

**Texto para discussão
sobre
DSS-Apoio à Logística do Transporte de Containers**

A DECISION SUPPORT MODEL FOR DYNAMIC ROUTING OF CONTAINERS AT THE GLOBAL TRADE

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Abstract

Global trade patterns and container routing have stressed the logistics adaptability in dynamic contexts, emphasising the importance of flexible real-time computer tools in management processes concerning routing and scheduling of product flows. These logistics operations are complex, requiring real-time decision support systems for up-to-the-moment re-evaluations. In this respect, this paper presents the main features of a decision support model for routing flows of containers across national boundaries under time window constraints. A simulated case study based on the experience of Brazilian carriers and logistics providers was build so that its corresponding data was used to validate the modelling approach and the computer implementation of the core module of the solution procedure.

Key words: Logistics, Routing of Containers, Shortest Path with Time Window

Resumo

O padrão das trocas comerciais globais e o roteamento de contêineres destacam a adaptabilidade da logística em contextos dinâmicos, enfatizando a importância de instrumentos computacionais em tempo real flexíveis para o gerenciamento de processos relativos à programação de rotas e o sequenciamento de fluxos de produtos. Essas operações da logística são complexas, requerendo sistemas de suporte à decisão para prontas reavaliações. Neste sentido, este trabalho apresenta as características principais de um modelo projetado para apoio às decisões de roteamento de fluxos de contêineres além dos limites geográficos nacionais sob restrições de janelas de tempo. Um estudo de caso foi simulado com base na situação observada em empresas de transporte e operadores logísticos brasileiros, de forma que os dados correspondentes foram utilizados para validar a abordagem da modelagem e a implementação computacional do módulo central do procedimento de solução.

Palavras-chave: Logística, Roteamento de Contêineres, Caminho Mínimo com Janelas de Tempo.

1. Introduction

The logistics network in the international trade of the global business environment, from the point of view of both space and time, is composed by a large number of links and nodes. The flow of products in the international market, from the factory to the consumer, is multimodal in nature, using land modes (rail, road) at both ends, and air services or shipping services overseas. Interface facilities, ports, storage depots, yards, etc. are nodal points that lead to additional costs and delays. Furthermore, railway and road links, associated with choices of port/airport terminals at both ends and air/shipping services in-between, make up a large number of combinations, leading to different door-to-door times and costs.

The sea links, represented by shipping line services, have undergone deep structural changes and innovative practices for resource sharing during the past two decades, comprised of mergers, acquisitions or strategic alliances among traditional competitors, and with strong impacts on the overall operations (Sheppard and Seidman, 2001). Additionally, ocean shipping alliances enter into partnerships or consolidate with motor or rail services to create intermodal door-to-door packages. These intermodal alliances provide integrated services as those offered by freight forwarders and express shipping like Federal Express. Alliances cooperate on land through the joint use of ports, terminals, equipment and other facilities. They are an imitation of sorts of the hub-and-spoken system, very common in airline practices.

For instance, the increasing demand for better quality service on a door-to-door basis induced the container shipping lines to worry about the associated land routes. Instead of deploying scarce financial resources into new inland ventures, such as trucking or rail services, ship owners started to organise the flow of containers along the main inland corridors, channelling them to selected ports. Land bridges, unit trains operating over rail corridors toward major ports, and the hub centre concept applied to the spatial distribution of cargo flows are transportation system features introduced to respond to demand requirements.

Transportation deregulation is a synergistic factor in integrating land and sea services. Deregulation has increased transportation alternatives in terms of frequencies, links, tariff rates, etc.. The logistics decisions now depend on a detailed real-time analysis of the transportation alternatives, simultaneously taking into consideration the space and time restrictions. Furthermore, a key issue in the design of international logistics networks is where, when and how the consolidation and customs procedures have to occur for a certain shipment. The procedures for export or import through consolidation terminals involve their location and the decision about which of them the logistics networks should include. In addition to that, the arrival and departures of cargoes through the terminals have to be synchronised, strengthening the use of the just-in-time approach in the distribution of products.

In such an environment, a decision support system designed to help logistics providers in selecting the best route, taking into account cost, time and space constraints is an important management tool (Psaraftis, 1988; Min and Cooper, 1990; Min and Eom, 1994). Since early deliveries are not necessarily welcome, in some instances cheaper routing alternatives may come into consideration. As the flow progresses, an unexpected delay at some point of the process may become apparent. At that time, the system should offer alternative paths to reroute the flow, in such a manner as to prevent delays at the delivery point. For example, if a rail connection has been planned at the destination port and a delay occurs, a faster, although more expensive, trucking alternative may be selected in order to deliver the cargo in time at the customer's facility (by simplification, air services are not included in this problem essay).

Although the flow of products in general presents such characteristics, this problem is much more acute when operating with containers. The flexibility of loading, unloading and stowing the boxes is such that integrated container systems are nowadays called "un-modal" (Fiore, 1986a, 1986b), in the sense that the supporting modes (rail, road, shipping) are of secondary

importance, being the container the "true mode" to be taken into consideration. This exceptional flexibility, when compared with break-bulk transportation, leads to tighter schedules and sudden route changes, a situation that favours the implementation of computer aids in management processes.

In this respect, this paper presents the decision support model - as a core module of a real-time decision support system, designed to help managers in routing the flow of containers along a relatively complex space-time network of an international distribution and consolidation problem. First, we introduce the problem of routing and scheduling of containers modelled as a mixed linear programming problem pertaining to a general class of vehicle routing problems with time window constraints, as well as previous work to model and solve this problem. Second, the problem solution procedures based on a dynamic network flow model are presented. Finally, Brazilian experience to validate the solution approach used and its computer implementation is highlighted.

2. The Problem

An export organisation has to ship containerised products from some specified plants to certain final overseas destination(s). Figure 1 presents a scheme of the general situation of such export organisations that generates a customer-controlled distribution and consolidation problem which solution has to obey transportation system operational and industrial availability time constraints.

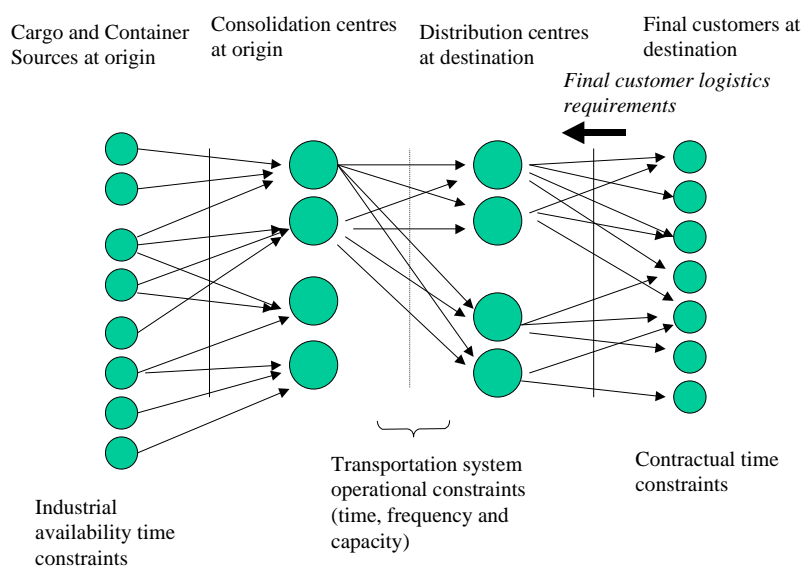


Figure 1- A many-to-many distribution and consolidation problem of an export organisation

Different time restrictions occur as, for instance, the dates (or time period) when the products will be available to the customer etc.. The logistics manager must be capable of acting on the distribution system in such a manner as to guarantee the level of service with a minimum total cost, associated with the compliance, for example, with agreement terms. For that purpose he will evaluate all the alternative routes and then choose the best option that obeys a time window in the destination of the export. Therefore, the logistics network of the organisation includes a pre-fixed number (T) of possibilities of consolidation points, transportation modes and their

schedules, intermediary stocking points, (DC) distribution centres at destination, etc.. In the event the many-to-many distribution and consolidation problem can be decomposed into (T + DC) equivalent-number of many-to-one problems, as we will discuss further, the logistics manager activity will be carried out for each homogeneous lot to be shipped. A homogeneous lot is composed by a certain quantity of cargo, with the same origin and destination, to be delivered in a same time period. We assume further that each homogeneous lot will not be split into smaller lots along the process, but rather will follow the route as only one lot.

The transportation network, the travelling times and costs in each link, the inventory carrying costs at each interface node, etc., are known beforehand. It is also assumed that a preliminary analysis has eliminated dominated alternatives, i.e. the ones with higher costs and no advantages when compared to other options. This will reduce the analysis to the relevant combination of elements, eliminating unnecessary evaluations. The most important time window to be considered is the one defined by the earliest and the latest delivery dates, as accepted in advance by the parties. Other time windows may occur along the route, depending on specific local constraints.

The dynamic environment of global trades imposes information changes that will lead to redefinition of the routing and scheduling problem faced by logistics managers. The dynamic aspect is related to the frequent rechecking of the optimal solution whenever a new set of information about demand requirements and/or global trade and transportation system changes becomes available. Consequently, the routing of a container or a lot of containers must be reviewed at some points of the process. To do so it is necessary to be able to periodically update data in the information system managed, and to apply the solution procedures again from that point onwards. This ability to constantly update the system is an important dynamic feature to be explored when designing a management system to aid the routing decisions at the operational level, and/or logistics strategy correlated decisions at the strategic/tactical one as well.

2.1. Model Framework

The perspective of logistics management according to the point of view of the exporter: manufacturer, or the Governmental Agency: defining planning directives, may present more complex aspects. This occurs as the production process and the transportation of export and import cargo should be viewed as interdependent activities in the strategic planning of its performance in the international trade. Nevertheless, the distribution and consolidation problem here is viewed under the light of the “logistics manager” or “distribution manager” of the company that is scheduling and controlling the flow of containerised products to its clients. This enables the simplification of the problem in the event production and cargo transportation are independent activities, which permits decomposing it according to consolidation strategies in many-to-one distribution sub-problems.

Among the components of the total cost of logistics (Stock and Lambert, 1993), the lot production cost can be discarded in the problem analysis also because transportation and production are independent activities. On the other hand, the cost of the “lost sales” is understood as the guarantee of an appropriate service quality to the client, that is, the compliance with the time window restriction at destination.

Two additional restrictions have to be included in the logistics network of the problem:

a) obligatory consolidation of transport, which means exportation (or importation) through the consolidation at the origin of the cargo, in intermediate consolidation centres or in the export port terminal of the cargo route, and

b) obligatory passage through one and only one Customs house in the country of origin and through one and only one in the country of destination of the export. A period of obligatory stay in transshipment points in countries left out of the commercial agreement for the verification of the documents of the cargo in transit is acceptable.

Therefore, the three situations below are considered possible in the composition of those networks:

- Consolidation of the transport followed by Customs clearance in different (physical) locations;
- Consolidation (or the opposite activities at distribution centres) followed by Customs clearance in the same (physical) locations;
- In the event the consolidation of the transport is carried out in the port terminal itself, then the Customs procedures will have to take place there.

In what concerns the cargo and vehicle routing problems with time windows, the periods during which the shipments and services have to arrive or start are decision variables, restricted by the time windows (Golden and Bodin, 1979). In what concerns the problem of distribution and consolidation of export shipments, the warehousing time period in the locations of the network is a decision variable dependent of the frequency of the maritime and continental transportation service. Its lower bound is the time period of obligatory stay at those locations. The treatment of those periods, together with transportation capacity constraints, in the modelling of routing problems involving shipping lines may mean changes in the basic structure of the general routing problem with time windows (Solomon and Desrosiers, 1988; Psaraftis et al., 1990). The consolidation of cargoes in containers and the fact that the problem is related to the management of small sized, homogeneous and undividable lots, however, enables the simplification of the modelling.

By consequence, in order to define the analytical model for the problem, the following hypotheses were made, which are of primary importance for the establishment of the logistics network:

- (a) It is assumed that the physical network formed by transportation links, terminals, warehouses, etc. have unconstrained capacity. This is acceptable as long as the shipped lots are small as compared to the general flow of containers;
- (b) Multiple routes linking the various sources to the final destination are available;
- (c) Full-container loads in the long-haul, allowing linear transportation cost functions; similar linearization of costs is considered in the short-haul, as a consequence of deliveries of homogeneous lots, instead of the trade-off analysis of frequencies and costs that must be made in general cases (Hall, 1987).
- (d) The short-term planning horizon is completely defined. Uncertainties are dealt with by periodic planning reviews.
- (e) It is assumed that all time variables, cargo quantities and unit costs are deterministic. Variable changes are taken into account whenever a revision of policy is made.
- (f) It is assumed that supply of land transportation is continuous over time since the capacity of vehicles is small when compared to the overall volume of cargo (this is also true for railroad when services are offered on a wagon-to-wagon basis or on a less-than-truck-load basis). Supply of maritime transport, on the other hand, is clearly discrete. We assume regular and pre-defined shipping frequencies.

Time windows can be generally classified into two groups (White, 1972; Desaulniers et al., 1999). The rigid ones, in which the cargo is never delivered before the earliest date, as opposed

to a flexible time window which is the one in which a cost or penalty is imposed whenever the restriction is violated. We have assumed a mixed situation: a cost or penalty is incurred whenever the cargo is delivered before the earliest date, but deliveries are not allowed to take place after the latest date.

2.2. The Analytical Model

(A) Initial Definitions

The logistics network is defined based on an oriented graph $G = (N, A)$, where $N = \{1, \dots, n\}$ is the set of nodes and A is the set of arcs, and also that:

- the locations in the physical network (origins, destination, ports, intermediate warehouses, transshipment points, consolidation/Customs centres) will correspond to the nodes in the logistics network, and
- the connections between locations in the physical network will correspond to the arcs in the logistics network considered disaggregated. Therefore, a path of this disaggregated network is equivalent to an arc of the logistics network (aggregated) previously referred to.

The regular shipping lines of maritime transport will be associated to arcs in the logistics network. If there are several ports of call of the ships in the continent of origin (or of destination) the regular lines should be associated to multiple arcs. The viable routes of the logistics network are composed by sequences of arcs capable of transporting and of nodes capable of stocking the lots produced for export. In associating the logistics network with the physical network, it is important to carefully observe the cases of export and import ports. Some of those locations may have double use, for example having the function of transshipment point and/or export (import) port. In these cases, the location should be associated to two nodes in the logistics network, one of them only the transshipment point and the other only the export and import port. This requires particular attention to the numbering of these arcs for the solution procedures, which will correspond to the creation of a multiple of artificial “ship” departures and arrivals.

The difference between the problems of movement of empty containers and the problems of moving lots of consolidated cargo is that the latter will have a particular destination to reach. Therefore, there will be no exchange of cargo lots or of full containers in the lines of the network. That is, the modelling of the flow of lots of container cargo does not consider the possibility of division of the lots in certain points of the network.

The strategic decision of routing and stocking homogeneous lots in networks of multiple origins to one sole destination through a consolidation centre is the result of a problem of minimising the total cost which decision variables represent:

- identifying number of the “ship” from the port of origin to the port of destination;
- warehousing places (nodes) and their duration (days, or midi-days);
- routes (to which, when on land, the continuous offer of certain modes of transportation are associated), and
- times of arrival of the lots at the points of the network.

(B) Problem Formulation

We consider the following notation for the problem formulation:

N = set of nodes (i) of the logistics network ordered in such a way in each arc (i,j),
 $i < j, |N| = n$;

A = set of arcs (i,j) of the logistics network associated with the original network,
 $|A| = m$;

A^1 = set of arcs associated with regular shipping lines, in such a way $A^1 \subseteq A$,
 $|A^1| = m^1; m^1 \leq m$;

A^2 = set of land arcs or cabotage shipping lines without frequency restrictions,
such that $A^1 \cup A^2 = A$;

E = set of nodes that corresponds to export ports in the logistics network, $N \ni E$;

I = set of nodes that corresponds to import ports in the logistics network, $N \ni I$;

P = set of nodes that corresponds to modal transfer/transshipment and intermediate
warehousing,

in such a way $\{I \cup E \cup P\} \supseteq N$,

as well as the variables as it follows:

c_{ij} = transportation cost of the homogeneous lot in the arc (i,j);

ca_i = warehousing cost of the homogeneous lot per time unit in the node i ;

ta_i = warehousing time period (hours or days) of the homogeneous lot in the
node i ;

t_i = arrival date of the homogeneous lot at node $i, i \in N$;

t_{ij} = transportation time (hours or days) of the homogeneous lot in the arc (i,j);

x_{ij} = binary variable $\{0, 1\}$, associated with the inclusion or not of arc (i, j) $\in A$
in the optimal route;

M = very high value for mathematical assertion;

∞_{ij} = unconstraint variable for mathematical assertion;

a_i = lower bound (temporal) of the arrival (or delivery) time window of
the homogeneous lot into node i ;

b_i = upper bound (temporal) of the arrival (or delivery) time window of
the homogeneous lot into node i ;

tpo_i = obligatory stay time period (hours or days) of the homogeneous lot in
node i ,

where $i \in \{I \cup E \cup P\}$;

$kmax_{ij}$ = maximum number of ships departures in arcs (i,j), (i,j) $\in A^1, i \in E$
and $j \in I$;

$d_{ij}(k)$ = departure date of the "ship" k of the line (arc) (i,j), where (i, j) $\in A^1$;

f_{ij} = time interval (days) between ships departures in the line (arc) (i,j), where
(i, j) $\in A^1$;

y_{ijk} = binary variable $\{0,1\}$ associated with the choice, or not, of the k number
departure of the "ship" in the arc (i,j), where (i, j) $\in A^1$ and $1 \leq k \leq kmax_{ij}$.

We can, then, formulate the analytical problem as a mixed linear programming problem,
constrained by the inequations and decisions variables from (I) to (XVII), as it follow:

$$\min \sum_i \sum_j c_{ij} x_{ij} + \sum_i ca_i ta_i$$

subject to:

$$t_i + ta_i + t_{ij} - t_j = \infty_{ij}, \text{ and} \tag{I}$$

$$(x_{ij} - 1) \cdot M \leq \infty_{ij} \leq (1 - x_{ij}) \cdot M, \quad \forall (i, j) \in A, \tag{II}$$

$$a_i \leq t_i + ta_i \leq b_i, \tag{III}$$

$$t p o_i \cdot \sum_{(i,j) \in A^1} x_{ij} \leq t a_i, \quad \text{and} \quad (IV)$$

$$t a_i \leq \sum_{(i,j) \in A^1} \cdot \sum_{k=1}^{k \max_{ij}} (d_{ij}(k) \cdot y_{ijk}) - t_i, \quad \text{and} \quad (V)$$

$$d_{ij}(k) = d_{ij}(1) + (k-1) f_{ij}, \quad (VI)$$

to $i \in E$, since

$$x_{ij} = \sum_{k=1}^{k \max_{ij}} y_{ijk}(k), \quad (VII)$$

$\forall i \in E$ and $j / (i,j) \in A$

$$t p o_i \cdot \sum_{(j,i) \in A^1} x_{ji} \leq t a_i, \quad \forall i \in I \quad (VIII)$$

$$t p o_i \cdot \sum_{(i,j) \in A^2} x_{ji} \leq t a_i, \quad \forall i \in P \quad (IX)$$

$$\sum_j x_{ji} - \sum_j x_{ij} = \begin{cases} -1 & \text{if } i = 1, \\ 0 & \text{if } i \neq 1 \text{ and } i \neq n, \\ +1 & \text{if } i = n, \end{cases} \quad (X)$$

$$(XI)$$

$$(XII)$$

to $\forall i \in N$,

where:

$$y_{ijk} \in \{0, 1\}; \quad (XIII)$$

$$x_{ij} \in \{0, 1\}; \quad (XVI)$$

$$\infty_{ij} \text{ is unconstrained}; \quad (XV)$$

$$t a_i \text{ and } t_i \geq 0, \text{ to } \forall i \in N. \quad (XVI), \text{ and } (XVII)$$

The objective function, known as total cost (or logistics cost) function is composed by the transportation and warehousing total costs components associated with the deliveries of each homogeneous lot in the logistics network. Decision variables are represented in the problem formulation from (XIV)-(XVII). The first two are related to the optimal routing choice, and the others to warehousing and cargo arrival times into nodes of the logistics network. The problem constraints are related, respectively, to:

(I)-(II): temporal restrictions for system co-ordination, which consider if the optimal path includes or not each link (i,j) considered.

(III) : time window at destination.

(IV)-(VII): warehousing time period at export ports, lower bounded by the obligatory stay time period at the place and upper bounded by the co-ordination time between the chosen “ship” departure date (restriction VI) and the cargo arrival into the port terminal (IV and V), subject to additional restriction (VII) representing aggregation of the binary decision variables for an unitary “ship” choice.

(VIII): warehousing time period at import ports, lower bounded by the obligatory stay time period at the port terminal.

(IX): warehousing time period at modal transfer or intermediate warehousing points, lower bounded by an obligatory stay time period.

(X)-(XII): restrictions of continuity and uniqueness of the routing solution.

2.3. Some Previous Results from the Literature

Many researchers have studied the problem of routing vehicles under time window restrictions. Some papers on the subject concerning this type of problem, its models and respective methods of solution were analysed. One did not seek, however, to carry out a review of the work done but concentrated mainly in searching for a solution that would guarantee flexibility and easy review of the structure of the model adopted as compared to the dynamic characteristics of the actual problem of routing and scheduling of containers.

The time characteristics of the planning problem focused permit it to be classified as a dynamic vehicle routing and dispatching problem. Nevertheless this problem has been addressed for years, it has emerged as an active area of research since analytical capabilities associated with technological advances recently increased (Gendreau and Potvin, 1998; Ronen, 1983; Ronen, 1988). During the past years an increase of algorithms intending to solve real world routing and scheduling problems has been noted (Dumas and Desrosiers, 1986; Solomon, 1987; Desrochers et al., 1988; Solomon and Desrosiers, 1988; Desrochers and Soumis, 1988, 1988a; Desrosiers et al. 1995; Desaulniers et al., 1999; Laporte et al., 2000; Larsen, 2000, among others). The size of the problems has increased and more realistic restrictions have been incorporated into the models.

In the solution of routing problems with time windows, optimisation algorithms are traditionally used based on principles of the implicit enumeration: the dynamic programming and the "branch and bound" technique. Desrosiers et al. (1988) studied the lagrangean relaxation of the restrictions of the problem. In this case, if a visit of the vehicles to each client is not obligatory, the lagrangean problem is a problem of the shortest path with time windows. Sorensen (Desrochers et al., 1988), in his dissertation, suggested a lagrangean decomposition for the problem solution. On the other hand, several authors solved routing problems with time windows by heuristic techniques, as for example Solomon (1987) who uses a sequential space-time insertion algorithm, and Solomon et al. (1988) and Koskosidis et al. (1989). Koskosidis et al (1992) propose an optimisation-based heuristics, based on the treatment of time windows that can be violated at a cost. Metaheuristic algorithms to generate upper bounds for the vehicle routing problem with time windows constraints are joined to classical heuristics, as well as lower bounds obtained through the decomposition approaches, as we can see in the survey presented by Desaulniers et al. (1999). Laporte et al. (2000) contributed by discussing classical and metaheuristics concerning the vehicle routing problem solution.

On the other hand, container routing studies have been concerned for a long time with the ocean segment. Kim's (1985) and Psaraftis et al.'s (1990) works are good examples of such an approach. During the last three decades some research efforts have touched the land segment of container movement. We can mention the pioneering works of White (1972), followed by Florez (1986), Dejax and Crainic (1987) and Antonisse (1988). Crainic et al. (1989,1990) propose a dynamic stochastic approach to represent management activities of container displacements on a day-to-day basis.

We stress the modelling approach of White's (1972) and Powell's (1988) works, which indicate the trend of employing the graph theory in container transportation issues for modelling and solving the problems. It is especially exemplified with the modelling of dynamic flows discussed in White's (1972) pioneer work and later on of Florez's (1986). Through the design of a space-time network associated to the original transportation network, the first

author uses the concept of network dynamic flows in the modelling of the problem of distribution of empty containers, solving it through the refinement of the algorithm out-of-kilter. In the same manner, Florez (1986) treats the strategy of positioning and leasing empty containers to meet the internal distribution and export needs of international shipping companies (in this case, U.S. Lines).

Some papers (Min and Cooper, 1990; Ronen, 1983; Powell, 1988; Psaraftis, 1988) emphasise the need to treat the routing problem with time windows integrated with the development of decision support systems, and the inherent problem complexity related to the dynamic characteristics of the demand and transportation system changes. In this respect, in his work of 1995 Psaraftis (Larsen, 2000) provides a survey of the past decades' results obtained for dynamic vehicle routing problems. Besides, we cite the survey on dynamic vehicle routing and dispatching presented by Gendreau and Potvin (1998). The authors also propose open directions for future works that include research on demand forecasting for constructing routes, algorithm developments to consider the relocation of vehicles to new services since demand requirements are evolving in the time, and other issues as parallel implementation.

3. Procedures to Solve the Problem

The space-time consolidation strategy of the transportation flows (e.g. from n origins A, B ... Z) in lots of containers starting from a consolidation centre (T) enables the decomposition of the problem into two main steps or sub-problems. The first one corresponds to finding the best route for the homogeneous lots from each origin to the consolidation centre, which is a destination common to a group of origins (concerning a many-to-one distribution problem). Once the possible consolidation transportation centres are defined, the logistic path is a result: (1) of the transported lot quantity, and (2) of the synchronisation and compatibility between the arrival dates of the cargo in the intermediate destination (T) with the time constraints of the problem. In summary, the lots of cargo from origins will be aggregated and loaded into containers in the consolidation centre (T) where they have to be available for export at a later date pre-defined as t_0 , greater than the earliest (possible) dates d for cargo arrival into the centre.

This step can be viewed in an inverted manner, that is, as a one-to-many distribution problem. In that case, the t_0 time limit is associated to the new origin (T), equivalent to the viable date of availability of the lot of containers in the consolidation/exportation centre (latest date of the export). This date (t_0) is determined starting from the minimum (viable) transit time from the location (T) of the logistics network to the destination of the export (D) which meets the time window at destination. From this point of view the programming of the possible (feasible) dates of availability of cargo lots (not consolidated) in the sources at origin is designed, which has to comply with the time restriction of the export agreement. In the event the mentioned dates are pre-determined and inflexible, in this step of the programming of the logistic path it will be possible to test if the service network is, or is not, capable of meeting the requirements of the exporter (importer).

The second step corresponds to the sub-problem of definition of the logistics path of exportation of the containerised lot, corresponding, as a rule, to a unitary flow of cargo (one sole shipment of a cargo lot or a lot of containers) from the origin of the consolidated cargo (T) to its destination (D). Therefore, starting from the strategy of consolidating the transportation in a time-space dimension, the problem of exporting cargo shipments (consolidated) is a problem reduced to one-to-one from the consolidation centre to the final destination.

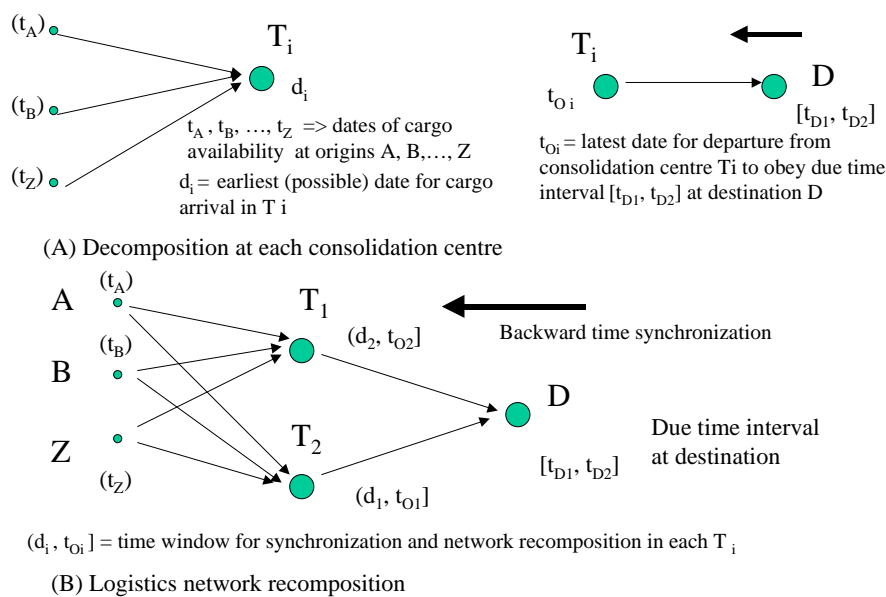


Figure 2- Network decomposition and recomposition strategies of the solution procedures

Figure 2 shows the decomposition strategy (that could be applied to the many-to-many distribution problem, where are considered (DC) distribution centres at destination countries, and a number of final clients to deliver products from these centres), at first generating many-to-one problems plus the one-to-one. These are decomposed in a multiple of one-to-one distribution sub-problems, equivalent to the number of origins of the cargo and the consolidation centres, which are solved in two main steps. Each one of the one-to-one problems corresponds to a direct link terminal-export destination and/or to the links origin-terminal (note that an arc of the network composed by direct links is, in fact, a path with intermediate points in the original network). Temporal co-ordination is considered in the posterior recomposition phase of the solution procedures in order to guarantee its viability and accordance with time requirements in the commercial agreements and operational restrictions.

3.1. The One-to-one Problem Solution as a Dynamic Network Flow Problem

The proposed procedures for solving the distribution and consolidation problem under consideration is based on the minimization of the total logistics cost for an optimum size of cargo lots transported in two distribution networks: one many-to-one (or vice-versa) and the other, one-to-one. In addition to that, the many-to-one distribution problem can be reduced to a number of one-to-one problems, interconnected by a synchronisation (subsequent) in (each) the terminal T .

As already discussed in the related literature, these distribution and consolidation problems can be treated as dynamic network flow problems. These dynamic problems are characterised by the movement of cargoes (vehicles) from one location to another through time, which is represented by the flow in the space-time network associated to the physical distribution network.

The fact that it takes place “in time” means that, once the cargo, or vehicle (we call simply “cargo”) has left a location in the physical network at a certain instant of time, it can only reach another location, or return to the starting point, in a later instant of time. An arc joining two points of the space-time network will see each possible cargo movement. The first point represents the location in the instant of time of departure of the cargo and the second one represents the location (eventually the same) at a later time, when the cargo arrives there (or remains or returns). The movement of cargo through the network is represented by the flow in a succession of the arcs mentioned above, composing the possible routes of the network. The stay (warehousing or co-ordination wait) in a certain location is represented by arcs connecting two points in the space-time network relative to the same point in space and different instants of time.

This network has the characteristic of not having cycles. Its nodes are numbered so that the arcs have starting extremities with lower indexes than their final extremities that is, in each arc (i,j) , $i < j$.

Therefore, for a certain time horizon, the total number of possible movements can be represented by a network of arcs connecting its various points (associated space-time network). The space-time network is built starting from the logistics (sub) networks associated with the direct links of the original network of the problem. This space-time network is composed of nodes “location in time” and directed arcs and has the following characteristics:

- each node (i, t) represents a certain location (i) at a certain time (t) , and
- each directed arc represents a direct path with a length corresponding to W units of time connecting a pair of nodes.
There are, basically, three types of arc, according to the events they represent:
 - ♦ actual transportation arc – connecting the nodes (i, t) and $(j, t + W(i,j))$, $j \neq i$, and where:
 $W(i,j)$ is the length of time required to carry out the transportation in arc (i, j) of the logistics network;
 - ♦ obligatory stay arc – connecting the nodes (i, t) and $(j, t + tpo(i))$,
 $tpo(i) \neq 0$, $j = i+1$,
where $tpo(i)$ is the time period of obligatory stay of the lot in the node i of the logistics network;
 - ♦ intermediate warehousing arc – connecting the nodes (i, t) and $(i, t+W(i, i))$ where $W(i,i)$ represents the length of intermediate warehousing time period in node i .

The network is prepared for the application of the solution algorithm by the introduction of the “fictitious destination” node, connected by arcs with the same cost (null, for example) to the nodes “location in time” of the final destination of the export problem. The space-time network thus defined has properties that facilitate building it, reducing its size and, consequently, the complexity of the solution algorithm such as (Cavalcanti Netto, 1991):

- (I) possibility of covering definition in the space-time network by shipping line defined by the pair: date of departure of the first “ship”, frequency of trips in export ports (nodes);
- (II) existence of parallel arcs representing the same event, and

- (III) the size: the number of nodes and arcs of the network can be reduced (viable space-time network) by using the time limits (time windows) obtained from the contracted date of delivery of the cargo at its destination, of the dates of offer of the transportation services and date (earliest) of availability of the shipment at its origin.

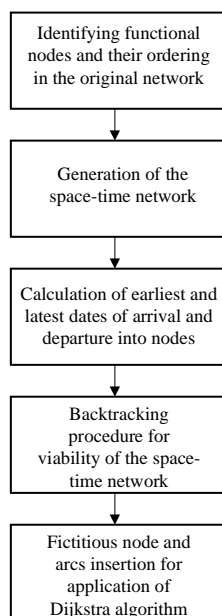


Figure 3- Preparation of the logistics network for problem solution

Figure 3 presents the sequence of steps that must be observed for preparing the logistics network for the application of the algorithm for problem solution. The points with more than one function in the physical network are viewed as divided prior to the construction of the space-time network (in the construction of the logistics (sub) network). Thus, in the space-time network, the nodes associated to a period of obligatory stay are divided in two, one of them a fictitious node. The arcs between these nodes are also fictitious, with transportation cost equal to the cost of obligatory stay in the node that originated them. The fictitious nodes do not originate intermediate warehousing arcs in the network. The time window at the destination will determine the feasibility in the space-time network of some “destination in delivery date” nodes. Only some “location in time” nodes meet the time window and are a part of the viable network.

The routing and stocking problem thus treated is, in fact, a problem of the shortest path between the “origin in the initial time “ and the “fictitious destination” in the space-time network. The intermediate warehousing costs and of obligatory stay in the nodes of this network are no longer associated to nodes and become associated to its arcs, as the actual transportation costs.

The viable network of each one of the $(n+1)$ actual routing problems with time window of homogeneous lots of cargo due to decomposition of real size export problems via consolidation centres is not larger than 5000 nodes. Its solution can be reached through the application of the shortest path algorithm between two points proposed by Dijkstra (see for example Minoux and Gondran, 1982) to the space-time network composed by viable nodes, with a cargo origin and a fictitious destination included in them. According to Bodin et al. (1983), up to that number of

search algorithms for the shortest path such as Dijkstra's have a good data processing performance, with no need for heuristics to reach a good solution.

3.2. The Synchronisation and Recomposition of the Logistics Network

To enable the forming of unique export lots in the consolidation terminal (centre) there should be a synchronisation of the times of arrival of the cargo lots at that point (node). Therefore, the limit date is defined compatible with the later date (possible) of availability of the already consolidated export lot. This later date is the link between the composition of the solution (final) of the problem, corresponding to the time constraint of the analytical model of the logistics network (Figure 3), which will be presented below.

The analytical model of the synchronisation and composition network of the final solution actually enables the evaluated strategy, and its formulation is based on the sequence of steps of the algorithm presented below.

Synchronisation and Recomposition Algorithm

The algorithm is developed according to the hypotheses:

- (a) Predominance (= choice) of the consolidation centre in relation to the other nodes to allocate the co-ordination activities between arrivals and departures;
- (b) Continuity of the land transport, that is, up to the consolidation centre, and
- (c) Generation of time windows for the consolidation centres so that the time constraints of the planning are complied with (e.g. time window at the destination, trip scheduling in the maritime transport, and earliest date possible (maximum) of availability of the cargo at the origins). The date of departure of the consolidated lot of cargo, calculated during the solution of the second step problem will be used as the upper (and rigid) limit of the time window of the problems of the first step, that is, the second sub-problem is treated as priority. It is important to emphasise that, in practice, the situation could be reversed, requiring re-evaluation of the solution procedure.

Step 1

Determine the time window in the potential centres of consolidation of the transport

$(d_{T_j}^{(i)}, t_{O_j}]$, so that

- (i) $t_{O_j} \in (d_{T_j}^{(i)}, dmt_{T_j}]$, and
- (ii) $d_{T_j}^{(i)} = \max_i (t_{T_j}^{(i)})$, $i \in O_j$

and further that (Condition of viability):

- (iii) $\max_i (t_{T_j}^{(i)}) \leq dmt_{T_j}$,

where

T_j = consolidation centre j , $j = 1, \dots, p$,

O_j = set of i nodes of origin with direct links to T_j ,

$d_{T_j}^{(i)}$ = earliest date of arrival of the i cargo shipments at T_j ,

t_{O_j} = date of departure of the unique cargo shipment from T_j ,

dmt_{T_j} = latest possible date of departure from T_j , and

$t_{T_j}^{(i)}$ = earliest possible date of arrival of the lot of i node at T_j .

Step 2

- (i) For each $i \in O_j$ determine $\delta_{T_j}^{(i)}$, the minimum waiting time of co-ordination at T_j , where

$$\delta_{T_j}^{(i)} = t_{O_j} - t_{T_j}^{(i)} \geq 0.$$

Step 3

Determine the total logistics cost C^*j through the expression:

$$C^*_j = \sum_{i \in O_j} (ca_{T_j} \cdot \delta_{T_j}^{(i)}) + \sum_{i \in O_j} (c^*_{i T_j} + c^*_{T_j D}), j = 1, \dots, p,$$

where:

ca_{T_j} = cost of the waiting of co-ordination at T_j per unit of time;

D = destination node of the export shipment;

$c_{i k}^*$ = total cost of the trip in the logistic path of the direct link (i,k).

Step 4

The solution of the problem is composed of the sequence of nodes $i \in R^*$ and of the programming of the dates of departure of the shipments at the nodes of the logistics network, where R^* is the route associated with the calculated total cost C_j^* .

4. Field Results for Validation of the Modelling Approach

4.1. Existing Situations

We can identify some existing situations in the Brazilian external trade that are benefited by a decision support system for management of the dynamic routing of containers. At first, we can focus on the situation of the Government Agency. Motivated by the goal of balance of the national economy, it can be interested in assessing the impact on cost and service quality of investments in transport infrastructure, port terminals and interior terminals for clearance services of the exports of a special steel in container. Or, in the export of coffee, the Agency can negotiate rates and tariffs differentiated to stimulate modal transfers of shipments to railway, or to reduction of the terminal handling costs (THC) in order to motivate the choice of certain port terminals in the export. According to the exporter, we can mention the coffee of Minas Gerais (Southeast of the country). The exporters prefer to consolidate the cargo in containers pre-cleared and sealed in special consolidation centres (dry ports) close to the origins and to transport them in convoys of trucks that only leave the dry ports when the ship moors in the port. With the reduction of the THC tariff for the cargo handling in certain ports, the exporters start to review their strategies, preferring to use them. The combination of strategies for transportation, Customs clearance, cargo loading, spatial and temporal consolidation and service level to the customer varies with the user of the system. The assessment of the cost (and of the opportunity) of the strategies resulting of the combination of different possibilities in the export can be undertaken with the support of these management systems.

Figure 4 schematises some of the situations we considered for the distribution and consolidation problems of the Brazilian external trade. T_1 , P_1 and P_2 are terminals qualified to accomplish Customs clearance and to consolidate the flow. P_3 is a consolidation centre and/or export port not qualified to clearance and T_2 is only capable to consolidate the flow. TO_1 and TO_2 are regional centres for cargo loading (and the inverse) in container. Each one of the situations corresponds to a distribution and consolidation problem whose resolution is equal to the definition of logistic paths of export through the proposed routing procedures.

When activities for cargo loading in container and consolidation of the export flow happen in different locations (as we can see in 4(a) of Figure 4), the sub-network of direct links between the origins of cargo, depots of empty containers and the central for loading containers are reduced to one node. This is an aggregated node of origin of containerised cargo. The corresponding network via terminal is simplified for the case observed in 4(b) (Figure 4). A latest date of departure of the cargo lot will be associated to this new origin as a result of the application of the two step procedures. In addition, the sub-network comprising the origins of cargo and of empty containers (A and B) and the centre for cargo loading (TO_1) corresponds to a new one-to-many distribution problem. Its solution will determine the logistics path by direct link consolidation centre/terminal-origin and the earliest dates of availability of the lots in the origins that make viable the cargo loading in container (and the posterior export).

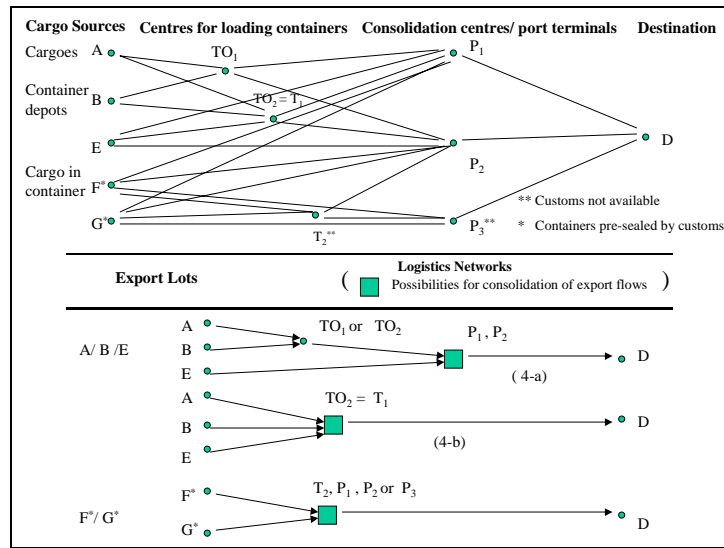


Figure 4- Brazilian situations observed in the exportation and their logistics networks

4.2. Field Results

The solution procedures and its associated algorithms have resulted of the analysis of the inherent characteristics of customer-controlled distribution and consolidation problems at the global trade. In this respect, the implemented algorithm has resulted of a previous survey of the experience and operations management of a Brazilian container operator and many maritime companies, as well as the European maritime transportation and global logistics provider CMA/CGM. These Companies provided the insights that allowed finding out key elements for the algorithm efficacy.

A simulated case study was built based on actual experience of Brazilian carriers and logistics providers in order to generate results to validate the computational core module of the solution approach. It corresponds to the second step of the decomposition strategy applied to the many-to-one distribution problems of Figure 4 (the unique one-to-one distribution problem terminal-destination). The data used was obtained in “averaged” values (Figure 5).

The study is related to the exports of coffee from the region close to Jundiaí in São Paulo (Brazil Southeast) under the logistics management and control of an operator of containers, which offices are located in São Paulo and in the neighbor State, in the City of Rio de Janeiro. This Company acts in the Brazilian external trade activities as a global freight forwarder or the logistic manager of the exports for its customers, many of them small-sized. The shipments originated in interior points of São Paulo's State are consolidated in homogeneous lots (and in containers) in the terminal of Pari (new origin of export lots), in the State's capital. The lots can, then, be exported through the terminal of containers TECON (Guarujá's City, in São Paulo) or the port of Rio de Janeiro, both in the logistics network of the Company, to a distribution centre in the port of Le Havre (France).

IMPRESSAO DOS DADOS SOBRE A REDE

REDE ORIGINAL DO PROBLEMA

NOS

CUSTO DE ARMAZENAGEM

TEMPO DE PERMANENCIA OBRIGATORIA NO NO

1

0.00

2

2	0.00	0
3	0.00	0
4	20.00	0
5	0.00	0
6	0.00	0
7	2.40	1
8	2.40	1
9	2.40	0
10	2.40	0
11	70.00	0

Portos de exportacao da rede original

No	Data da saida do navio	Intervalo entre saidas de navios(dias)
9	10	7
10	5	4

Arcos comecando no no	1	Custo de transporte	Tempo de viagem(dias)
1 - 2		160.00	1
1 - 3		150.00	2
1 - 5		510.00	2
1 - 6		520.00	2
Arcos comecando no no	2	Custo de transporte	Tempo de viagem(dias)
2 - 4		40.00	1
Arcos comecando no no	3	Custo de transporte	Tempo de viagem(dias)
3 - 4		30.00	1
3 - 7		140.00	1
Arcos comecando no no	4	Custo de transporte	Tempo de viagem(dias)
4 - 5		670.00	2
4 - 6		670.00	1
4 - 7		140.00	1
Arcos comecando no no	5	Custo de transporte	Tempo de viagem(dias)
5 - 8		30.00	1
Arcos comecando no no	6	Custo de transporte	Tempo de viagem(dias)
6 - 8		50.00	1
Arcos comecando no no	7	Custo de transporte	Tempo de viagem(dias)
7 - 10		115.00	1
Arcos comecando no no	8	Custo de transporte	Tempo de viagem(dias)
8 - 9		75.00	1
Arcos comecando no no	9	Custo de transporte	Tempo de viagem(dias)
9 - 11		2300.00	24
Arcos comecando no no	10	Custo de transporte	Tempo de viagem(dias)
10 - 11		2350.00	28

Nao ha arcos comecando no no 11

JANELA DE TEMPO NO DESTINO: [32 : 42]

A origem da remessa de carga de exportacao e o no: 1

O destino da remessa e o no: 11

A data de disponibilidade da carga e: 5

Figure 5- Data for the field test (in Portuguese, according to current data system)

The physical network of feasible arcs associated with the one-to-one distribution problem was composed of 11 (eleven) physical locations (nodes). The short-term planning horizon was equivalent to 38 time intervals (measured in mid-day). The transportation costs in the arcs of the original network were measured in US dollar/transported lot and the storage/warehousing costs in US dollar/time unit of stay in each node. The space-time network associated with the logistics network was generated by the executable version of the computer code VISUAL FORTRAN for IBM PCs. It had 1337 nodes "location in time", while the network prepared for the (final) application of the shortest path algorithm just had 78 nodes. The solution was obtained in less than 10 seconds (in reality, it includes the 8,18 seconds for initial ordering, generation of the space-time network, time restrictions calculation and backtracking, and preparation of the network for the application of that algorithm). This solution corresponds to the times of arrival and of departure of the singular homogeneous lot into/from locations of the optimal route between the origin/consolidation centre to the destination of the export that provides the minimum cost logistics path, as well as the time of stay (obligatory or coordination) in them (Figure 6).

O caminho de custo minimo foi encontrado
 O custo total do percurso de exportacao e 0.28E+04

CAMINHO DE CUSTO MINIMO DE EXPORTACAO

no(dia neste no)	sucessor(dia neste no)	Tempo de arma zenagem no no (dias)
1(5)	1(7)	2
1(7)	3(9)	*****
3(9)	3(10)	1
3(10)	7(11)	*****
7(11)	7(12)	1
7(12)	10(13)	*****
10(13)	11(41)	*****

FIM DO ARQUIVO

Figure 6 – Problem solution (in Portuguese, as generated by the current computational system)

The current computational system (Salie) corresponds to an optimized version of the original EXPORT (Cavalcanti Netto, 1991). It corresponds to the formalisation of the solution methodology of the one-to-one distribution problem. The basic information generated by the computer are stored and accessed based on lists of successors of the nodes, built for their physical, logistics and space-time networks (“generated”, “changed” and “prepared” according the characteristics of the problem). Dijkstra’s algorithm is applied in determining the shortest path. Its implementation met the restrictions of speed of execution and utilisation of work memory compatible with the available space in PCs.

5. Concluding Remarks

The consolidation of the flow of containers according to space and time dimensions means its orientation towards a composition of cargo lots in certain locations of the logistics network and, from there, to handle the consolidated flow, in order to accomplish economies of scale in long-distance cross-borders transportation systems. From this viewpoint, the problem corresponds to the case of the many-to-one distribution through the consolidation (or Customs) centre (or “shipping via consolidation terminal”).

According to the proposed procedures and modelling framework, optimal logistic routes for this distribution problem results of the synchronisation of (n+1) one-to-one routing problems with time windows of homogeneous cargo lots that are or can be containerised, undividable and small in size. A decisive choice factor for the approach of dynamic networks to model and solve these one-to-one problems is the ease with which it can be included in the model changes in the variables and restrictions resulting from the adjustments and new requirements in the decision context. The dynamic routing procedures defined to solve the routing and scheduling of containers problem is characterised by being very easily reprogrammed. It is possible to identify possible extensions of the problem by including new hypotheses (for example: to discontinue all the transportation services, strategy of re-defining the routes in situations of delay) with, consequently, no relevant impact on the procedures, in the models and solution algorithms.

The implemented computer system was based on the procedures detailed in the sections of this paper (a lexicographical-type ordering and a backtracking procedure for reducing of the number of nodes for the viability of the network prepared to apply the algorithm of shortest path). It applies to original networks of equivalent size to the network expanded (space-time) potential, which means 3600 nodes (value limited by the chosen planning horizon of 60 intervals of time). Results of computational implementation (in C++) of algorithms applied to solve shortest path with time window problems in dense graphs of 5000 nodes are available in

the recent literature (Cunha and Swaitt, 2000). These results reinforce the efficacy of the proposed procedures and its current implementation for routing with time window problems involving consolidation of flows in its general many-to-many version. In this respect, the distribution and consolidation problem considered had better to be generalised as a network flow problem of lots of products, or of batches of communication protocols.

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