THE FUEL STATIONS CHOICE FLEXIBILITY STUDY AND ITS IMPACT ON THE LENGTH OF DELIVERY ROUTES

[1]Jacek KALETA, [2]Marek KARKULA, [3]Grzegorz TARCZYŃSKI

[1]Samat Polska sp. z o.o., ul. Opolska 18, 31-323 Kraków, Poland, EU, jacek.kaleta@samat.pl

[2]AGH University of Krakow, al. Mickiewicza 30, 30-059 Kraków, Poland, mkarkula@agh.edu.pl

[3]Wroclaw University of Economics and Business, ul. Komandorska 118/120, 53-345 Wrocław, Poland, EU, grzegorz.tarczynski@ue.wroc.pl

https://doi.org/10.37904/clc.2023.4850

Abstract

The paper presents a real decision problem regarding the issue of planning the supply of LPG (a popular fuel in Poland) to petrol stations. A description of the elements of the decision problem is presented: inventory in station readings and forecasts, petrol station categorization, and planning and scheduling of tank truck delivery journeys. A linear programming model for Vehicle Routing Problem with Time Windows (VRPTW) was used to optimize routes. Planning and scheduling are developed for a three-day time horizon. The presentation contains a detailed description of the specifics of fuel supplies in the Polish market. Thus, the necessary modifications of the original VRPTW model are developed. The key change implemented by the research team was to make service station selection more flexible with the stock levels planned to be replenished on a specific date. Thanks to these adjustments, the modified VRPTW model better assigns fuel stations to the generated routes, which translates into more favorable values of the selected goal function (we anticipate the possibility of optimizing both route lengths, CO_2 emissions, as well as the use of a metacriterion that considers both goal functions). However, it should be noted that the degree of improvement of the solutions depends on the specificity of the geographical region for which the calculations were performed. The paper also presents problems with the practical implementation of the proposed changes in the VRPTW model.

Keywords: VRPTW, delivery planning, optimization, VMI concept

1. INTRODUCTION

Cooperation between suppliers, customers, and carriers is an important component of supply chain management. Both the academic literature and the experience from practice show significant relationships between the depth of the relationships between supply chain participants and the mutual benefits derived from them. One implementation of VMI management strategies in the transportation industry is the HMI concept (Haulier Managed Inventory), or carrier managed inventory. Often, product distribution companies expect the carrier to provide not only a specialized transportation service, but also a service for planning deliveries to end users. In this case, it is possible to speak of the imposition of the VMI method as a prerequisite for the dominant partner to fulfill the commercial contract.

The concept of VMI/HMI has seen the development of numerous models on the ground of operations research, as well as many methods for their solution. These issues are known in the literature as IRP (Inventory Routing Problem). The classic IRP problem concerns the repeated distribution of a homogeneous product from a single warehouse using a homogeneous fleet of vehicles to multiple customers within a given planning horizon [1].

The research included in this paper responds to a demand arising from practice. The paper presents a real decision-making problem concerning the issue of planning the supply of LPG (a popular fuel in Poland) to gas stations. The results of the work are the built mathematical models for the IRP issue and simulation results for real data. The key achievement obtained by the research team was to make the selection of fuel stations more flexible by the inventory levels planned to be replenished on a specific day. Thanks to these adjustments, the modified VRPTW model better assigns fuel stations to generated routes, which translates into more favorable values of the selected objective function (we anticipate the possibility of optimizing both the length of routes, CO2 emissions, and the use of a metacriteria that considers both objective functions).

2. LITERATURE REVIEW

In the literature, the problem of integrated inventory planning with vehicle routing was initiated more than 30 years ago in a manuscript by Bell et al. [3]. Bertazzi and Speranza presented an interesting tutorial on IRP problems [4]. The authors discussed the basic IRP problem with only one vehicle available and considered the extension of this problem to the multi–vehicle case. Practical applications of IRP and its extensions can be found in various industries, such as retail, fresh food distribution, fuel distribution and others. An extensive application of the VMI concept and the IRP problem has been found for the distribution of perishable products. A review of the literature on this issue is presented in a manuscript by Shaabani [6]. Cui et al. [5] presented a novel framework for the uncertain inventory routing problem, minimizing the risk that inventory levels violate acceptable ranges and providing adaptive solutions based on uncertain demand. Wang et al. [8] discussed the uncertainty order-up-to-level (UOU) policy that offers a more efficient inventory replenishment strategy in uncertain production-inventory routing systems, with higher confidence levels and a large uncertainty leading to a trend towards zero-cost difference between the two policies. Solyali et al. [7] analysed two robust mixed integer programming formulations for inventory routing under demand uncertainty, ensuring feasibility and minimizing total costs in transportation, inventory holding, and shortage costs. Alvarez et al. [1] proposed a two-stage stochastic programming formulation that can optimize inventory routing and vehicle routing decisions in uncertain supply chains, with varying effects on supply and demand uncertainty. Archetti & Ljubić [2] analysed aggregated formulations for the Inventory Routing Problem. The authors proposed different exact solution approaches based on these IRP formulations.

Despite the large number of available articles on the IRP problem, there is still a lack of works that consider more than one criterion and take into account environmental objectives. In our work we try to fill this gap.

3. PROBLEM STATEMENT

The replenishment of LPG stocks at gas stations can occur through two methods: 1. Gas station managers place orders for a specific quantity on a given day; 2. The supplier independently determines the delivery dates and volumes. In Poland, LPG gas supplies primarily adhere to the second concept, referred to as Vendor Managed Inventory (VMI). The VMI concept necessitates planning deliveries over an extended time horizon, allowing for more effective fleet management and the determination of shorter delivery routes, thereby enhancing the company's economic performance.

In this article, we present the results of the research conducted in line with the VMI concept. The LPG transport company collects telemetric readings of inventory levels at serviced gas stations multiple times a day. These readings, along with historical data and expert knowledge (considering dynamic fluctuations in demand during cultural and sports events, public holidays, or extended weekends), enable planners to forecast stock levels at individual stations for upcoming delivery days. Subsequently, fuel stations are categorized for each day: urgent stations (at risk of stock-out, necessitating replenishment on the specified day), additional stations (stock levels can be replenished on the given day) and remaining stations (stock levels too high for replenishment on the given day). The next step involves creating delivery routes. In its simplest form, the planner independently selects gas stations for the tanker's route, ensuring that the forecasted demand is met and the route remains within the confines of a specific subregion. The subsequent step involves solving the linear programming model for the Vehicle Routing Problem with Time Windows (VRPTW) to optimize the delivery route. Stations are added to the route based on urgency and additional stations are included to fully unload the tanker before returning to the base.

To evaluate designated delivery routes, the delivery company utilizes Key Performance Indicators (KPIs), including the number of stock-outs at serviced gas stations in a specific period and the distance required to deliver 1 ton of LPG to customers (tankers are loaded at a constant ambient temperature, and the unit of measurement is a ton, whereas customers receive LPG gas in liters). While the ideal number of stock-outs is zero, external factors may impede timely deliveries, such as road accidents and associated roadblocks. Consequently, the research assumes that there are no sales discontinuity at gas stations, instead focusing instead on the second KPI (measuring the distance [km] required to deliver 10,000 dm^3 of LPG gas).

4. DESCRIPTION AND ANALYSIS OF RESEARCH RESULTS

The presented research results demonstrate how, within a four-week planning horizon, the KPI value is influenced by the number of additional stations (considering both the minimum number and a larger number, which impacts route optimization); and the length of the planning horizon (ranging from one day, with routes determined separately for each day, to three days, employing a modified VRPTW model for route optimization).

Historical data from two supply areas, R01 (Gdańsk agglomeration) and R03 (a larger area in western Poland), were analyzed in simulations covering 28 consecutive days. Deliveries were strategically planned to prevent stock-out situations. The calculations were executed on a computer with a Core i7-12700K processor using Python, the MIP library, and the Gurobi solver, with the practical constraint of a calculation time of 300 seconds.

Table 1 provides a description of the R01 and R03 regions covered by the simulation, including the number of gas stations in each region. **Figures 1** and **Figure 2** show the locations of the base and gas stations on the Poland map.

Table 1 Description of simulated gas stations' areas

Area	No. gas stations	Distance from a base to LPG fuel stations [km]			Distance between LPG fuel stations [km]		
		Avg	Min	Max	Avg	Min	Max
R01	44	17,98	2,68	41,17	16,28	0,11	53,13
R03	32	350,71	224,60	498,97	127,82	2,52	383,55

Source: own elaboration.

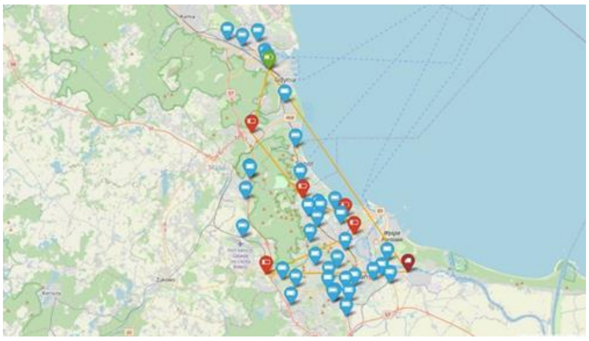

Figure 1 The locations of gas stations in R01 area (Gdańsk agglomeration)
Source: own elaboration using Python folium library

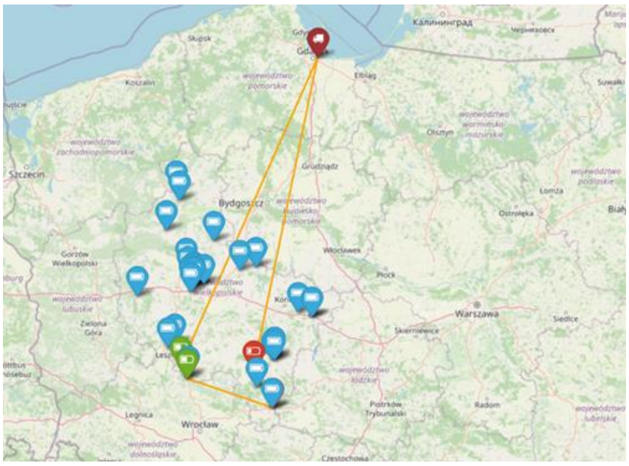

Figure 2 The locations of gas stations in R03 area (gas stations are territorially more scattered)
Source: own elaboration using Python folium library

The maximum gas supply at gas stations depends on the size and number of tanks and differs significantly. The smallest reservoirs in the studied regions have a volume of 4,850 dm^3, and the largest – 20,000 dm^3. However, it is only possible to fill the tanks to the safety level, which is approximately 85% of the maximum volume and is slightly different for each tank. Also, not all the resources of LPG stored in the tank are available - usually about 10-15% of the raw material is the so-called dead state, i.e. raw material that the pumps are unable to collect. For example, for a 20,000 dm^3 tank, the dead state may be 2,500 dm3 and the maximum filling level 85%. Then the maximum supply of gas for sale is 14,500 dm3. **Table 2** contains information on the maximum supply and daily demand at gas stations in the surveyed regions.

Table 2 The maximal supply and daily demand of LPG on gas stations in the areas

Area	Maximal supply of LPG gas on gas station [dm^3]			Daily demand on gas station [dm^3]			Daily demand as a percent of maximal supply [%]		
	Average	Min	Max	Average	Min	Max	Average	Min	Max
R01	10825	6578	17740	1509,5	116	5501	15,5	1,5	60,6
R03	7939	3130	13600	1688,6	30	4350	19,3	0,2	69,8

Source: own elaboration.

Simulations of fuel deliveries in both regions were carried out on a rolling basis, i.e., when determining the list of urgent and additional stations in the following days, the deliveries made in the previous days were considered. For the R01 region, after conducting simulations for 28 consecutive days, increasing the flexibility in the selection of additional stations resulted in a reduction of the KPI value by more than 10% and for the R03 region by more than 7%. In the R03 region, it was also examined how the extension of the planning horizon to 3 days affects the length of the generated routes - here the KPI decreased by almost 10% compared to the original variant (**Table 3**). Such KPI reduction values are very satisfactory from a business point of view and constitute the basis for further research. It is worth highlighting that no stock-out situations occurred in the simulations. Changes in KPI values over time are presented in **Figures 3 and 4**.

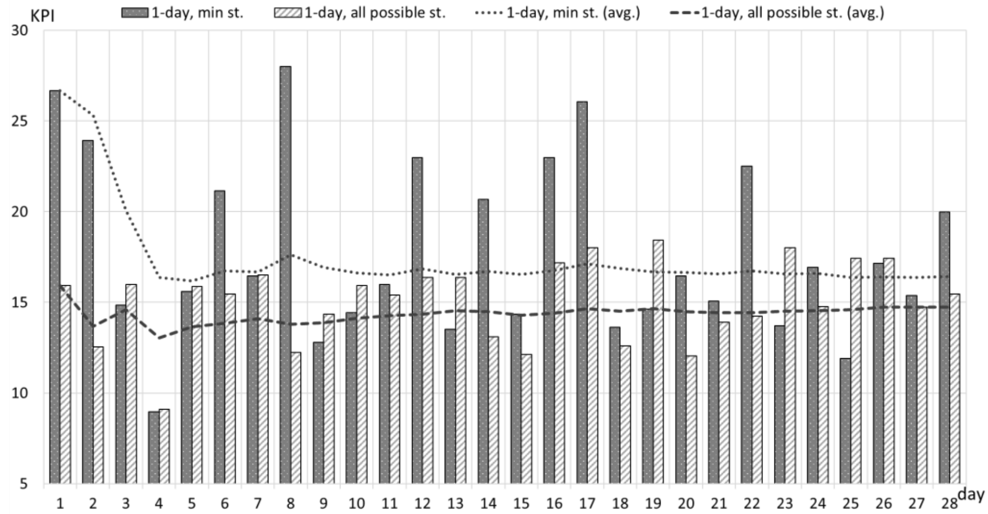

Figure 3 KPI daily values and change over time in the area R01 for two simulation variants
Source: own elaboration

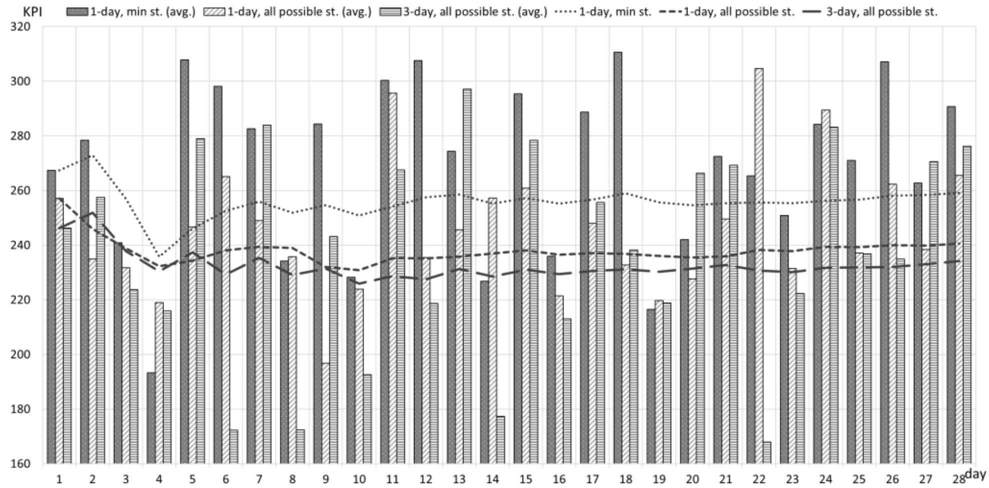

Figure 4 KPI daily values and change over time in the area R03 for three simulation variants
Source: own elaboration.

Table 3 KPI value after 28 days for different of simulation

Area	R01		R03		
Planning horizon	**1-day**	**1-day**	**1-day**	**1-day**	**3-day**
Additional stations	min	all possible	min	all possible	all possible
KPI value	16,44	14,75	259,18	240,56	234,22
Improvement (%)	0,00	10,29	0,00	7,19	9,63

Source: own elaboration.

When evaluating the obtained solutions, we pay attention to one more aspect: the quality of the solutions of the modified VRPTW model. **Table 4** contains information on the size of the tasks solved. Increasing the planning horizon to three days significantly increases the number of routes generated (and therefore the number of nodes considered in the graph by the VRPTW model is larger). **Table 5** contains information on the quality of the solutions obtained. For one-day planning, an optimal solution was found for most instances within the assumed calculation time (300 s). For planning in a three-day horizon, even an increased calculation time (600 s) did not guarantee optimal solutions. The obtained GAP values provide information about the theoretical possibility of improving the obtained results; they express the quotient of the obtained value of the objective function by the lower limit of the objective function determined by the solver, reduced by 1.

Table 4 Size of instances

Area	No. designated routes in one day			No. stops on routes in one day		
	Avg.	Min	Max	Avg.	Min	Max
R01	1,68	1	3	9,39	5	16
R01	1,71	1	3	10,43	5	18
R03	1,36	1	2	8,96	4	20
R03	1,36	1	2	8,96	4	14
R03	4,04	3	5	27,36	19	33

Source: own elaboration.

Table 5 Quality of results and computation time

Area	Planning horizon	Additional tank stations	Computation time [s]			No. instances w/o optimal solution	Max GAP (%)
			Avg.	Min	Max		
R01	1 day	min	22,7	0,0	300,1	2	23,25
R01	1 day	all possible	67,6	0,1	300,1	2	24,80
R03	1 day	min	14,7	0,0	300,0	1	20,81
R03	1 day	all possible	7,7	0,0	140,8	0	0,00
R03	3 day	all possible	600,0	600,0	600,1	28	18,85

Source: own elaboration.

5. CONCLUSIONS

In the article, we describe the decision-making process related to making decisions regarding the planning of LPG gas supplies to gas stations in accordance with the VMI concept. We have shown that increasing flexibility in the selection of additional stations and extending the planning horizon can improve the KPI by up to 10%. However, the modifications that we have proposed increase the size of the VRPTW model and extend the computation time. The next stage of the analysis will be to examine other criteria for assessing the quality of the solutions obtained (e.g. minimizing CO_2 emissions during deliveries) and checking how the quality of telemetry readings and demand forecasts at gas stations affect the risk of stock-outs. A very important factor that influences the correct planning of delivery routes in line with the VMI concept is the forecast of demand at LPG gas stations and the combination of it with telemetry readings. We did not analyze this problem in the research, but further work is planned in this area.

ACKNOWLEDGEMENTS

The study was partially funded by the National Centre for Research and Development (NCBR), Poland under the POIR.01.01.01-00-0265/21 programme – R&D project titled "Inventory routing optimization for petrol stations".

REFERENCES

[1] ALVAREZ, A., CORDEAU, J.-F. JANS, R., MUNARI, P. MORABITO, R. Inventory routing under stochastic supply and demand. *Omega*, 2021, vol. 102, 102304. DOI: https://doi.org/10.1016/j.omega.2020.102304.

[2] ARCHETTI, C., LJUBIĆ I. Comparison of formulations for the Inventory Routing Problem. *European Journal of Operational Research*, 2022, vol. 303(3), pp. 997–1008. DOI: https://doi.org/10.1016/j.ejor.2021.12.051

[3] BELL, W., DALBERTO, L., FISHER, M., GREENELD, A., JAIKUMAR, R., KEDIA, P., MACK, R., PRUTZMAN, P. Improving the distribution of industrial gases with an on-line computerized routing and scheduling optimizer. *Interfaces*, 1983, vol. 13(6), pp. 4–23. DOI: https://doi.org/10.1287/inte.13.6.4

[4] BERTAZZI, L., SPERANZA M.G. Inventory routing problems with multiple customers. *EURO Journal on Transportation and Logistics*, 2013, vol. 2(3), pp. 255–275. DOI: https://doi.org/10.1007/s13676-013-0027-z

[5] CUI, Z., LONG, D.Z., QI, J., & ZHANG, L. Inventory Routing Problem under Uncertainty. *Operations Research*. 2023, vol. 71(1), pp. 378–395. DOI: https://doi.org/10.1287/opre.2022.2407

[6] SHAABANI, H. A literature review of the perishable inventory routing problem. *The Asian Journal of Shipping and Logistics*, 2022, vol.38(3), pp. 143–161. DOI: https://doi.org/10.1016/j.ajsl.2022.05.002

[7] SOLYALI, O., CORDEAU, J., LAPORTE, G. Robust Inventory Routing Under Demand Uncertainty. *Transportation Science*, 2012, vol. 46, pp. 327–340. https://doi.org/10.1287/trsc.1110.0387

[8] WANG, C. NI, Y., YANG, X. The inventory replenishment policy in an uncertain production-inventory-routing system. *Journal of Industrial and Management Optimization*, 2023, vol. 19(1), pp. 549–572. DOI: https://doi.org/10.3934/jimo.2021196