DESIGNING A DSS FOR OPTIMISING LOGISTICS OPERATIONS IN E-COMMERCE ENVIRONMENT

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Abstract

The objective of this paper is to outline the design and implementation of a Decision Support System for improving tactical and operational logistics decisions, in the presence of an Internet based order-handling system.

Introduction

The importance of logistics operations seems to have been underestimated or overlooked by many electronic merchants. For several of them, the outstanding quality of their electronic services has generated great volumes of sales and top ranking market shares; still these same companies suffer substantial losses and cash flow problems, or even bankruptcy (as in the recent case of e-Toys). It seems that there exists a lack of integration between the two parallel value chain systems, the one that generates value over the Internet, and the one that generates place utility of products.

The high bearing of the latter is particularly evident in relation with corporate logistics functions, and stems from the following facts:

1. The high cost associated with product distribution or transportation, respectively for business to consumer and business to business models.
2. The impact of distribution efficiency on the level of service offered to the consumers.
3. The impact of transportation efficiency on the quality and cost efficiency of business to business transactions.
4. The stochastic and dynamic nature of Internet generated demand, as regards both temporal and spatial dimensions.

The purpose of the described system is to integrate the two disjoint value chain systems, by offering advanced services for the optimisation of corporate logistics functions.

System development context

The system presented is currently being developed as part of an Internet based solution funded by the European Commission DISTRICT project [Marques et al. 2000, Zografos et al 2000]. The architecture of the overall solution is presented in the following diagram.

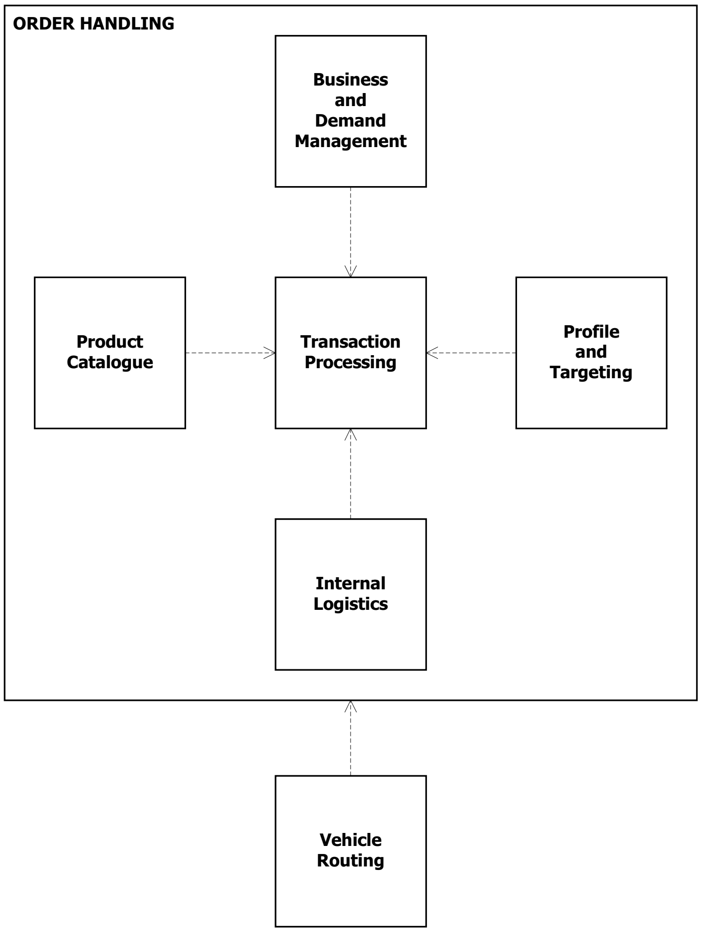

Figure 1: High level architecture of the DISTRICT solution

The Product Catalogue module manages the presentation of products and services through a standard interface. It permits offering products through the web, providing general user services such as searching for a given product etc.

The Transaction Processing module manages the selling process. It supports the entry of orders through the web interface provided by the Product Catalogue, as well as in person, by phone, fax and e-mail. It also offers other business services, such as order checking, order status reporting, stock reporting etc.

The Profile and Targeting module collects information on individual customers and groups of customers, in order to enable the customisation and personalisation of the services offered by the system. It also provides facilities to create business rules and support marketing efforts (advertising, discounts, direct mail, cross-sells, up-sells etc.).

The Business Management module provides general decision support information. Critical business data are stored in a data warehouse, which can be then mined for ordinary business statistics as well as to uncover market trends and segments. It also provides services for identifying and influencing customer demand trends, in cases of strongly periodical patterns.

The Internal Logistics module is responsible for monitoring the physical status of each order it passes through the various stages of the transaction, from order entry to the onset of delivery.

Last, the Vehicle Routing subsystem, the focus of this paper, has been designed to handle tactical and operational vehicle routing and scheduling requirements. It is largely independent from the rest of the system modules (collectively labelled as Order Handling in the diagram above) and is able to operate in any relevant context, provided that the appropriate type and detail of relevant order information can be made available.

Architectural design

The specific system implementation currently under development entails two instances, one dealing with a business to consumer distribution model, the other with a business to business transportation model. The system architectural design presented is common for both business cases.

Internet commerce prerequisites the existence of some sort of order handling system like the one outlined previously, which at a minimum offers services for order placement, verification, processing and transmission. The order information thus obtained is in a form readily usable by the logistics optimisation system, and presumably stored in some sort of relational database.

The high level architectural design of the logistics optimisation system, i.e. the logical packages that constitute the system and the dependency relationships between them, is defined in the following diagram.

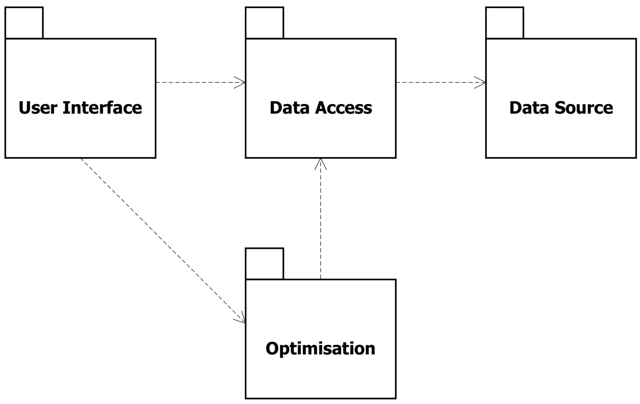

Figure 2: Logical packages of the logistics optimisation system

The classes contained in the User Interface package implement the interface of the human actor with the system, as regards the control of the system Use Case and the presentation of its results. The User Interface package requests the services of Optimisation classes for the generation of new schedules. The functionalities provided by the User Interface package relate to:

- Presenting in suitable format of the distribution/ transportation data.
- Printing suitable reports for the dissemination of the schedule to the vehicle crews.
- Presenting or modifying data stored in the local database.
- Controlling and reporting and the progress and status of the optimisation process.
- Reporting possible errors and their causes to the user.

The Optimisation package includes the classes that correspond to the transportation/ distribution mathematical models and the algorithms that are employed for their solution. The optimisation package could be viewed as providing two distinct but interdependent functionalities. The first functionality is the abstraction of the roadway network to a complete mathematical network, and is realised by instantiating and solving a shortest path model. The actual vehicle schedules are generated by vehicle routing models and algorithms that process the order data and the abstract network topology information, as provided by use of the services of the Data Access package.

The Data Access package contains the classes that will implement the interface with the local system database as well as the Remote Database actor. These classes will be responsible for the retrieval and storage of data to the Data Source package.

The Data Source package itself comprises the two database types that are included in the system. These are the local relational database, which contains order and optimisation specific data, and the local spatial database, including topological data about the roadway network.

The information contained in these databases has been determined by the requirements of the corresponding mathematical models. A classification thereof can be obtained from the following table.

Information Format / **Information Type**	**Topological**	**Tabular**
Geographical	Roadway network topology	Roadway network attributes, address information, roadway network operational rules, travel costs
Business Specific	Vehicle routes	Vehicle information, order information, shortest path cost matrices, assignment and sequence of visits

Table 1: Information types and formats

The system database has been generically designed in order to be able to accommodate several variations of the vehicle routing problem. It is capable of handling heterogeneous vehicle fleets, multiple depots, time windows, split operations and pickup and delivery constraints. Also, the system is largely independent from the specific schema of the available spatial data or the implementation of the remote database.

The level of detail of the spatial information required by the system is quite high, so as to allow for the implementation of an automated procedure for identifying the location of sites of interest (such as depots and stops) on the roadway network, as well as generating readily applicable crew directions.

A dynamic view of the system is presented in the following activity diagram.

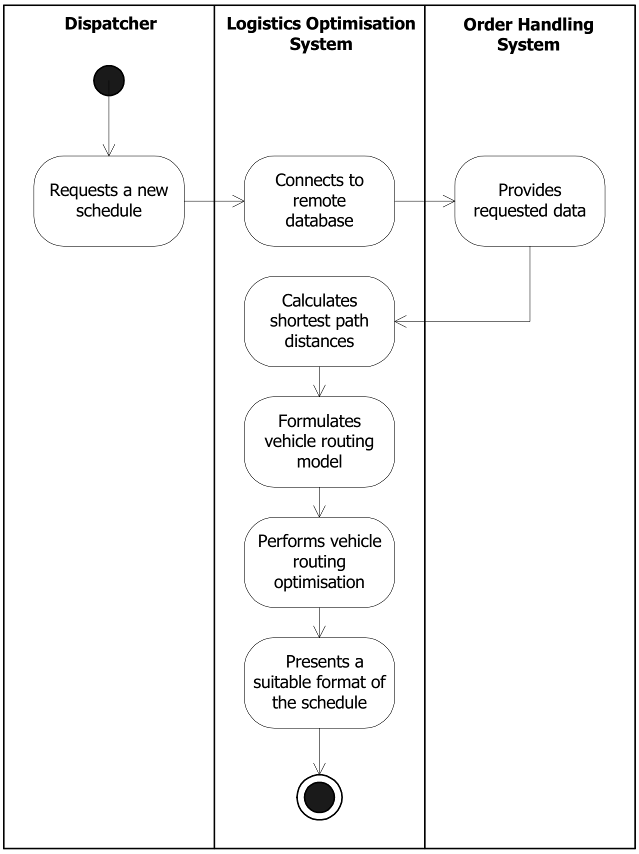

Figure 3: Dynamic system behaviour

Vehicle routing requirements

Specific requirements for the implementation of the system vehicle routing functionality were obtained by designing relevant questionnaires and disseminating them to future system users. A summary of the results of this survey are presented below, both for the business to business and for the business to consumer case.

Model characteristic	Business to Consumer	Business to Business
Size of the vehicle fleet	At the operational level of the decision making process, the number of vehicles is considered fixed. At the tactical level, the system must be able to prescribe the optimum fleet size.	At the operational level of the decision making process, the number of vehicles is considered fixed. At the tactical level, the system must be able to prescribe the optimum fleet size and mix.
Homogeneity of the vehicle fleet	The vehicle fleet can be modelled as homogeneous.	The system must be able to handle different vehicle types.
Homogeneity of the commodities	The order component commodities can be treated as homogeneous (as far as regards transportation requirements).	The order component commodities may have special transportation requirements (such as refrigeration) and thus cannot be treated as homogeneous.

Model characteristic	Business to Consumer	Business to Business
Design of service districts	The random nature of Internet generated demand does not allow for an efficient design of service districts.	Not a business requirement.
Temporal constraints	The system must be able to take into account temporal delivery constraints. This does not imply that each consumer can define his own time window for delivery, but rather that he can select from a number of predefined delivery shifts.	The system must be able to take into account temporal delivery constraints and each customer can define his own time window for delivery.
Optimisation time horizon	Equal to the duration of the predefined delivery shifts. Normally several times per day.	Normally more than once per day, on an ad hoc basis.
Vehicle capacity constraints	Each order is packaged in standard boxes. Vehicle capacity is expressed in these units.	Both order volume (expressed in standard units) and order weight must be taken under consideration.
Nature and location of operations	There exists a single central depot from where all vehicle routes emanate.	There exist multiple garages from where vehicles begin their service, and multiple depots from where orders are picked up.
Candidate objectives	At the operational decision level, minimisation of the total time of travel. At the tactical level, minimisation of the total vehicle routing cost.	At the operational decision level, minimisation of the total time of travel. At the tactical level, minimisation of the total vehicle routing cost.
Other distribution policies	Each order must be fulfilled by a single vehicle.	Fulfilment of each order by more than one vehicle is allowed.

Table 2: System model requirements

Mathematical models

Two generic vehicle routing models [Desrochers et al, 1990] have been so far identified for inclusion in the system, corresponding to each of the business cases under consideration. It is noteworthy that the system has been designed to allow for the implementation of several other vehicle routing problem formulations with limited or no development effort.

The business to customer delivery process has been modelled as a single depot, heterogeneous vehicle routing problem, augmented by capacity and total travel time restrictions. A formal definition of the model is as follows.

Let there be a complete network G (N, A), N being the set of nodes and A the set of arcs. For each arc $\{i, j\} \in A$ there exists a number $t_{ij}>=0$, denoting the travel time associated with traversing the arc from node i to node j. Each arc {i, j} represents the most efficient path for travelling from node i to node j. As a direct consequence of this, it holds that $t_{ij} <= t_{ik} + t_{kj}$, for any given $i, j, k \in N$.

The set of nodes N includes a single distinct point that represents the depot. For reasons of convenience, it will be hereafter assumed that the index of the depot node is 1 and that the indices of customer nodes will be greater than 1. With each node $i \in N$ are associated an integer number $q_i >= 0$ (demand for the delivery of a quantity q) and a number $s_i >= 0$ (service time required to physically deliver the order).

Let V be the set of available vehicles. With all vehicles is associated a common integer property $q >= 0$ (the maximum quantity that vehicles are capable of carrying at any given time) and a property $t >= 0$ (the maximum travel time allowed for vehicles). Last, x_{ijv} is a binary assignment variable that equals 1 only if the tour of vehicle v contains the arc {i, j}.

Given the previous, the model may be formally expressed as follows.

1. $$\text{Minimise} \sum_{i\in N}\sum_{j\in N}\sum_{v\in V} t_{ij}\, x_{ijv}$$

2. $$\sum_{j\in N}\sum_{v\in V} x_{1jv} <= |V|$$

3. $$\sum_{j\in N, j\neq i}\sum_{v\in V} x_{ijv} = 1, \ \forall\, i\in N, i > 1$$

4. $$\sum_{j\in N, j\neq i}\sum_{v\in V} x_{jiv} = 1, \ \forall\, i\in N, i > 1$$

5. $$\sum_{j\in N} x_{jiv} = \sum_{j\in N} x_{ijv}\ , \ \forall\, i\in N, \ \forall\, v\in V$$

6. $$\sum_{i\in N}\sum_{j\in N} x_{ijv}\, d_j <= q, \ \forall\, v\in V$$

7. $$\sum_{i\in N}\sum_{j\in N} x_{ijv}\, (t_{ij} + s_j) <= t, \ \forall\, v\in V$$

8. $$x_{ijv} \in S$$

The 1st expression provided above states that the objective of the model is the minimisation of the total time of travel. The 2nd expression ensures that the number of vehicles that is introduced into the network does not exceed the total number of available vehicles. Expressions 3 and 4 force exactly one vehicle to visit and leave each customer, while the 5th set of equations enforces the connectivity of vehicle tours. The 6th and 5th expressions guarantee that vehicle capacity and the maximum travel time allowed will not be exceeded.

Last, the variables of the model belong to a special set, such that sub routes (routes that do not include the depot node) are eliminated from the feasible space. A possible set of constraints that ensure this condition is the following.

- $s_i >= s_j + 1 - (1 - x_{ijv})\, M, \ \forall\, i, j\in N, i>1, \ \forall\, v\in V$
- $s_i <= s_j + 1 + (1 - x_{ijv})\, M\ , \ \forall\, i\in N, i>=1, \ \forall\, v\in V$
- $s_1 = 0$

The first set of constraints states that, if the arc {i, j} is contained in the tour of a certain vehicle, then there exist two nonnegative numbers s_i and s_j such that $s_i >= s_j + 1$. In this case, the next constraints ensure that $s_i <= s_j + 1$, hence $s_i = s_j + 1$.

In the case that the arc is not part of the tour, then s_i can take any value in a range that is determined by M (where M is a suitably selected large number). This, in effect, permits the variable to assume any possible value and renders the constraint non restrictive. After the solution of the model, the values of s indicate the sequence that nodes are visited in a given tour.

The business to business transportation model identified is more complex. It can be classified as a multiple depot, heterogeneous fleet, split pick up and delivery problem, augmented by time window constraints. Transportation is provided by vehicles that may belong to different companies, thus originating from different bases, and involves moving fresh produce from producer sites to wholesaler warehouses. A possible formulation for this problem is the following.

Let there be a complete network G (N, A), N being the set of nodes, A the set of arcs. For each arc $\{i, j\} \in A$ there exists a number $t_{ij}>=0$, denoting the travel time associated with traversing the arc from node i to node j. Each arc {i, j} represents the most efficient path for travelling from node i to node j, i.e. it holds that $t_{ij} <= t_{ik} + t_{kj}$, for any given $i, j, k \in N$.

The set of nodes N includes a set B of distinct nodes that represent the vehicle bases. For reasons of convenience, it will be hereafter assumed that the base indices will be the first |B| in the superset N of nodes. In the set of nodes is included the subset P of supply nodes, as well as the subset of demand nodes, to be denoted by W. For each member p of P there exists a one to one correspondence with a member w of W (and thus hold that |P|=|W|). For reasons of convenience, it is assumed that a member of P with index i in N will correspond to the member of N with index i + |P|.

With each node i of N are associated a number w_i and an integer number q_i, the sign of which denotes the type of transportation service to be provided, i.e. pick up or delivery. These represent correspondingly representing a demand for transportation effort of weight w or volume q. If $i \in P$ then q_i , $w_i>0$, while if $i \in W$ then q_i , $w_i<0$. There also exists a property $s_i>=0$, denoting the service time required to physically pickup or deliver an order. With each node $i \in W$ are associated a number l_i and a number u_i (earliest and latest time for the provision of the delivery service).

A set V of available vehicles is also defined. For each vehicle $v \in V$ there exist: an integer number $q_v>0$ (the maximum volume that vehicle v is capable of carrying at any given time), a number $w_v>0$ (the maximum weight that vehicle v is capable of carrying at any given time), a number $mc_v>0$ (the cost of utilising the vehicle v for one unit of travel time, if the vehicle is indeed moving), a number $wc_v>0$ (the cost of utilising the vehicle v for one unit of travel time, if the vehicle is not moving), and a property $t_v>0$ (the maximum travel time allowed for the vehicle). Last, each vehicle has a base node, which can be denoted by b_v.

Given the set of vehicles V and the set of supply sites P, a new set F (v, p), $v \in V$, $p \in P$ can be defined. F is the set of forbidden vehicle to order assignments, i.e. if the vehicle v is not capable of transporting the type of order that needs to be picked up from node p, the element {v, p} exists in F. This allows the modelling of situations where, for example, a specific order requires transportation by a refrigerator vehicle.

The following definitions are required to complete the formulation of the model:

- x_{ijv} , a binary variable that equals 1 if the tour of vehicle v contains the arc {i, j}.

- cv_{iv} , an integer variable that corresponds to the volume picked up or delivered by vehicle v at node i.
- tv_{iv} , an integer variable that corresponds to the volume that vehicle v is carrying by the time of departure from node i.
- cw_{iv} , a variable that corresponds to the volume picked up or delivered by vehicle v at node i.
- tw_{iv} , a variable that corresponds to the volume that vehicle v is carrying by the time of departure from node i.
- tt_{iv} , a variable that denotes the total travel time of vehicle v, by the time of physical arrival at node i (the physical arrival at demand nodes may differ from the time of onset of delivery service, in the case of demand nodes).
- $wt_{iv} >= 0$, a value equal to the waiting time of a vehicle incurred at node i, i being a member of W (since waiting time can be incurred only at supply nodes, which are qualified by time windows).

Given the previous, the model may be formally expressed as follows.

1. $$\text{Minimise} \sum_{i\in N}\sum_{j\in N}\sum_{v\in V} t_{ij}\, x_{ijv}\, mc_v + \sum_{i\in W}\sum_{v\in V} wt_{wv}\, wc_v$$
2. $$\sum_{i\in N} x_{biv} = 0,\ \forall\, v\in V, \forall\, b\in B,\ b\neq b_v$$
3. $$\sum_{i\in N} x_{biv} <= 1,\ \forall\, v\in V,\ b = b_v$$
4. $$\sum_{j\in N} x_{jiv} = \sum_{j\in N} x_{ijv}\ ,\ \forall\, i\in N,\ \forall\, v\in V$$
5. $$\sum_{j\in N} x_{jiv} = 0,\ \forall\, \{i, v\}\in F$$
6. $$cv_{iv} <= \sum_{j\in N} x_{jiv}\, M,\ \forall\, i\in P,\ \forall\, v\in V$$
7. $$-cv_{iv} <= \sum_{j\in N} x_{jiv}\, M,\ \forall\, i\in W,\ \forall\, v\in V$$
8. $$cv_{iv} = -cv_{(i+|P|)v}\ ,\ \forall\, i\in P,\ \forall\, v\in V$$
9. $$\sum_{v\in V} cv_{iv} = v_i\ ,\ \forall\, i\in P$$
10. $$cv_{iv} >= 0,\ \forall\, i\in P,\ \forall\, v\in V$$
11. $$tv_{iv} >= tv_{jv} + cv_{iv} - (1 - x_{jiv})\, M,\ \forall\, v\in V,\ \forall\, i\in N, i\neq b_v\ ,\ \forall\, j\in N$$
12. $$tv_{iv} <= tv_{jv} + cv_{iv} + (1 - x_{jiv})\, M,\ \forall\, v\in V,\ \forall\, i\in N, i\neq b_v\ ,\ \forall\, j\in N$$
13. $$tv_{iv} <= v_v\ ,\ \forall\, i\in P,\ \forall\, v\in V$$
14. $$cw_{iv} = (w_i / v_i)\, cv_{iv}\ ,\ \forall\, i\in N, i\notin B,\ \forall\, v\in V$$
15. $$tw_{iv} >= tw_{jv} + cw_{iv} - (1 - x_{jiv})\, M,\ \forall\, v\in V,\ \forall\, i\in N, i\neq b_v\ ,\ \forall\, j\in N$$
16. $$tw_{iv} <= tw_{jv} + cw_{iv} + (1 - x_{jiv})\, M,\ \forall\, v\in V,\ \forall\, i\in N, i\neq b_v\ ,\ \forall\, j\in N$$
17. $$tw_{iv} <= w_v\ ,\ \forall\, i\in P,\ \forall\, v\in V$$

18. $tt_{iv} >= tt_{jv} + t_{ji} + s_j + wt_{jv} - (1 - x_{jiv}) M, \forall v \in V, \forall i \in N, i \neq b_v, \forall j \in N$

19. $tt_{iv} <= tt_{jv} + t_{ji} + s_j + wt_{jv} + (1 - x_{jiv}) M, \forall v \in V, \forall i \in N, i \neq b_v, \forall j \in N$

20. $tt_{iv} <= tt_{(i+|P|)v}, \forall v \in V, \forall i \in P$

21. $tt_{iv} <= t_v - (s_i + wt_{iv} + (1 - x_{ibv}) t_{ib}), \forall v \in V, \forall i \in W, b=b_v$

22. $tt_{iv} <= u_i, \forall v \in V, \forall i \in W$

23. $wt_{iv} >= l_i - tt_{iv}, \forall v \in V, \forall i \in W$

The objective of the model is the determination of a set of routes such that the total cost of transportation is minimal. The cost of transportation is directly related to the time required to traverse the arcs. Moreover, waiting costs can be incurred at delivery nodes, since the physical arrival of the vehicle may be earlier than the lower bound of the time window that qualifies the node. Waiting and travel times are multiplied by the relevant marginal costs of the corresponding vehicles.

The 2nd expression ensures that routes begin only from the respective vehicle base. The 3rd set of constraints prohibits vehicles to depart from their respective bases more than once, simultaneously constraining the number of vehicles that may leave each base. The 4th set enforces the connectivity of vehicle routes, by requiring the vehicle that enters a certain node to also depart from it. The 5th set of constraints is quite straightforward, explicitly prohibiting vehicles to enter a node, if they the specific vehicle/ order assignment is forbidden.

Expressions 6 and 7 ensure that a vehicle picks up or delivers a quantity from a certain node only if the node is contained in the vehicle path. The constraints of the 8th set ensure that if a vehicle picks a quantity up from a supply node, it must deliver the same quantity to the corresponding demand node. The 9th set of equations stipulates that each supply node is fully serviced, while the 10th set enforces only pick up operations to be made at supply nodes.

Constraint sets 11 and 12 are required for the calculation of the total volume that each vehicle is carrying by the time it has serviced a certain node. Expression 13 guarantees that the total quantity carried by the time of departure from each supply node will not exceed the vehicle volume capacity. The 14th set of equations is relevant and enforces weight capacity feasibility (a proportional relationship is assumed to exist between the volume and the weight of a given order).

The 15th and 16th sets of constraints are required for the calculation of the time of physical arrival of vehicles at nodes, which may or may not coincide with the time of onset of service, for nodes qualified by time windows. Equations 17 state that arrival at a supply node is prior to arrival at the corresponding demand node (an order has to be picked up before being delivered). Equations 18 limit the total travel time of each vehicle to less than its maximum allowed travel time.

Last, constraint set 19 restrains vehicles from visiting demand nodes after the time available for delivery has elapsed, while the 20th set calculates the waiting time that is incurred when the arrival of a vehicle is earlier than the lower bound of the time window.

The model defined above assumes that supply sites have a one to one relationship with demand sites. In the context of the specific business to business transportation process this implies that the supply sites of the model cannot be directly mapped to producers, as one might think at a first glance.

Instead, each actual producer node p must be cloned to a number of plasmatic nodes p_1, $p_2 \ldots p_n$, n being the total number of orders that have been issued to the producer. The travel time between each pair of these plasmatic nodes is of course 0, since in reality they are all located on the same node of the road network. The distance between each plasmatic node and another node of the network is that of the original producer node. The other attributes of the plasmatic node (weight, volume, vehicles allowed, service time required) are unique to it and correspond to those of each individual order. The same procedure must be followed with respect to the wholesaler sites. With each different order issued by a wholesaler, a wholesaler pseudo node is created with its own order specific attributes.

Concluding remarks

The proposed system design utilises GIS and optimisation models in order to offer advanced vehicle routing capabilities. Its implementation for the business to consumer case suggests that it can provide good solutions for the distribution problem of Internet, fresh food retailers.

Acknowledgements

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