight is commonly used to describe a broad range of quality factors (these are described later in this section). Formally (but not restricted to), in this field what one tends to think of as the 'length' of an edge is known as its 'weight'. The term 'weight' is used because graphs are not limited to representing locations on a plane or in space; consequently edges could represent time, cost, and so on, generally a quantity which is to be kept minimal when going from any vertex to another.

Quality Factors

Cost

Cost in most problems is the direct monetary cost of a product or service. Some examples of costs in transportation include:

- Lease, taxation or tolling of infrastructure including roads, train tracks, shipping channels, canals, aeroplane corridors, bridges, etc. these costs occur in transit on the edges (arcs) of a transport network.
- Transfer costs associated with the transfer of goods, usually from one mode of transport to another, or from transit to storage, ship → truck, truck → train, plane → warehouse, etc. These costs occur at the nodes (vertices, cities) of the transport network.
- Storage of goods, often a suitable carrier is not available to transport goods therefore a holding fee or warehouse rental cost may be incurred while the goods are awaiting transfer. This cost will be incurred at a node of the transport network.
- Damage to goods, if goods are soiled or damaged during transportation, insurance or replacement costs may be incurred by the carrier.
- Lease of vehicles and fixed and variable running costs associated with vehicles.

Length

Length is most commonly used to describe a geographical distance; this must not be confused with cost, as cost may often not be directly related to length.

Time

Time constraints in transportation are as follows:

- Goods are often perishable, therefore these goods must be delivered to their destination in less than or equal to the amount of time allocated.
- Some edges have time dependent traffic conditions, meaning it may be quicker to transport at a particular time in the day/week/year.

It is often not a simple edge time that will be factored into a quality measurement of a transportation system, rather the door-to-door time. For the case of air transport the longest edge in the total journey may be short, but forwarding the goods to their final destination may involve holding time and more transportation adding considerably to the total time.

Problems

Transportation Problems can be thought of as either dynamic or static, but not both. The difference between a dynamic and a static problem is discussed quite well in [2]. The key feature of a dynamic problem is that it has limited access to information about the problem. In the case of the Vehicle Routing Problem it may know some customer demands a-priori and be able to plan a route based on this information, however at run time more information will become available changing the problem domain.

The distinction has to be made that simply changing customer demands during runtime does not imply a dynamic environment unless these demands are kept hidden from the algorithm until runtime. This is discussed further in the relevant subsection - Dynamic Transportation Problems, and unless specified any other description hereon refers to a static instance of the problem.

Shortest Path Problem

A shortest-path problem involves a weighted, possibly directed graph described by a set of edges and vertices. Given a start vertex, the goal is to find the shortest existing path between the start vertex and any of the other vertices in the graph. Each path, therefore, will have the minimum possible sum of its component edges' weights.

Thus, a graph whose edges are all of equal weight is *unweighted*, whereas a graph with edges of differing weights is *weighted*.

There exist many techniques for solving the shortest path problem, some of the better known algorithms are Dijkstra's [3], A* [4] and Bellman-Ford [5].

Vehicle Routing Problem

Perhaps one of the most commonly studied and discussed transportation problems is the vehicle routing problem or VRP. The VRP in its simplest form can be explained as follows.

Given a set of vertices: $V = \{v_0, v_1, ..., v_n\}$, with a depot located at v_0 and the subset: $V' = V \setminus v_0$, being the set of n cities.

The vertex set V is connected via an edge set: $E = \{(v_i, v_j) \mid v_i, v_j \in V; i \neq j\}$.

A matrix C of non-negative weights (cost, distance, time, etc.) exists where each element c_{ij} corresponds to an element e_{ij}.

Customer demands are represented by the vector d.

Vehicles belong to the set H.

The route of vehicle h_i is represented by R_i.

For the case $c_{ij} = c_{ji}$ for all $(v_i, v_j) \in E$ the problem is symmetric and we can redefine the edge set E as $E = \{(v_i, v_j) \mid v_i, v_j \in V; i < j\}$.

Each vertex $v_i \in V'$ has a quantity q_i of goods to be delivered associated to it. Thus the aim of the VRP is to determine a set of m vehicle routes of minimal total cost, beginning and ending at a depot v_0, such that every vertex in the set V' is visited exactly once by one vehicle.

We can consider a service time t_i which is the time required to unload q_i goods at vertex v_i. It is a requirement that the total time of any vehicle route R_i does not exceed a specified amount D. The total time is calculated by adding the service times t_i and the costs c_{ij} (which in this case are equal to time) associated with a route.

There exist multiple variations of the classic VRP and these instances are discussed under the relevant headings, a majority are discussed in [6].The motivations for these variations are to add complexity or to model real-world instances more closely [7]. The most common variations are henceforth listed and discussed.

Capacitated VRP – CVRP

The additional constraint of CVRP is that each vehicle has a uniform limited capacity. The affect of this additional constraint is that each vehicle must adhere to not only a timing schedule but now a capacity constraint. If the total capacity of a vehicle is Q then the additional restriction to derive CVRP from the formal definition of VRP is that $\forall H : \sum_{i=1}^{n} d_i \leq Q$, that is for all vehicles h_i the sum of the demands d_i on their corresponding route should not exceed the total capacity of the vehicle Q .

VRP with time windows – VRPTW

Multiple Depot VRP – MDVRP

VRP with Pick-Up and Delivering – VRPPD

Split Delivery VRP – SDVRP

Periodic VRP – PVRP

Travelling Salesman Problem

The TSP is a popular path optimization problem described as:

Given a set of n vertices and weights for each pair of vertices, find a roundtrip of minimal total weight visiting each vertex exactly once.

The set of n vertices can be represented as geographical coordinates, Cartesian coordinates or even as a matrix of weights between vertices. How the vertices are represented is not important as long as a weight between every node can be calculated.

Most popular TSP data sets contain a 2-Dimensional coordinate set. Since the only concern is about the weight between nodes and not the nodes themselves there is no real difference between a 2D and a 3D representation, only that one more variable is included in the 3D distance calculation.

A large catalogue of TSP problems and literature can be found at TSPLIB [8].

Other problems

Multi-commodity freight transportation

Most freight transportation systems exhibit a multi-commodity nature, where several distinct commodities may be required to be transported simultaneously or in succession [9]. This problem can be characterised by a set of commodities placed throughout an underlying transport network. The objective is to flow the commodities through the network at minimum cost without exceeding edge capacities [10]. Integer multi-commodity flow problems additionally require that each commodity flow along a single route in the network.

Empty Vehicle Repositioning

After a destination has been reached, and the goods transported to that destination unloaded, the real world does not have the luxury that we have in computers of restarting the system. The vehicle used to transport the goods in this instance must now begin a new tour, and if no goods are available for transportation at its current location, the vehicle must reposition itself to a location which has goods to transport, hence empty vehicle repositioning.

Empty vehicle repositioning must be kept to a minimum since there is no cash inflow (only outflow in the form of running costs associated with the vehicle) associated with this activity. Often repositioning costs are built into the cost of transporting goods, for example transporting goods to remote locations may incur a higher repositioning cost, hence this may affect the cost of transporting the goods to this location.

Forecasting

Efficient production and warehousing will often avoid costly holding and storage of goods; it is obvious that you can't sell goods that are sitting in a warehouse therefore the less time goods spend in transition the better.

Forecasted transport solutions are used to anticipate goods demand and counter shortages in supply. This is a risky practice however, and unless an accurate forecasting method is employed it can often lead to oversupply.

Dynamic Transportation Problems

Any of the problems listed in the previous section can be altered in some way to become a dynamic problem. This section firstly discusses what is meant by the term dynamic and how it applies to this field of research, it then goes on to outline some of the possible problem alterations and also provides preliminary insight into the expected effects of some of these changes.

Definition

The definition of dynamic which will be discussed in this section refers to the accessibility of problem domain related information. While many 'dynamic' problems are defined by edge, vertex or other problem specific parameters changing as time progresses, if this information is known a priori then the system ceases to be truly dynamic as if it is known that an edge will be unavailable at some specific time then our solution will be able to compensate for it ahead of time.

The definition of dynamic which is useful to the class of problems defined is: There is a probability of a change occurring, as well as a probability of when this change will occur as well as where it will occur. While any change now follows an underlying probability distribution, this distribution may not be known a priori to the user otherwise it would be possible to solve the system ahead of time using a probabilistic analysis.

What parameters should be dynamic? Is a question that can only be answered with another question, which is, what are you trying to model? The main motivation found for most researchers to introduce dynamic constraints into their problems is so that they can more closely resemble reality. Another motivation is to introduce complexity into the system which is often used as a means for testing the robustness of an optimisation technique.

Dynamic Shortest Path Problem

The static shortest path problem consists of two basic elements, vertices and edges; therefore by modifying how these elements behave we can create a dynamic shortest path problem.

- Insertion or removal of vertices and/or edges. At any time an edge or vertex (and hence all edges connecting to that vertex) may become impassable for a period of time, or indefinitely.
- Modification of edge/vertex parameters. Most edges and vertices will contain specific quality parameters (cost, length, time) hence it is possible to vary these parameters over a specified or unspecified range.

Dynamic Vehicle Routing Problem

The general static vehicle routing problem consists of several parameters, including a connection graph like that of the shortest path problem containing vertices and edges. Since the connection graph is similar to that of the shortest path problem we can deduct that the same modifications can be made to introduce dynamic behaviour here. Some more VRP specific parameters can be modified however:

- Number of customers can be varied.
- Customer demands can vary. This may mean that a delivery vehicle will contain an excess of a commodity to cope with an anticipated increase in customer demand.
- With the VRPTW the customer's time window could shrink, expand or shift over time so that a vehicle may arrive at what was an acceptable time when it received its initial orders, but now it is forced to wait until the start of the new time window or it may have missed the time window altogether.
- Vehicles are not 100% reliable and therefore there may exist a probability of a breakdown or accident. This could lead to two possibilities:
    - Another vehicle must meet this truck en-route to transfer the goods for transport and delivery in the field.
    - The goods inside the broken-down vehicle can be supplied by the distribution depot and therefore the customers can be served through the distribution centre via different vehicles.

- In the MDVRP a depot could be forced to close down for a period of time and vehicles routed to it will be required to re-route to a neighbouring distribution depot.

Dynamic Travelling Salesman Problem

The general static travelling salesman problem consists of several parameters, a connection graph like that of the shortest path problem containing vertices and edges. Like in the vehicle routing problem we can deduce that the same modifications can be made to introduce dynamic behaviour here.

Conclusion

References

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