SIMULATION MODEL FOR IRP IN PETROL STATION REPLENISHMENT

Dražen Popović [a,*] , Milorad Vidović [a], Nenad Bjelić [a]

[a] University of Belgrade, Faculty of Transport and Traffic Engineering, Department of Logistics, Serbia

Abstract: *Quality of a two-echelon distribution system, comprised of vendor and a set of clients, is greatly dependent on vehicle routing and inventory management. Simultaneous optimization of these two segments in distribution systems is commonly known as Inventory Routing Problem (IRP), where decision maker must determine delivery quantities and vehicle routes in a planning horizon of several days. For successful implementation of IRP, a Vendor Management Inventory (VMI) concept must exist in which vendor is responsible for inventory management at clients' side. Many models for solving the IRP in different systems are based on deterministic input data, although in real life these systems have some level of uncertainty. In this paper we observe IRP approach in petrol station replenishment, where we present simulation approach for applicability analysis of deterministic solution to systems with stochastic nature.*

Keywords*: simulation, inventory routing problem, heuristics, petrol station replenishment.*

1. INTRODUCTION

Inventory Routing Problem (IRP) is a relatively new field that is gaining an increasing attention in recent years by the international research community. There are many different definitions of IRP in available literature and perhaps the most comprehensive definition is given by Coelho et al. (2014): "*IRP can be described as the combination of vehicle routing and inventory management problems, in which supplier has to deliver products to a number of geographically dispersed customers, subject to side constraints*". IRP comprises of two subsystems with a strong interdependence, the vehicle routing and the inventory management, which are being simultaneously optimized. Andersson et al. (2010), based on the literature survey in various industries, defines three basic benefits that can be achieved with the IPR: economic benefits, flexibility of service, and improved robustness of the system due to better coordination. IRP can be observed as an extension to the vehicle routing problem in a sense of taking into consideration the inventory management segment, usually in the planning horizon of several days. The basic prerequisite for the implementation of IRP is the Vendor Managed Inventory (VMI) concept, which implies the application of modern information and communication technologies. To solve IRP, many authors develop models that use deterministic data input (deterministic consumption) to simplify the problem and enable the solving of the problem instances. In real systems, consumption has stochastic character and this simplification may lead to adverse effects, primarily as shortages or excesses of inventories and unplanned changes in

[*] d.popovic@sf.bg.ac.rs

the realization of the delivery plan. Applicability analysis of the deterministic solutions to the real system of stochastic nature can be made with the use of simulation.

This paper is one part of the doctoral dissertation (Popović, 2015) where we present heuristic's solutions (which presumes deterministic consumption) applicability analysis to the system with stochastic consumption using simulation. We observe petrol station replenishment problem in which fuel must be distributed from one depot to a set of petrol stations, where each station has stochastic consumption in real life. In the proposed simulation, stochastic consumption can result in the possibility of two negative events which represent two additional performances for evaluating the quality of solutions (in addition to inventory and routing costs): inventory shortages due to unplanned high consumption, and the need for urgent deliveries to minimize the inventory shortages.

The rest of this paper is organized as follows. Section 2 contains brief literature review with main focus on stochastic IRP. Section 3 presents IRP in petrol station replenishment problem formulation with deterministic consumption. In Section 4 we present proposed heuristic and simulation models used for applicability analysis of deterministic solution to systems with stochastic fuel consumption. Test instances and computational results are presented in Section 5. Conclusions and future research directions are given in Section 6.

2. LITERATURE REVIEW

Two most recent IRP review papers (Andersson et al. 2010, Coelho et al. 2014) made similar IRP classification based on the most important problem characteristics, presented in Table 1. IRP related papers usually observe deterministic systems to simplify the problem and to obtain the solution, where consumption is represented with some expected value. One of the first papers that observed IRP with demand uncertainty was by Federgruen and Zipkin (1984) where this uncertainty can lead to inventory stock-out. Golden et al. (1984) also observed IRP with consumption uncertainty where they developed heuristic model based on clients' service emergency. Berman i Larson (2001) analysed somewhat different case of stochastic IRP where drivers don't know exact client's demand quantity before visiting that client.

Table 1. IRP classification (derived from Andersson et al. 2010, Coelho et al. 2014)

CHARACTERISTIC	POSSIBLE OPTION			
Time horizon	Finite	Infinite		
Structure	One-to-many	Many-to-many	Many-to-one	
Routing	Direct	Multiple	Continuous	
Inventory policy	Fixed	Stock-out	Lost sale	Back order
Fleet composition	Homogeneous	Heterogeneous		
Fleet size	Single	Multiple	Unconstrained	
Number of products	Single	Many		

In some papers authors use simulation to analyze applicability of deterministic IRP solution to real-life systems with stochastic nature. One of those papers is Jaillet et al. (2002) where heating oil distribution from one depot to a set of customers was observed. Rolling horizon framework was used to obtain solution for longer time period and Monte Carlo simulation was used to test the solutions. Customers' consumption was randomly generated from a truncated normal distribution. Hemmelmayr et al. (2010) used simulation approach to analyze different distribution concepts in blood delivery to healthcare institutions where blood consumption was randomly generated from a truncated normal and uniform distribution. From stochastic IRP literature, some general conclusions can be made that are applicable to petrol station replenishment and therefore incorporated in the approach presented in this paper: solution from deterministic IRP is obtained by an approximation of stochastic consumption/demand;

simulation can be used to analyze applicability of deterministic IRP to stochastic systems; preventive and corrective measures are necessary to decrease negative effects of uncertainty; rolling horizon framework is used to obtain solution in longer time period.

3. PROBLEM FORMULATION

Two main decisions to be made in IRP petrol station replenishment are: (1) fuel quantities to be delivered per each fuel type to set of petrol stations in predefined planning horizon of several days; (2) according to delivery quantities, route construction for fuel delivery from one depot to set of petrol stations. Objective function, in the process of decision making, tries to minimize total costs which are comprised of routing and inventory costs. Routing cost is defined by total travel distance of all vehicle routes, while inventory costs are defined by average inventory levels of different fuel types at petrol stations. Observed IRP can be described as distribution of several fuel types ($j \in \{1, 2, ..., J\}$) in one-to-many system with homogenous fleet of vehicles in planning horizon of several days ($t \in \{1, 2, ..., T\}$). In each day of the planning horizon one petrol station $i \in \{1, 2, ..., I\}$ can be served with only one vehicle. Each petrol station has constant daily consumption per each fuel type q_{ij} and underground tank of known capacity Q_{ij} (one for each fuel type). It is not allowed that inventory levels in petrol stations for any fuel type fall below predetermined safety stock level. Fuel is transported by a fleet of vehicles F with vehicles that have compartments. Only full compartments can be delivered to petrol stations. Number of compartments in a vehicle for fuel distribution usually varies from 4 to 6 and we test proposed model with three vehicle types. Given the total number of compartments in vehicles and more than one fuel type, in practice one vehicle can serve up to three petrol stations in a single route (Cornillier et al. 2009), and this limitation is applied in our model.

4. HEURISTIC AND SIMULATION MODELS FOR IRP IN PETROL STATION REPLENISHMENT

Observed IRP in petrol station replenishment is a complex combinatorial problem, as is the case with most IRP problems (Anderssson et al., 2010), where optimal solution cannot be obtained in acceptable computational time. Therefore, a heuristic approach is a necessity and we have developed a Variable Neighbourhood Search (VNS) model (Figure 1.a). This VNS model considers fuel consumption as a deterministic value in order to obtain delivery plan for a given planning horizon. Since fuel consumption is uncertain in real life, we developed simulation model to analyze applicability of a VNS solution to the stochastic case (Figure 1.b). Both, heuristic and simulation models were implemented using C++ programming language on PC Intel(R) Core(TM) i3 CPU M380@2.53GHz with 6 GB RAM memory.

4.1 VNS heuristic

The VNS metaheuristic was introduced by Mladenović and Hansen (1997) with the basic idea of systematic change of neighbourhoods in the process of finding improvement of current best solution. Therefore, VNS is based on multiple neighbourhoods in which algorithm attempts to find local best solution. Search of local minimum of multiple neighbourhoods improves chances to find a global minimum. We have developed general VNS heuristic that has the following procedures: initial solution, shaking procedure, local search procedure. Initial solution is created by delivering minimum fuel quantity (one full compartment) at the latest possible moment (day of planning horizon) regarding level of safety stock. Then, vehicle routes (for each day of planning horizon) are created using Sweep algorithm which are improved by Swap and Reallocate/Insertion (VND-route) procedures. Last step of obtaining the initial solution is Compartment transfer procedure which tries to improve the solution by changing the day of a fuel compartment delivery. This initial solution can be additionally improved by two inventory local search (VND-IR) procedures: reallocation of a single fuel compartment delivery between days of planning horizon; reallocation of all fuel compartments in a petrol station between days of planning horizon. Shaking procedure is used to partially and in gradually intensified manner "destroy" (parameters of destruction are increased) current best solution and then to reconstruct it to obtain some new solution which is located in another segment of solution space (compared to current best solution). From this new solution, VND procedures with randomized order of neighbourhoods (RVND-route and RVND-IR) are used to obtain improvement. Finally, new solution is compared with the current best solution. If the new solution is better than the current best solution, then it becomes current best solution (and shaking procedure parameters are reseted). VNS heuristic algorithm is presented in Figure 1.a.

4.2 Simulation approach

Having a sufficient amount of fuel in petrol stations that can meet the consumption is a basic requirement for solution excellency in petrol station replenishment problem. In the case of stochastic consumption there is a risk of stock-out due to the possibility of excessive consumption. To avoid stock-outs, safety stocks are used (as a preventive measure) which have the role of meeting the extreme fuel consumption deviations. Larger consumption deviations require a higher level of safety stock that causes higher inventory costs. A solution which will be based only on raising safety stock is not cost-effective (high costs related to capital stock). To avoid a high level of safety stocks, with simultaneous satisfaction of stochastic consumption, concept of emergency fuel delivery (as a corrective measure) for those petrol stations which are in danger of stock-out is a necessity. Simulation is being used for the analysis of the applicability of deterministic solutions in terms of routing and inventory costs, as well as additional negative effects of inventory stock-outs and the number of emergency deliveries.

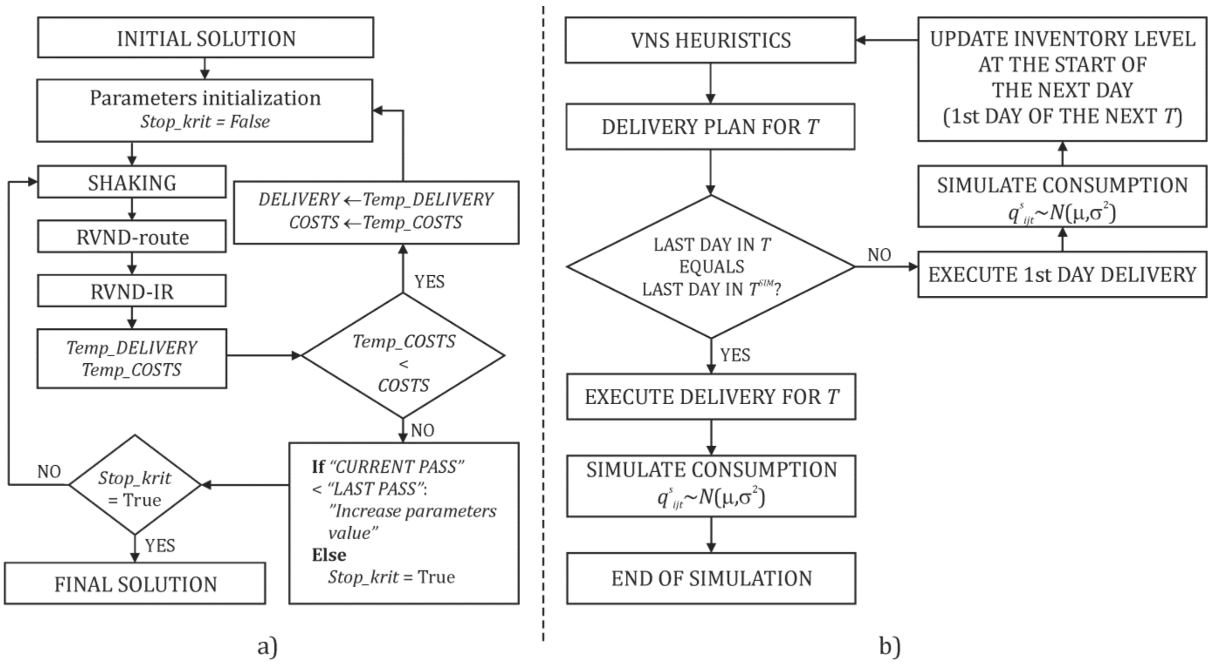

Figure 1. VNS heuristic and simulation algorithms

The basic idea of simulation approach is to obtain solution for a planning horizon using VNS heuristic, and then to simulate daily fuel consumption using appropriate random distribution. To simulate consumption we used Normal distribution $q^s_{ijt} \sim N(\mu, \sigma^2)$ (truncated left from zero to forbid negative consumption), as it was used in some other papers (see Jaillet et al. 2002, Hemmelmayr et al. 2010). After the realization of deliveries and simulated consumptions, model checks the inventory level of al fuel types in all stations. If inventory level falls below safety stock level, an emergency delivery is activated. Any excessive fuel consumption that cannot be satisfied is registered as stock-out. Length of simulation planning horizon T^{SIM} is limited by computational time, and this was the reason why we introduced a rolling planning horizon in which we used VNS heuristic to solve successive shorter periods $T<T^{SIM}$. In the simulation, from each solution of a shorter period T only first day delivery was executed (expect the shorter period T at the end of T^{SIM}) where this first day takes into account expected costs of entire shorter period T. Simulation algorithm is presented in Figure 1.b.

5. COMPUTATIONAL RESULTS

In the proposed simulation approach we observed following instances' characteristics: 15 petrol stations; 3 fuel types; fleet size is F=4; transportation cost per travelled kilometre is 2 €/km; daily inventory holding cost is 1 €/1000 l; daily fuel consumption per type q_{ij} can randomly take values from intervals [1000-3000 l], [800-2000 l], [500-1500 l]; petrol stations' underground tanks per fuel type can have random values from intervals [30000-50000 l], [20000-40000 l], [20000-30000 l]; petrol station inventory level per fuel type at the start of simulation can randomly take values from [2*q_{ij}, 8*q_{ij}]; petrol stations are randomly located in a square [-100, 100] km, while depot is located at [0,0]; simulation planning horizon is T^{SIM}=16 days, while each shorter period is T=4 days. We have randomly generated 100 test instances with 10 simulation runs per each instance. Additionally, we tested the impact of following parameters on solutions' quality:

- different consumption deviation: $\sigma=0.2*\mu$, $\sigma=0.3*\mu$, where $\mu=q_{ij}$;
- different vehicle types [K – number of compartments, Qo – compartment capacity]ϵ{[4, 8800 l], [5, 7000 l], [6, 5800 l]};
- different levels of safety stocks: $V=0.5*q_{ij}$, $V=1.0*q_{ij}$, $V=1.5*q_{ij}$, $V=2.0*q_{ij}$.

Simulation results are presented in Table 2. Results show that increase in safety stock level consequently increases both inventory and routing costs (due to increase in delivery quantities). Depending on the level of consumption deviation different safety stock level is required to reduce stock-outs to practically zero (between 1.0*q_{ij} and 1.5*q_{ij}). Additionally, number of emergency deliveries is higher with higher level of consumption deviation. Vehicles with more compartments have lower total costs but also more emergency deliveries and stock-outs.

Table 2. Simulations results for 100 test instances (average with 10 repetitions)

σ	Vehicle type [K, Qo]	V [q_{ij}]	Routing costs [€]	Inventory costs [€]	Total costs [€]	CPU time [sec]	Emergency deliveries	Stock-outs [l]
0.3*μ	[4, 8800 l]	0.5	10968.9	5348.5	16317.5	8.6	6.76	292.3
		1.0	11323.6	5875.0	17198.6	8.8	7.33	22.4
		1.5	11720.2	6447.3	18167.5	8.5	7.06	0.8
		2.0	12122.1	6987.7	19109.8	8.7	6.96	0.0
	[5, 7000 l]	0.5	11149.9	4883.2	16033.1	11.3	7.29	323.0
		1.0	11485.3	5393.5	16878.9	11.8	7.94	24.2
		1.5	11947.7	5954.8	17902.5	11.4	7.59	1.1
		2.0	12328.7	6481.9	18810.6	11.7	7.37	0.0
	[6, 5800 l]	0.5	11397.5	4598.3	15995.8	14.1	7.82	379.8
		1.0	11731.2	5090.1	16821.3	14.7	8.42	32.1
		1.5	12178.7	5644.8	17823.5	14.4	8.02	0.1
		2.0	12540.8	6177.9	18718.7	14.8	7.87	0.0
0.2*μ	[4, 8800 l]	0.5	11059.7	5317.7	16377.4	8.7	4.59	47.2
		1.0	11388.9	5848.0	17236.9	8.9	4.92	0.7
		1.5	11813.1	6416.7	18229.9	8.6	4.77	0.0
		2.0	12189.2	6956.4	19145.6	8.7	4.53	0.0
	[5, 7000 l]	0.5	11231.1	4858.7	16089.9	11.5	4.81	52.1
		1.0	11534.6	5364.6	16899.2	12.0	5.31	0.6
		1.5	11987.0	5914.5	17901.5	11.6	5.22	0.0
		2.0	12356.0	6445.2	18801.2	11.9	5.12	0.0
	[6, 5800 l]	0.5	11424.9	4560.0	15984.9	14.3	5.23	56.9
		1.0	11773.6	5059.8	16833.4	15.0	5.65	2.1
		1.5	12224.2	5607.5	17831.7	14.6	5.33	0.0
		2.0	12547.9	6141.9	18689.8	15.0	5.36	0.0

6. CONCLUSIONS

Simulation can be used to analyze petrol station replenishment problem in different environments and to choose the most suitable distribution variant (e.g. vehicle type, safety stock level). Based on simulation results presented in this paper, general conclusion can be made that the total inventory and routing costs decrease with the increase of the number of vehicles' compartments (smaller capacity of a single compartment). On the other hand, looking at the aspect of service (number of emergency deliveries and stock-outs) vehicles with smaller number of vehicles' compartments (larger capacity of a single compartment) are more suitable. Decision makers must determine the degree of importance between quality of service (possible loss of revenue) and the total inventory and routing costs, and based on that to design distribution structure and policy. Potential research directions are adjustments of the proposed model to different petrol stations replenishment distribution structures as well as modifying the proposed models for use in different business systems with similar characteristics, such as the collection of waste and recyclables, transport of live animals, collection of milk or olive oil, distribution of frozen products that are kept at different temperatures, etc.

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