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An Integrated Inventory Location Routing Problem Considering CO_2 Emissions

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Abstract

This paper considers an integrated Inventory Location Routing problem ILRP which consists of optimizing the operating costs, risks and routing's CO_2 emissions related to a Hazmat supply chain. The goal is to determine: the location of a set of capacitated depots to open, customers allocated to them, quantities delivered from these depots to customers per period, and the sequence in which customers are served by a heterogeneous fleet of vehicles. To solve the problem, an exact bi-objective model is designed and tested for small and medium size instances. A case study is proposed to prove industrial practicality of the model. The results show that the proposed solution resolves decently the medium size instances.

Keywords: Supply chain design, Inventory-Location-Routing Problem, Green Routing, Bi-objective model, Case study

1 Introduction

Logistics management is a making decision approach used to govern supply chain functions, in order to distribute goods according to customers demand and taking into consideration various constraints including cost reducing.

The design of efficient supply chains has become more challenging in view of environmental regulations, especially for Hazmat supply chain. Companies must making decisions on facility location, inventory management, and distribution while considering the environmental impacts of these decisions. Some decisions may conflict, such as storage and transport decisions. In fact, in order to comply with regulations and risk management policies at the storage level, fixed installations may reduce their fixed stocks by increasing the number of delivery which would increase the risk and CO_2 emissions at the transportation level (de Marcellis-Warin et al.2013) [6]. That's why it's important to integrate the strategic, tactical, and operational decisions in order to minimize costs, risks, and CO_2 emissions.

In this paper we study an Integrated location routing problem (ILRP) with heterogeneous fleet and considering a multi-period decisions. The objective is to optimize location and opening costs of depots, distribution and inventory management, with considering transport and storage constraints of a Hazmat case and routing's CO_2 emissions.

Therefore, Section 2 reviews the literature on the integration of three decisions level (strategic, tactical and operational).The mathematical model of the problem and the computational study are provided in Section 3. A real case application is described in Section 4 and finally, Section 5 is devoted to conclusions and future research.

2 Literature review

Researchers classify the decisions for supply chain management into three categories: strategic, tactical, and operational. The classical approach for optimization of logistics systems is the decomposition into sub problems according to these decision levels. This approach has many advantages such as simplification of modeling and problem solving techniques. However, this can often lead to a sub optimality of solutions because it doesn't take account of the whole problem (Prodhon 2006) [15]. Several researchers studied the benefits of integration of supply chain decisions.

In the literature, many papers integrate two supply chain levels decisions. Location-Routing Problem (LRP) combines two decision levels, a strategic level which is the facility location and operational or tactical level associated to the vehicle routing problem (VRP). Laporte (1992) [11] presents a first classification of this problem; other reviews have been made in this direction by Nagy and Salhi (2007) [14], and more recently by Prodhon and Prins (2014) [16]. Another case is Inventory-Routing Problem (IRP), this problem integrates inventory management (tactical level) and vehicle routing (operational level), it was surveyed in (F. Baita et al. (1998) [3], A. Kleywegt et al. (2002) [10], M.Vidovic et al. (2014) [23]). Finally, the integration of facilities location problem and inventory management is named Inventory-Location Problem (ILP), Daskin et al. (2002) [5] and Shen (2005) [19] studied different variants of ILP.

Recently, the progress of operations research and computer science encourages researchers to think to solve more complex and larger problems, and thus have a more global vision of supply chain problems. This will help to anticipate interactions between decisions levels. The Inventory Location-Routing Problem (ILRP) can be seen as an approach to integrate the three components (depot location, vehicle routing and inventory management) into one model, in order to optimize the supply chain design and minimize the total costs. Considering stochastic demand, Lui and Lee (2003) [12] and Liu and Lin (2005) [13] presented a location-routing problems (LRP) including nonlinear inventory costs in the objective function. They consider a single product and multi-depot with unlimited capacity. To solve this problem, Lui and Lee (2003) [12] used a two-phase heuristic method, and Liu and Lin (2005) [13] proposed a hybrid heuristic based on the Tabu Search (TS) and Simulated Annealing (SA). Another nonlinear stochastic model is studied by Shen and Qi (2007) [20] to integrate the location, inventory, and the routing approximate costs. Javid and Azad (2010) [1] present a stochastic model to find simultaneously the decisions of location, allocation, inventory at depots and routing. The authors propose, an exact solution and then a heuristic method based on hybridization of tabu search (TS) and simulated annealing (SA). For deterministic demand, Ambrosino and Scutella (2005) [2] use a linear programming relaxation for the ILRP. Hiassat and Diabat (2011) [9] studied an inventory location routing problem with deterministic demand for perishable product. They propose a multi-period model formulated as Mixed Integer Program (MIP). Recently, Guerrero et al. (2013) [7] present an algorithm for a multi-period ILRP with deterministic demand. They propose a hybrid approach to optimize simultaneously location of depots, allocation of retailers to depots, inventory at both depots and retailers, and multi-period routing. The algorithm optimizes globally the components of the problem by sharing information between decisions levels. Guerrero et al. (2015) [8] investigate a relax and price heuristic for the same problem. They coordinate the generation of new columns in the pricing problem and update of Lagrangian multipliers. Results show important cost savings and efficient computation if compared to the previous heuristics.

We can note that little research has been done to study solution methods for the ILRP especially in comparison with the integration of two supply chain levels decisions. And there is no work, to our knowledge, that incorporate environmental aspects and a heterogeneous fleet.

In our case, we study an ILRP for Hazmat with inventory decisions at clients and considering multi-period decisions with random data inspired from our real case problem. The main contribution of this work is the integration of CO_2 emissions in the objective function and considering a heterogeneous fleet.

3 Problem definition and model formulation

We consider a supply chain design problem, in which, we have to distribute a hazardous product from a single manufacturer to a set of customers, through a set of intermediate depots with heterogeneous fleet. The goals that will be taking into account in this model are to minimize both of the total cost and the routing CO_2 emissions. The first objective function includes the followings costs: (i) the opening and operating costs of depots, (ii) the delivering cost from depots to customers, and (iii) the inventory costs at customers level. The second objective function minimizes the CO_2 emissions.

Let I denote the set of m candidate depots, J the set of n customers, and T the set of p periods in the planning horizon, V a set of vehicles types indexed by v.

For each $i \in I$ let O_i be the cost of opening a depots at site i and let Cap_i be its capacity. Each customer j has a deterministic and non-constant demand d_{jt}, $\forall t \in T$. Consider R as the set of all feasible routes with at most a fixed number of customers. A route starts from the depot, visits a subset of customers at most one time and then returns to the depot. The routes are generated before solving the model, and thus allows subtour constraints elimination. z_{jr} and w_{ir} are respectively defined as follows: for each route $r \in R$ and customer $j \in J$, z_{jr} is equal to 1 if route r visits customer j and 0 otherwise, and for each route $r \in R$ and depot $i \in I$, w_{ir} is equal to 1 if route r begin from depot i and 0 otherwise. A capacity Cp_r and a routing cost C_r are associated with each route $r \in R$.

The following are the main assumption of the presented model.

- The demand of customers is deterministic.
- Inventory level at customers and depots is limited in order to take into account the storage constraints of hazardous products.
- A route starts and terminates at the same depot, and visits at less one client
- Vehicle fleet is heterogeneous (different capacities).
- A customer demand is supplied by only one distribution center.
- Depots and costumers have a limited storage capacity.

Our model integrates the location problem with the inventory and routing problem, taking into account capacity constraints, and the distribution CO_2 emissions.

Parameters

N_v Number of vehicle type $v \in V$
O_i Opened cost of depot $i \in I$
C_r Transportation cost of route $r \in R$
f_{jt} Inventory holding cost of customer $j \in J$ in time period $t \in T$
Cp_r Capacity of route $r \in R$ (equal to the capacity of the vehicle assigned to the route r)
$z_{jr} = 1$ If route $r \in R$ visits customer $j \in J$
$w_{ir} = 1$ If route $r \in R$ visits depot $i \in I$
d_{jt} Demand of customer $j \in J$ in time period $t \in T$
S_{j0} Inventory level at customer $j \in J$ at the beginning of time period $t = 1$
S_{max} Maximum inventory level at customers

Cpd_i Maximum storage capacity at depot i
bv_r=1 If route r∈R is deserved by vehicle type v and 0 otherwise
$ECO2_r$ CO_2 emissions quantity of a route r ∈R

Decisions variables

X_i = 1 if depot i ∈ I is opened and 0 otherwise
Y_{rt} =1 if routes r ∈ R is selected in time period t∈T and 0 otherwise
S_{jt}= Inventory holding of customer j∈ J in the end time period t ∈ T
Q_{jrt}= Quantity delivered to customer j∈ J by route r ∈ R in time period t ∈ T

The hazardous materials regulations limit the storage and the transportation quantities and this increase frequency of transportation, and thus augment the environmental impacts due to CO_2 emissions. That is why we decide to add this environmental impacts in the objective function. The estimation of CO_2 emission for transportation requires complex calculations, which can only represent an approximation because of the difficulty of quantifying some variables as driving style, weather conditions, congestion, and the like (Palmer, 2007 [17], Van Woensel et al., 2001[22]). To calculate the emissions factor CO_2 we use a similar method as that used in S. Ubeda et al. (2011) [21].Table 1 shows the emissions factor for several capacity scenarios between full loaded and empty vehicles. To calculate the CO_2 emissions quantity of a route r, we multiply the emissions factor by distance.

Table1- Estimation of CO_2 emission factors

State of the vehicle	weight laden (%)	consumption (l/100 km)	fuel conversion factor(kg CO_2/l)	Emission factor Kg CO_2/km
Empty	0	29.6	x2.61	0.773
Low loaded	25	32.0		0.831
Half loaded	50	34.4		0.9
High loaded	75	36.7		0.958
Full load	100	39.0		1.018

Model

$$min \sum_{i\in I} O_i x_i + \sum_{t\epsilon T}\sum_{r\epsilon R}(C_r + Eco2_r)y_{rt} + \sum_{t\epsilon T}\sum_{j\epsilon J} f_{jt}S_{jt} \qquad (1)$$

Subject to:

$$\sum_{r\epsilon R} z_{jr}y_{rt} \le 1 \quad \forall j \epsilon J, \forall t \epsilon T \qquad (2)$$

$$\sum_{j\epsilon J} q_{jrt} \leq Cp_r\, y_{rt} \quad \forall r \,\epsilon\, R, \forall t \,\epsilon\, T \tag{3}$$

$$y_{rt} \leq \sum_{i\epsilon I} w_{ir} x_i \quad \forall r \,\epsilon\, R, \forall t \,\epsilon\, T \tag{4}$$

$$\sum_{r\epsilon R} \sum_{j\epsilon J} w_{ir} q_{jrt} \leq Cpd \quad \forall i \,\epsilon\, I, \forall t \,\epsilon\, T \tag{5}$$

$$S_{jt-1} + \sum_{r\epsilon R} z_{jr} q_{jrt} = d_{jt} + S_{jt} \quad \forall j \,\epsilon\, J, \forall t \,\epsilon\, T \tag{6}$$

$$S_{jt} \leq S_{max} \quad \forall j \,\epsilon\, J, \forall t \,\epsilon\, T \tag{7}$$

$$\sum_{r\epsilon R} b_{vr} y_{rt} \leq N_v \quad \forall t \,\epsilon\, T, \forall v \,\epsilon\, V \tag{8}$$

Objective function (Equation1) includes the sum of location transportation and inventory cost. The first term represents the total fixed cost to open the selected depots, the transportation and CO_2 emissions costs are minimized by second term, and the last term represents the inventory holding cost. Constraints (2) guarantee that each customer is visited once at most in any time period. Constraints (3) indicates the capacity constraints of vehicles. Constraints (4) indicates that the routes start and end with the opened warehouse. The capacity of each depot is presented in constraints (5). Equation (6) represents the inventory balance. Equation (7) ensure that the inventory level at a customer never exceeds maximum storage limits due to the hazmat regulations. Equation (8) is the fleet size constraints for each type of vehicle and per period.

4 Computational Results

The data was generated as follows:
- Number of customers: 4, 8, 10, 15 and 20.
- The maximum number of customers per route is 4.
- Number of depots: 2, 3 and 5.
- Number of time periods: 5
- Demand of a customer per time period: random integer in the interval [0, 5].
- Inventory cost for customer j: random number in the interval [4.6, 5].
- Location (x_i, y_j) of customer j : random integer numbers in the interval [0, 500].
-Transportation cost: $C_r = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$
- Capacity of the heterogeneous fleet and number of vehicles is a constant which is inspired from the real case.
- Maximum storage capacity value at depot and at client depends of the security regulation of hazmat.

In order to validate the model, we solve some scenarios of randomize generated data. We used the CPLEX Opl version 12.5.1. in a 2.40 GHz Intel(R) Core(TM) i3-2370 CPU. A summary of computational results is reported in the following table. In the first column of these tables we presents the instance (costumers, depots, time period), the second column is the objective function parameters, the last columns present successively the objective function value, and the computational time. To tackle our multi-objective optimization problem we use a lexicographic weighting method. A pre-defined priority order is tested and established between objectives. For example, four weights are compared to determine the best one for the CO_2 emissions objective.

Table 2- Results

Instances	O.F parameters		O.F values				CPU(s)
	Cr	Eco2r	Oi	Cr	Eco2r	fjt	
4C/2D/5P	1	0	9848858	10844	0	2437,6	2
	1	1	9848858	11307	3056,375	2523,475	2
	1	100	9848858	11765	2745,7	2522,325	2
	1	1000	9848858	11765	2745,7	2470,975	2
8C/2D/5P	1	0	9848858	14672,6	0	6201,34	7,2
	1	1	9848858	14421,4	3735,86	6528,06	9,2
	1	100	9848858	13976,2	3575,98	7445,24	17,4
	1	1000	9848858	13984,2	3576,08	7355,44	32
10C/2D/5P	1	0	9848858	15326,6	0	11966,4	53,838
	1	1	9848858	15974,8	3574,56	11949,2	67,022
	1	100	9848858	15890,4	3430,34	12197	445,2
	1	1000	9848858	15890,4	3430,34	12204,6	169
15C/3D/5P	1	0	880000000	30246,25	0	17730,5	105
	1	1	880000000	30021,5	10525,175	17887,5	78
	1	100	880000000	29202,5	9433,725	18692,5	300
	1	1000	-	-	-	-	-
20C/3D/5P	1	0	1260000000	34439	0	24474	2131.2
	1	1	1260000000	34564	9650,9	25392	2167.8
	1	100	1260000000		5560.9	24950	36958
	1	1000	-	-	-	-	-

IV case study

In this section, a real case application has been developed for supply chain design of a leading company in the drinking water distribution sector. This company use chlorine for water disinfection. Chlorine is the most predominant disinfectant due its low cost installation and residual biocidal effect (Rodriguez, M.J. et J.B. Sérodes, (2001)) [18], and efficacy of chlorine disinfection for enteric viruses (Bigliardi, L et.al 2006) [4]. However, it is highly toxic and considered to be among the most dangerous of hazardous materials. To minimize the risks related to the use of chlorine and improve risk management of its business, the company should optimize chlorine supply chain while respecting storage and transport constraints. The problem consists of 20 delivery points (water treatment station) served directly from one supplier. The fleet of vehicles is composed of two types capacity trucks. The goal of this study is to determine the set of depots to open, they are the starting points of the delivery route. In practice, we note there is only routes that visit a small number of customers. Therefore, we generate all feasible routes with no more than three customers The objective function consists to minimize total cost and CO_2 emissions. A pseudoreal data is generated, especially for the geographical coordinate of depots and inventory costs. The planning horizon is three time periods (a period is one month). Customers demands are deterministic, but may vary from one period to the next. The demand are generated as a uniform distribution in the range [1, 9] for high season and in the range [1, 5] for low season. The data of customers and depots are given in Table 3 and Table 4.The results of 12 simulations are reported in Table 4. The second column of this table indicate the scenarios obtained by selecting 5 among 6 depots. Columns called O.D, CR, ECO2, CI, CD respectively indicate the chosen depots, routing costs, CO_2 emissions quantity, inventory costs and the opening costs of depots. "OF" gives the value of the objective function, and finally the CPU time is given in seconds. The second scenario gives the best objective function for the low and high season. To ensure the robustness of the obtained solution, we also simulate a scenarios with a peak demand. Table 5 presents the results of this simulation that confirm the robustness of our solution. In this section, we tested a realistic datasets for our model. Results shows that our solution can be regarded as a simulation tool to help decision-makers to optimize a real situation.

Table3- Depots data

Depots	Coordinate		Capacity	Fixed cost
D1	583900	394950	30	800000000
D2	319100	324100	10	780000000
D3	311950	160150	30	700000000
D4	74600	420600	10	640000000
D5	180220	110960	20	840000000
D6	454111	550636	10	680000000

Table4- Results of low and high season scenarios

		OD	CR	ECO2	C I	CD	O.F	CPU
low season	SC1	D3-D4	21429	4538.2	3112.4	1 340 000 000	1 340 478 363	576.50
	SC2	D3-D4	20970	4015.6	3498.3	1 340 000 000	1 340 426 032	205.11
	SC3	D3-D6	21098	4769.9	3697.2	1 380 000 000	1380501784.6	192.30
	SC4	D1-D4	22310	4253.1	3581.5	1 440 000 000	1 440 451 197	158.81
	SC5	D3-D4	21661	4461.5	3490.6	1 340 000 000	1340471299.9	119.04
	SC6	D3-D4	19705	4061.4	3500.2	1 340 000 000	1 340 429 349	473.24
High season	SC1	D1-D3-D5	31801	4548.9	4045.7	2 140 000 000	2 140 493 178	569.97
	SC2	D1-D3-D4	28750	3886.5	6357	2 140 000 000	2 140 423 761	238
	SC3	D1-D3-D6	29099	4240	6279	2 180 000 000	2 180 459 453	188.81
	SC4	D1-D4-D5-D6	29518	4870	5975.7	2 960 000 000	2 960 522 489	166.25
	SC5	D1-D3-D4	30284	3878.4	6435.7	2 140 000 000	2140424564.3	119.97
	SC6	D3-D4-D5-D6	30167	5761.9	6233.3	3 640 000 000	3 640 757 565	239.37

Table5- Robustness analysis

	OD	CR	ECO2	C I	CD	O.F	CPU
SC1	D1-D3	21508	3295.8	5881.5	1 500 000 000	1 500 356 972	517.14
SC2	D1-D3	22096	3316.6	5966.2	1 500 000 000	1 500 359 718	286.12
SC3	D1-D3	22772	3356	5311	1 500 000 000	1 500 363 684	313.44
SC4	D1-D4-D5	21560	3664.5	5460	2280 000 000	2 280 393 470	373.84
SC5	D1-D3	22169	3366.4	5741	1 500 000 000	1 500 364 554	249.84
SC6	D3-D4-D5	23799	4707.2	5095	2180 000 000	2 180 499 617	425.04

V Conclusion

This paper consider a bi-objective inventory location routing problem ILRP that optimizes the operating costs, risks and routing‘s CO_2 emissions related to a Hazmat supply chain. The goal is to determine: the set of depots to open, costumers allocated to them, inventory decisions, and routes with a heterogeneous fleet of vehicles so as to satisfy the customers’ demand in each period of the planning horizon. We modeled the problem as an exact bi-objective integer linear program where the main decision variables are binary variables for the selection of depots to open, inventory variables and the set of feasible routes. We have thus no subtour constraints. To validate the model, some tests data instances have been generated. We have also studied an industrial real case to illustrate the problem. The results show that the proposed model solves medium instances with a reasonable computational time. The future work is both the development of a heuristic method, based on a guided generation of routes, and also the testing of some more large scale instances.

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