A MULTIPERIODIC VEHICLE ROUTING PROBLEM IN THE CONTEXT OF REVERSE LOGISTICS: A MODELING FRAMEWORK

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Abstract: This paper considers a multiperiodic vehicle routing problem for reverse logistics. A logistics network with *n* stores, *r* warehouses and a heterogeneous fleet of vehicles is defined. The network comprises three different flows: a direct one from warehouses to stores, a reversed one from the stores to warehouses and an internal one between stores and warehouses. We present a classical direct formulation of the model as well as a set partitioning formulation. We propose hybrid methods to solve this problem, using the column generation technique, where sub problems are solved with constraint programming techniques.

Keywords: Reverse logistic, Operational Logistics, Transportation systems.

1 Introduction

"Reverse Logistics", as defined by the "American Reverse Logistics Executive Council" (Rogers and Tibben-Lembke, 1998) is: "*The process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or of proper disposal*".

More and more manufacturers are confronted to the problem of "Reverse Logistics". Many different elements can be returned to their point of origin (warehouse, plant, etc.): products having reached their end of life, products to be repaired, packaging, spare parts, etc. Different reasons led manufacturers to design a reverse logistic system: legislation evolution, commercial advantage, environmental issues, etc. For example, a very recent European law (July 2005) forces manufacturers of equipments (household electrical appliances, consumer electronics, telephony, data processing) to take into account the treatment of the waste of their products, recycling and possible elimination. Moreover, reverse logistics can engender several types of recovering activities: product recovery, component recovery, material recovery and energy recovery.

In this paper we consider the problem of the optimization of transport activities and inventory management in a two levels network composed of warehouses and stores. Three types of flows have to be considered over a multiperiodic planning horizon: direct flows from manufacturers to clients, reverse flows from clients to manufacturers and "internal" flows between stores and between warehouses. Because of its combinatorial complexity we propose to solve our problem using hybrid methods (combining constraint programming and operations research techniques). Constraint programming (from artificial intelligence) and linear programming (from operations research) are two complementary techniques, to solve combinatorial optimization problems. Recent works for really hard real-life problems involve hybrid techniques that efficiently combine the advantages of the two methods.

In this paper, we will first review the literature on related topics. Then we will expose our model and detail our solution approach for a single depot version of our model.

2 Literature Review

Two lines of work are of interest in our particular problem. First, we will review techniques used for solving vehicle routing problems and reverse logistics problems (this review is based on Bostel et al. (2005)); we will focus our study to the operational level of reverse logistics. Second, we will review classical hybrid approaches used to solve vehicle routing problems. However as far as we know, none exist for reverse logistics problems.

2.1 Vehicle Routing Problem and Reverse Logistics

Our problem is linked to the Vehicle Routing Problem (VRP) and particularly to the Inventory Routing Problem (IRP). In this kind of problem the routing problem and the inventory problem are solved together. A review of the hierarchical approaches (allocation then routing) can be found in Ball (1988).

In this field, some works are in relation to reverse logistics. Crainic et al. (1993) proposed a multi-periodic and stochastic model for the allocation of empty containers in the area of transportation planning of containerized goods. Their model was applied to land transportation of maritime containers for international trade. Del Castillo and Cochran (1996) studied production and distribution planning for products delivered in reusable containers. The return of containers is a constraint for the production system. Krikke et al. (1999) studied the recycling of computer screens for the ROTEB company. The purpose is to analyze the economic viability of screen recycling and to validate the viability practice models. Duhaime et al. (2001) analyzed the problem of reusable containers for Canada Post. They used a minimum cost flow model showing that stock out can be avoided if containers are returned quickly. Feillet et al. (2002) studied the problem of the tactical planning of interplant transport of containerized products. They developed vehicle routing models with gains aimed at determining interplant circuits for the combined transport of containers and the positioning of empty trucks. They applied their models to a real case in the automotive industry.

2.2 Hybrid Methods for the VRP

Several hybrid techniques have been proposed for solving vehicle routing problems. Caseau and Laburthe (1998) proposed a method to solve large VRP (thousands of customers and hundreds of vehicles). Their method kept the advantages of an insertion method (flexibility and adaptability) but they proposed some improvement regarding the quality of the solutions. Instead of using a local search when a solution is built they applied the principle of progressive local optimization and used the 3-opt method for improvement at each insertion. Rousseau et al. (2002) used constraint programming to solve the sub-problem in a column generation approach. Indeed, in order to solve the VRPTW (Vehicle Routing Problem with Time Windows) with column generation they solved a shortest elementary route problem with constraint programming. They developed a new constraint named CBC (Can Be Connected) which can be used to solve TSP (Traveling Salesman Problem) or VRP (Vehicle Routing Problem) instances.

To the best of our knowledge, no work combining the three different types of flows simultaneously on a multi-periodic context have been published. Moreover, good results obtained by hybrid approaches to somewhat related problems incite us to use them in order to solve our problem.

3 Modeling Framework

In this section, we present the general framework we used to express our problem.

3.1 Description of the general problem

We consider n stores, r warehouses and a single product. Each store i has a given storage capacity of products Sm_i. Each warehouse j has a storage capacity of products C_i (this capacity may be infinite). Deliveries from the warehouses to the stores are made through the use of a fleet of v (possibly unlimited) identical vehicles. Vehicles are not allocated to a particular warehouse; they may depart from and return to any warehouse. The delivery planning is scheduled on a H days period. Each store i is able to provide a forecasted demand D_i^t for a given day t. Future store demands are updated at the end of each day according to the real volume V_i^t of sales realized on that day. Orders are processed on day t. Products are packaged onto pallets containing γ items.

Five different movements are possible in this system:

- Products delivered from the warehouses to the stores on pallets at day $t+1$.
- From day $t+2$, empty pallets may return from stores to one of the warehouses in order to be reused in the packaging of new products.
- According to the updates done on the projected demands, product balancing may occur for stock in stores. If one store has an excess of products due to an over estimation of the demand, the surplus of stock can be transferred to another store which needs products. This flow is called internal *flow*.
- Customers buy products in the stores. They can return their products if they are not satisfied up to α days after the purchase date. When one product is returned to the store, it is subsequently returned to one of the warehouses to be re-packed. Then it can come back in one store β days after its return to any of the warehouses.
- According to warehouses availability, empty vehicles and empty pallets can be transferred to move from warehouse to warehouse.

Figure 1 illustrates the type of network studied.

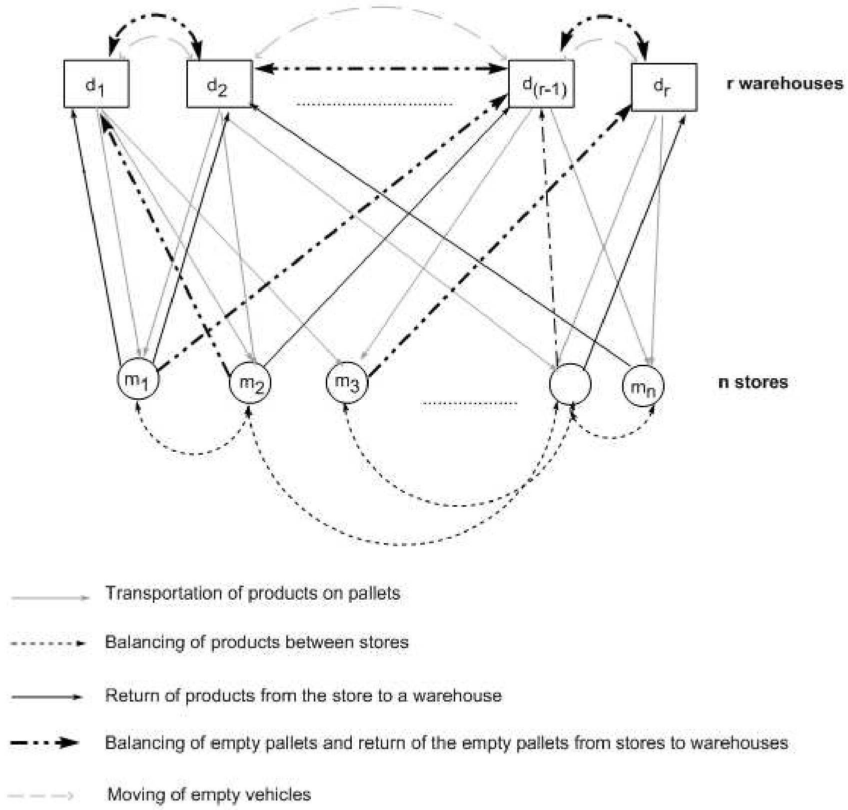

Fig.1. Representation of the logistics network

The overall goal is to minimize the sum of routing and storage costs over the planning period. Routing costs can be divided into two parts: a fixed cost of using one vehicle and a variable cost based on distance. Storage costs are the combination of storage costs in the warehouses and storage costs in stores for loaded pallets, empty pallets, and returned products.

3.2 First Restricted Mathematic Model

The following formulation is developed as a modeling tool but it will not be the bases of solution techniques. As stated before, we restrict the model presented in this paper to a single warehouse network with unlimited capacity and a homogenous fleet of vehicles *i.e.* $r=1$ and $C_1=\infty$. We consider $I=n+1$ "stores" (i = 0 … I) (as store 0 will represent the warehouse). We consider a planning horizon $H = T+1$ (t = 0 ... T). The fleet is composed of $v = V+1$ vehicles (v = 0 ... V).

As in the general model, each store i has a storage capacity Sm_i, a projected demand D_i^t for day t and an actual sale amount V_i^t. Service time for store i (Corresponding to the necessary time to treat its demand: load time plus unload time…) is s_i. Store i has S_0^i products at the beginning of the day 0. Store i is required to maintain at least $Smin_i$ items of product in stock. Store i may be visited during time window $[e_i,l_i]$. Store i is separated from store j by d_{ij} kilometers (this also works for store 0 the warehouse). For a given day t, r_i^t pallets are returned from clients to store i.

The warehouse supply rate is $Appro_0$ in products per day.
Each vehicle has a storage capacity Sv_v and runs at the speed k kph.
Vehicle related costs are the following:

- each vehicle v has a fixed cost (when used) Cf_v.
- each vehicle v has kilometric cost Cv_v.
- loading and unloading costs respectively Cl and Cu.

Storage related costs are the following:

- daily storage cost $Cpdt$ for products
- daily storage cost $Cpal$ for pallets

Some fixed necessary information is provided regarding volumes:

- an empty palette occupies a units of surface
- a full palette occupies b units of surface
- $txPalV$ represents the number of empty pallets in a full pallet.

We define the following variables:

$XNd^t{}_0$: storage level in the warehouse at the beginning of the day t.
$XNm^t{}_i$: storage level of full pallets in the store i the day t.
$Xpal^t{}_i$: storage level of empty pallets in the store i the day t.
$XPdt^t{}_i$: storage level of products which must be returned form store i to the warehouse.
$XNv^t{}_{vi}$: storage level in vehicle v upon its arrival at store i on day t.
$XI^t{}_v$: number of visited stores by vehicle v at the day t.
$x^t{}_{ii'v}$: binary variable equals to 1 if the vehicle v visited store i' immediately after store i on day t, 0 otherwise.
$Y^t{}_v$: binary variable equals to 1 if vehicle v is used on day t, 0 otherwise.
$\mathrm{Xappro}^t{}_{iv}$: number of full pallets delivered to store i by vehicle v on day t.
$z^t{}_{iv}$: number of empty pallets taken by vehicle v from store i on day t to the warehouse.
$W^t{}_{iv}$: number of products taken by vehicle v from the store i on day t to the warehouse.
$B^t{}_{ii'v}$: number of products taken from store i to store i' on day t with vehicle v.
$T^t{}_{iv}$: visiting instant to store i by vehicle v on day t.

The objective of this model is to minimize the total storage and routing costs. The overall mathematical program is presented below:

$$
\begin{aligned}
\min f = {} & (\sum_{i=1}^{I}\sum_{t=1}^{T}(Cpdt \times (XNm_i^t + XPdt_i^t) + Cpal \times XPal_i^t)) \\
& +(\sum_{t=1}^{T}(Cpdt \times (XNm_0^t + XPdt_0^t) + Cpal \times XPal_0^t)) \\
& +(\sum_{v=1}^{V}\sum_{t=1}^{T} y_v^t Cf_v + \sum_{i=0}^{I}\sum_{\substack{i'=0 \\ i'\neq i}}^{n}\sum_{v=1}^{V}\sum_{t=1}^{T} x_{ii'v}^t Cv_v d_{ii'}) \\
& +(\sum_{i=0}^{I}\sum_{t=0}^{T}\sum_{v=0}^{V}(Cl + Cu)(\frac{z_{iv}^t}{txPalV} + \frac{w_{iv}^t}{txPal} + \sum_{i'=0}^{I}\beta_{ii'v}^t + XAppro_{iv}^t))
\end{aligned}
\tag{1}
$$

Subject to:

$$\forall i > 0 \quad \forall t \quad aXPal_i^t + cXPdt_i^t + bXNm_i^t \leq Sm_i \tag{2}$$

$$\forall i > 0 \quad \forall t \quad XNm_i^t \geq Smin_i + D_i^{t+1} \tag{3}$$

$$\forall i > 0 \quad \forall t \quad XNm_i^{t+1} = XNm_i^t - V_i^t + \sum_{v=1}^{V}\sum_{i'=1}^{I} \beta_{i'iv}^t - \sum_{v=1}^{V}\sum_{i'=1}^{I} \beta_{ii'v}^t + \sum_{v=1}^{V} XAppro_{iv}^t \tag{4}$$

$$\forall v \forall t \forall i \quad Sv_v \geq XNv_{vi}^t - b \times XAppro_{iv}^t - b\sum_{i'=1}^{I} \beta_{i'iv}^t + b\sum_{i'=1}^{I} \beta_{ii'v}^t + c \times w_{iv}^t + a \times z_{iv}^t \tag{5}$$

$$\forall t \forall v \quad M > 0 \quad y_v^t \leq \sum_{i=0}^{I} \sum_{\substack{i'=0 \\ i' \neq i}}^{I} x_{ii'v}^t \leq My_v^t \tag{6}$$

$$\forall i > 0 \quad \forall t \quad XPal_i^{t+1} = XPal_i^t - \sum_{v=1}^{V} z_{iv}^t + \frac{V_i^t}{txPal} \tag{7}$$

$$\forall i > 0 \quad \forall t \quad XPdt_i^{t+1} = XPdt_i^t - \sum_{v=1}^{V} w_{iv}^t + r_i^t \tag{8}$$

$$\forall t \forall v \forall i \quad M >> 0 \quad \sum_{\substack{i'=1 \\ i' \neq i}}^{I} x_{ii'v}^t \leq (z_{iv}^t + w_{iv}^t + XAppro_{iv}^t + \sum_{i'=1}^{I} \beta_{i'iv}^t) \leq M \sum_{\substack{i'=1 \\ i' \neq i}}^{I} x_{ii'v}^t \tag{9}$$

$$\forall i \forall t \forall v \quad \sum_{\substack{i'=0 \\ i' \neq i}}^{I} x_{ii'v}^t = y_{iv}^t \tag{10}$$

$$\forall i \forall t \forall v \quad \sum_{\substack{i'=0 \\ i' \neq i}}^{I} x_{i'iv}^t = y_{iv}^t \tag{11}$$

$$\forall t \forall v \quad \sum_{i=1}^{I} \sum_{\substack{i'=1 \\ i' \neq i}}^{n} x_{ii'v}^t \leq XI_v^t - 1 \tag{12}$$

$$\forall t \qquad XNd_0^{t+1} - XNd_0^t = a\sum_{v=0}^{V}\sum_{i=1}^{I} z_{iv}^t + b\sum_{v=0}^{V}\sum_{i=1}^{I} w_{iv}^{t-\beta} - b\sum_{v=0}^{V}\sum_{i=1}^{I} XAppro_{iv}^t + c\sum_{v=0}^{V}\sum_{i=1}^{I} w_{iv}^t + Appro_0 \tag{13}$$

$$\forall t \quad \sum_{v=0}^{V}\sum_{i'=1} x_{0i'v}^t \leq V \tag{14}$$

$$\forall t \quad \sum_{v=0}^{V}\sum_{i'=1} x_{i'0v}^t \leq V \tag{15}$$

$$\forall t \forall v \forall i \in XI_v^t \qquad e_i \leq T_{iv}^t \leq l_i \tag{16}$$

$$\forall t \forall v \forall i \forall i' \quad M \gg 0 \quad (1 - x^t_{ii'v})M \geq T^t_{iv} + s_i + kd_{ii'} - T^t_{i'v} \tag{17}$$

$$\forall v \forall t \quad y^t_v \in [0,1] \tag{18}$$

$$\forall i \forall i' \forall v \forall t \quad x^t_{ii'v} \in [0,1] \tag{19}$$

$$\forall i \forall i' \forall v \forall t \quad \beta^t_{ii'v} \in \mathbb{N} \tag{20}$$

$$\forall v \forall i \quad w^t_{iv} \in \mathbb{N} \tag{21}$$

$$\forall v \forall i \quad z^t_{iv} \in \mathbb{N} \tag{22}$$

- Constraint 2 expresses the fact that for each store, each day, the total volume must not exceed the capacity storage of the facility.
- Constraint 3 ensures that if the store is serviced at the end of the day, its stock meets the projected demand for the next day.
- Constraint 4 computes stock at day *t+1* (for a given store) considering stock of full pallets at day *t*, sales of day *t*, transfers to another store and deliveries from the warehouse.
- Constraint 5 considers storage levels in vehicles. It insures that when servicing a store, a vehicle does not leave (considering the delivery, the pallets to be transferred to another store, the material to be returned to the warehouse) while exceeding its storage capacity.
- Constraint 6 applies when a vehicle is used to link two stores.
- Constraint 7 considers the empty pallets in a store at day *t+1* by considering the previous empty pallets stock, the vehicle collection, the empty pallets due to sales.
- Constraint 8 considers the same relations for returned pallets.
- Constraint 9 enforces coherence between variables related to vehicles and their activity.
- Constraint 10 (resp. 11) imposes that at most one store is visited immediately after (resp. before) store *i* by vehicle *v* on day *t*.
- Constraint 12 avoids sub-tours.
- Constraint 13 controls the level of stock in the warehouse on day *t+1* considering the level of day *t*, returns from stores (empty pallets and returned products) and deliveries.
- Constraints 14 and 15 limit the number of tours to *V* each day.
- Constraint 16 ensures the time window observance.
- Constraint 17 is used to compute the visiting date for each store.

3.3 Second Mathematical Model and Solution Technique

We aim at solving large real life applications using our model. We present below a partitioned model and column generation techniques that will be more appropriate to the solution of large problem. We first define two notations that will be used after: a *route* is a feasible order of visiting sites with the quantity of products collected, transferred and picked-up which respects the capacity of the vehicle, the time windows of the sites (Constraints: 5, 10, 11, 12, 16 in part 3.2); a *sequence* is a planning of visiting days for one site which respects: the safety level of storage and the capacity of the site (Constraints: 2, 3 in part 3.2). In order to facilitate the understanding of our model, let us first introduce the set partitioning formulation and column generation techniques. Column generation was first introduced by the work of Gilmore and Gomory (1963). We can find a description of this method in Barnhart et al. (1998). To explain the column generation method we first use a simple routing example where all the clients must be visited (first constraint) and the number of vehicles is restricted (second constraint).

$$\begin{cases} \text{Minimize} : z = \sum_{r\in\Omega} c_r.x_r \\ \text{Subject to} : \\ \forall i \in N \quad \sum_{r\in\Omega} x_r a_{ir} = 1 \\ \sum_{r\in\Omega} x_r \le M \\ x_r \in \{0,1\} \end{cases}$$

where we consider:

- Ω: the set of feasible routes
- M: the number of available vehicles
- A: matrix of binary coefficients a_{ir} equals to 1 if the client i is in the tour r.
- c_r: cost of the route *r.*
- x_r: binary variables equal to 1 if the route r is realized, 0 otherwise.

This so called master problem comprises a large number of columns. The technique therefore involves solving a linear programming relaxation involving only a subset of the columns of matrix *A*. New columns are generated as needed when their reduced costs are negative. These columns are generated by a sub-problem.

Let us now turn to our original problem, constraints 2, 3, 14 and 15 expressed in part 3 will provide the structure of the master problem. The others, related to determine a valid route for a given vehicle and sequences of visiting days will lead to the sub-problems to be solved in order to provide the successive columns needed for the optimization of a linear relaxation of the master problem. In this decomposition, the *A* matrix can be represented in the following way:

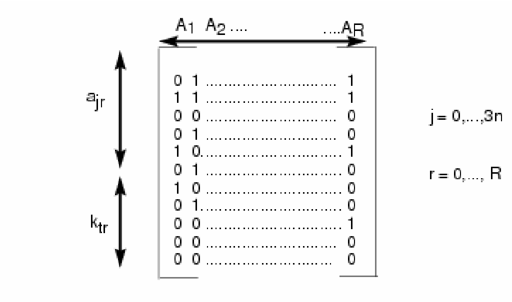

Fig.2. Matrix A

Columns in our model will be devoted to routing (for a vehicle) and sequence of visiting days. They will be generated as solutions of a constraint satisfaction problem. Let Ω_1 be the set of feasible routes for the problem and Ω_2 the set of feasible sequences. Each valid route respects the capacity of the vehicle, the time windows of the stores and visits each store at most once. Let us make the following notations to describe the features of the routes regarding product delivery, product pick-up or to-be-returned materials pick-up. We therefore consider the three following sets of 0-1 constants:

- a_{3ir} equal to 1 if route *r* visits store *i* for a product delivery and *0* otherwise,
- $a_{(3i+1)r}$ equal to 1 if route *r* visits store *i* for a product pick-up, *0* otherwise
- $a_{(3i+2)r}$ equal to 1 if route *r* visits store *i* for a materials collection, *0* otherwise.

With this information, it is possible to determine in which day vehicle *r* can be used. This is reported in variable k_{tr} which is equal to 1 if route *r* can be executed on day *t* and *0* otherwise**.** In the same way we have b_{3ts}, $b_{(3t+1)s}$, $b_{(3t+2)s}$ which are sets of 0-1 constants which respectively represent the quantity of product delivered, picked-up and transferred by the sequence s the day t. A cost c_r is associated to route r and a cost c_{is} is associated to the sequence s for the site i. Let be x_r a variable equal to 1 if the route r is used in the optimal solution and equal to 0 otherwise and θ_{is} a variable equal to 1 if the sequence s is associated to the site i and equal to 0 otherwise. The objective is to minimize the storage and routing costs. We have DS_{ist} and DR_{ir} which respectively represent the quantity of products delivered to store i on day t by sequence s and the quantity of products delivered to store i by route r. In the same way, we have PS_{ist} and PR_{ir} for the quantity of material picked-up and TS_{ist} and TR_{ir} for the products transferred between stores.

Our master problem can be now written like this:

$$\text{Min} : z = \sum_r c_r x_r \quad + \quad \sum_i \sum_s c_{is}\theta_{is} \tag{1}$$

$$\text{Subject to :}$$

$$\forall i \quad \sum_s \theta_{is} \quad = \quad 1 \tag{2}$$

$$\forall t \quad \sum_r k_{tr} x_r \quad \leq \quad V \tag{3}$$

$$\forall i \forall t \quad \sum_r DR_{ir} a_{3ir} k_{tr} x_r \quad - \quad \sum_s DS_{is} b_{3ts} \theta_{is} = 0 \tag{4}$$

$$\forall i \forall t \quad \sum_r PR_{ir} a_{(3i+1)r} k_{tr} x_r \quad - \quad \sum_s PS_{is} b_{(3t+1)s} \theta_{is} = 0 \tag{5}$$

$$\forall i \forall t \quad \sum_r TR_{ir} a_{(3i+2)r} k_{tr} x_r \quad - \quad \sum_s TS_{is} b_{(3t+2)s} \theta_{is} = 0 \tag{6}$$

In this model the objective (1) is to minimize the routing and storage costs while respecting constraints. The first constraint represents the fact that one store has only one sequence. The second ensures that at most V vehicles are used. And finally, the three following constraints express the fact that the quantities determined in the route must be in coherence with these determined in the sequence for the deliveries (4), picks-up (5) and transfers (6).

Alternatively to the frequently used dynamic programming approach, we propose to solve the sub-problems with constraint programming techniques. To that purpose, we are developing a routing dedicated constraint (taking into account vehicle capacity, time windows, etc.) in order to generate accurate and efficient routes. We expect that this will unable us to solve the sub-problems efficiently.

4 Conclusion

We propose a new model for a multiperiodic vehicle routing optimization problem in a network including reverse logistics. Three types of flows are considered simulteanously. We propose a set partitioning model using two types of columns for a version of the problem limited to one warehouse. We use the column generation technique to solve the model, where sub problems are solved with constraint programming techniques. We will then develop a Branch and Price technique for solving the full model.

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6 Biography

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Narendra JUSSIEN is deputy-head of the Constraint Programming team at Ecole des Mines de Nantes. He obtained his PhD in computer science from Rennes University (France). In 2004, he became president of the French Constraint Programming Association. His main research interests are hybrid techniques combining OR and CP approaches.

Zhiqiang LU obtained his Ph.D. at the Ecole des Mines de Nantes / IRCCyN in 2003. His thesis was on Hierarchical Planning and Optimization of Logistic Systems with Reverse flows. He is now an Assistant Professor in Operations Research and Logistics at Shanghai Jiao Tong University.