LOGI – Scientific Journal on Transport and Logistics
Vol. 15 No. 1 2024 DOI: 10.2478/logi-2024-0009

Design of Restrictive Conditions for Simultaneous Loading and Unloading of Goods with Different Temperature Regimes in Vehicle Routing Problem

Jaroslav Kleprlík[1*] and Markéta Brázdová[2]

[1]*University of Pardubice, Faculty of Transport Engineering, Department of Transport Technology and Control, Studentská 95, 532 10 Pardubice, Czech Republic; Email: jaroslav.kleprlik@upce.cz,*
[2]*University of Pardubice, Faculty of Transport Engineering, Department of Informatics in Transport, Studentská 95, 532 10 Pardubice, Czech Republic; Email: marketa.brazdova@upce.cz*

***Corresponding Author:** Jaroslav Kleprlík

Received: 29 February 2024; Revised: 13 June 2024; Accepted: 17 July 2024; Published: 3 September 2024

Abstract: This paper deals with the vehicle routing problem involving simultaneous loading and unloading of goods with different temperature regimes. Existing modifications of the problem as well as current software products do not focus on the transport of goods with different temperature regimes. In this paper, restrictive conditions for the joint transportation of goods with multiple temperature regimes are determined, which can be used within various types of optimization algorithms that address vehicle routing problems. Considering the proposed conditions in these algorithms will increase the utilization of the vehicle payload, and load space while complying with the established mandatory rules for the transport of foodstuffs. This will reduce the number of journeys required to carry out the transport, thus resulting in savings in operating costs.

Keywords: Operational research, vehicle routing problem, simultaneous loading and unloading, new restrictive condition, multiple temperature regimes

1. Introduction

Vehicle routing problem (VRP) is a very topical issue in the field of road transport and logistics, involving the distribution of the required quantity of goods, products, materials, etc. from one or more depots to other vertices of the network (serviced vertices) using a certain number of available vehicles, each of which has a defined specific payload, loading area size, and load space size (hereinafter referred to as capacity). Each vehicle departs from the depot and, after covering its transport route, returns to the point from which it departed (i.e., the same depot). The goal is to schedule the distribution so that the total transportation cost is minimal. In the case of a simpler problem where the products are delivered from a single depot, the Clark-Wright algorithm is used, while for more complex problems with multiple depots, the Tillman and Cain algorithm is recommended [1]. More recent methods for solving these types of problems include the so-called metaheuristics [2]. In their basic form, these methods assume a homogeneous fleet and do not consider factors such as time windows or the complexity of transporting goods with different temperature regimes. VRP is also applicable to shopping centers, where the configuration of the road network influences the design and construction of their distribution routes [3]. The decision of selecting appropriate routes to bypass potential closures is addressed by [4].

2. Analysis of the Development and Current State of Solving Vehicle Routing Problem

Vehicle Routing Problem has a wide range of applications. Practical problems are most often solved using various modifications of heuristic algorithms. To determine the current state of solving various types of the vehicle routing problem, an analysis of professional publications and specialized software was performed.

The most commonly used method algorithm for solving the Vehicle Routing Problem is the heuristic method proposed by Clarke and Wright in 1964, which operates with a homogeneous fleet and a single depot. The basic version of the problem addresses only capacity constraints [5]. However, there are many additional constraints that can be incorporated into the basic problem.

Since its introduction, the Clark-Wright method has undergone many modifications. These include a variant for the multi-depot problem [6], extension to address the simultaneous collection and distribution of goods [7], and modifications to the original savings criterion [8]. In some modifications, the optimization criterion is travel time [9], while in others, the criterion incorporates additional customer requirements [10]. Other modifications of the algorithm use probabilistic approaches [11] or solve the problem using computer simulation [12].

A modern trend in solving the Vehicle Routing Problem involves the use of metaheuristics. These are advanced heuristic methods that build upon other types of heuristics, often inspired by the reflexive behavior of animals or working with natural phenomena. The most commonly used metaheuristics include genetic algorithms, simulated annealing, climbing algorithms, or ant colony optimization (ACO) [2]. The ACO algorithm, designed by Marco Dorigo in 1992 [13], is based on the group foraging behaviors of ants. Although their movement is seemingly chaotic when examined individually, ants move systematically and along an optimal path.

2.1 Practical Applications of the Vehicle Routing Problem

Various modifications of heuristic algorithms are most often used to solve the Vehicle Routing problem in practice; it is also quite common to use a combination of some heuristics with the Clark-

Wright algorithm. The modification of the algorithms is always individual, depending on the nature of the problem to be solved.

Metaheuristics or their combination with the Clark-Wright algorithm have been used to solve problems in many fields. [14] dealt with the simultaneous collection and distribution of refrigerated goods for a single depot. They proposed their own heuristics based on the principle of genetic algorithms. A hybrid heuristic algorithm was applied to the mail delivery problem in [15]. The algorithm is a combination of the Clark-Wright and metaheuristic algorithm. The combination of metaheuristics in solving the VRP is also used by [16] and [17]. [18] used the Clark-Wrigt algorithm for the distribution of food from restaurants to customers.

The research by [19] addresses the reverse logistics problem with cross-docking, while [20] focus on the Vehicle Routing Problem considering time windows and heterogeneous vehicle fleet. The researchers deal with the problem of distributing goods to customers, including installation using two heterogeneous fleets.

The comparison of different types of metaheuristic methods combined with the Clark-Wright algorithm provides interesting results. The research by [21] compares two types of heuristics with the Clark-Wright algorithm in the drug distribution domain. The study by [22] deals with the issue of green logistics. To reduce the cost of fresh food distribution and achieve the goal of green logistics, the GFLHF-VRP model (Green Fresh Food Logistics with Heterogeneous Fleet Vehicle Route Problem) was introduced. A new approach to the modeling of environmental risk assessment in the transport sector is introduced by [23].

The above review shows that the use of the Clark-Wright algorithm or a combination of some types of metaheuristics is a common approach to solving the Vehicle Routing Problem under different parameters and conditions. The use of different modifications of the Clark-Wright algorithm appears to be more efficient than metaheuristic methods in some cases. However, none of the aforementioned studies has addressed the problem of transporting goods with different temperature regimes, which is the focus of this paper. We propose adding a specific constraint that will facilitate the transport of goods with three different temperature regimes, in accordance with the Agreement on the International Carriage of Perishable Foodstuffs and on the Special Equipment to be Used for such Carriage (UNECE) [24].

The proposed constraint can be included as an additional condition to the set of existing constraints in methods addressing the Vehicle Routing Problem. When programmed and incorporated into special software for the scheduling of the Vehicle Routing Problem, it will allow optimizing the transport of goods with three different temperature regimes while following the conditions of the ATP Agreement. This will enable increasing the use of payload and vehicle load space.

2.2 Software for the Vehicle Routing Problem

In addition to scholarly publications, four available software packages designed for the vehicle routing problem, which are used by carriers to optimize their transport operations, were analysed. The aim is to enhance their efficiency regarding the use of vehicle payload, minimising the transport distances, and reducing the transport time. The analysed software packages include Plantour [25], Rinkai Routing [26], Tasha [27], Kira [28].

The specialized software products mentioned in the paper are presented as examples of computer-aided tools in the field of perishable foodstuff transport. The paper states that the addressed constraints are not included. The use of the aforementioned software products was thus not possible. Moreover, these software products cannot be modified due to the rights of their authors. The paper proposes a suitable extension of these software products in future versions, as this is an important and interesting aspect for transport operators handling foodstuffs.

3. Task Characteristics

When addressing complicated transport problems, it is necessary to apply a systematic approach involving decomposition of the problem into manageable subtasks. In the context of the Vehicle Routing Problem, a complex problem is the determination of routes that comply with restrictive conditions. Routes can be determined using the Clark-Wright algorithm or metaheuristic methods such as simulated annealing, climbing algorithms, genetic algorithms [2], or ant colony optimization [13] can be used. However, it is always necessary to adapt these algorithms to the specific characteristics of the problem.

Assume a situation where the problem has already been decomposed into subtasks. One of them is determining the admissibility of the generated route in terms of cargo temperature regimes. When using the Clark-Wright algorithm, the optimization criterion is to maximize the resulting savings. The maximum value element is always selected from the savings matrix, determining which routes will be combined into one. The restrictive condition for merging routes is vehicle capacity; the sum of the cargo capacities of the two merging routes must not exceed the allowed vehicle capacity. Constraints on the allowed temperature regimes serve as an additional restrictive condition for the task. Routes will only be merged if the combined cargo does not exceed vehicle capacity and if the merging is admissible in terms of different temperature regimes. An admissibility test for temperature regimes should be carried out at each vertex of the new route projected. The test should be carried out first for unloading and then for loading the vehicle.

4. Design of the Restrictive Condition for Solving

The principle of solving the problem is to determine the states of the cargo temperature regime that can occur before unloading goods and to determine the transitions between the states of the cargo regime after unloading. A similar procedure is repeated for vehicle loading. Since unloading always precedes loading, the cargo temperature regime must always be verified in the order given, i.e., unloading of the goods followed by loading.

Variables used:

auto_N	the quantity of non-frozen goods loaded on the vehicle,
auto_M	the quantity of frozen goods loaded on the vehicle,
unloading_N	the quantity of non-frozen goods unloaded at the vertex,
unloading_M	the quantity of frozen goods unloaded at the vertex,
loading_N	the quantity of non-frozen goods loaded at the vertex,
loading_M	the quantity of frozen goods loaded at the vertex,
cargo_mode	the temperature regime of the cargo loaded on the vehicle,
vehicle_mode	the temperature regime of the vehicle.

Each vehicle has a defined temperature regime (vehicle_mode). This variable represents the allowed temperature regime for the cargo in the vehicle. It can take the values M, N, M + N, N + M, K, where:

M means that the vehicle can only transport frozen goods

N means that the vehicle can only transport non-frozen goods (dry or chilled, which can be transported together)

M + N means that the vehicle can transport goods in a combination of temperature regimes (the vehicle must have a bulkhead); the order of the regimes must be observed, i.e., frozen goods are loaded first, then non-frozen goods, and vice versa for unloading

N + M means that the vehicle can transport goods in a combination of temperature regimes (the vehicle must have a bulkhead); the order of the regimes must be observed, i.e., non-frozen goods are loaded first, then frozen goods, and vice versa for unloading

K means that the vehicle can transport goods in a combination of temperature regimes (the vehicle must have a bulkhead); the order of regimes does not matter

The vehicle enters a vertex (which can be either a served vertex or a depot) in the cargo_mode regime. This state variable can take the values P, M, N, M + N, N + M, K, where:

P means an empty vehicle: $auto\_M = 0 \wedge auto\_N = 0$.

M means that only frozen goods are loaded on the vehicle: $auto\_M > 0 \wedge auto\_N = 0$.

N means that the vehicle is only loaded with non-frozen goods (dry or chilled, which can be transported together): $auto\_N > 0 \wedge auto\_M = 0$.

M + N means that the vehicle is loaded with both frozen and non-frozen goods (the vehicle must have a bulkhead), with the non-frozen goods unloaded first: $auto\_M > 0 \land auto\_N > 0$.

N + M means that the vehicle is loaded with both non-frozen and frozen goods (the vehicle must have a bulkhead), with the frozen goods unloaded first: $auto\_M > 0 \land auto\_N > 0$.

K the vehicle is loaded with a combination of frozen and non-frozen goods, regardless of the order (this can occur, for example, if both frozen and non-frozen goods are loaded into an empty vehicle at one vertex, all of which are unloaded at the next vertex of the route): $auto\_M > 0 \land auto\_N > 0$.

When arriving at the vertex, the quantity (auto_N + auto_M) is already loaded on the vehicle. After arriving at the vertex, the goods are unloaded first. The quantity of goods unloaded at the vertex is given by (unload_N + unload_M). The transition between the states during unloading is shown in Figure 1. An example of the transition between the states during unloading can be seen in Table 1.

Table 1 The example of transitions between states during unloading. Source: authors

Cargo regime before unloading	Description of unloading	Cargo regime after unloading
M+N	$unloading\_N = auto\_N \land unloading\_M = 0$	M
	$0 < unloading\_N < auto\_N \land unloading\_M = 0$	M+N
	$0 < unloading\_N < auto\_N \land unloading\_M = 0$	M
	$unloading\_N = auto\_N \land unloading\_M = auto\_M$	P
N+M	$0 < unloading\_M < auto\_M \land unloading\_N = 0$	N+M
	$unloading\_M = auto\_M \land unloading\_N = 0$	N
	$unloading\_M = auto\_M \land 0 < unloading\_N < auto\_N$	N
	$unloading\_M = auto\_M \land unloading\_N = auto\_N$	P

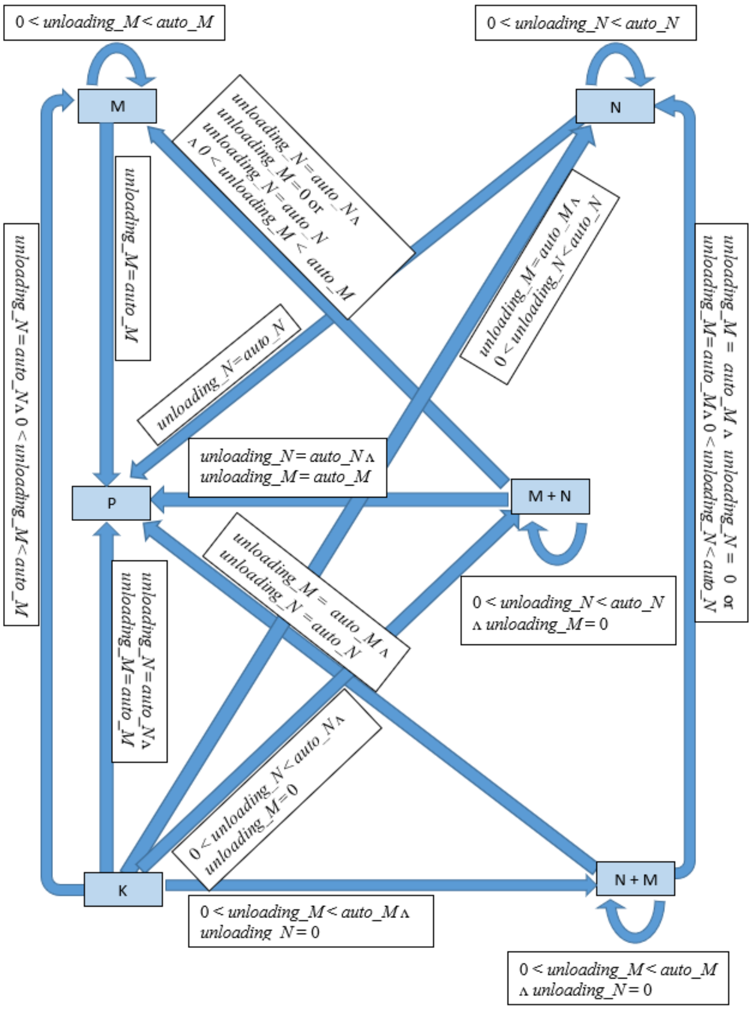

Fig. 1 Transition between the states during unloading. Source: authors

Situations that could occur during unloading but are not permissible according to the algorithm are not shown in the graph. These scenarios are described in Table 2.

Table 2 Non-permissible unloading situations. Source: authors

Cargo regime before unloading	Description of unloading	Cargo regime after unloading
M+N	$0 < unloading\_M \leq auto\_M \wedge unloading\_N = 0$	NOT POSSIBLE
M+N	$0 < unloading\_M < auto\_M \wedge 0 < unloading\_N < auto\_N$	NOT POSSIBLE
N+M	$0 < unloading\_N \leq auto\_N \wedge unloading\_M = 0$	NOT POSSIBLE

The table detailing transitions between states during loading is created in a similar way as in Table 1 for unloading.

After unloading, loading takes place at the vertex. The quantity of goods loaded at the vertex is determined by (loading_N + loading_M). The transition between cargo regime states during loading is described in Figure 2. The vehicle regime must be checked if an empty vehicle is being loaded or if goods are being loaded with a different temperature mode from that of the goods already loaded on the vehicle. If loading goods of the same temperature regime as the goods already loaded on the vehicle, vehicle regime verification is not necessary as it must be compatible with the regime of the goods already loaded.

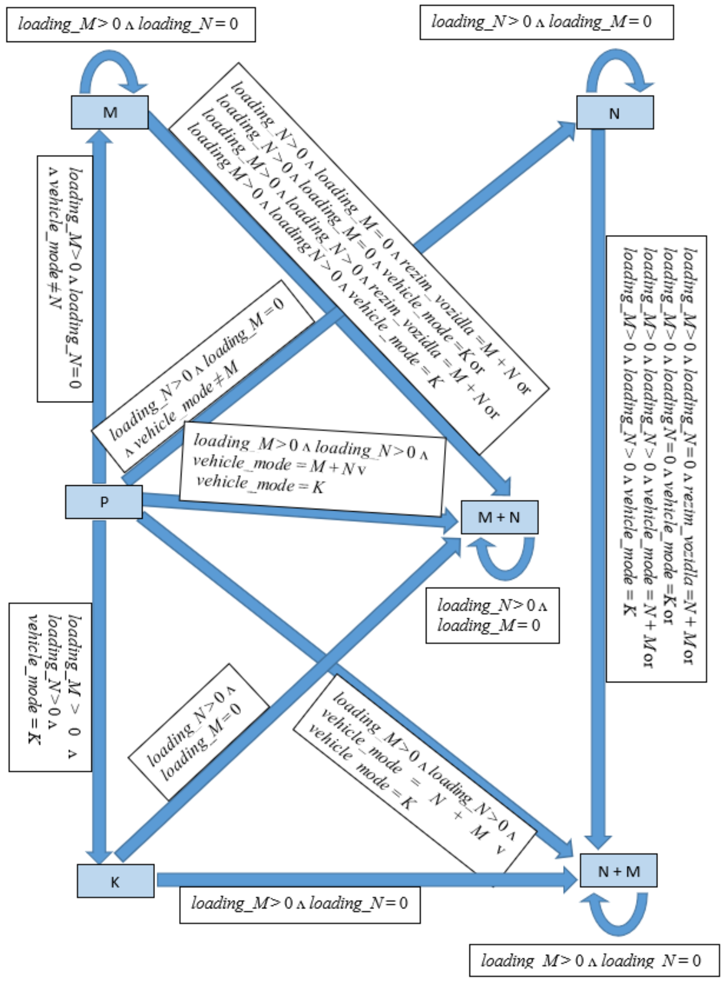

Fig. 2 Transitions between states during loading. Source: authors

Again, situations that could occur during loading but are not permissible according to the algorithm perspective are not included in the graph.

If the cargo regime upon leaving the depot is K, the regime must be adjusted based on the change in the state at the next served vertex. The adjustment is omitted if all frozen and chilled goods are unloaded at the vertex immediately following the depot, resulting in a change of the cargo regime to P. Otherwise, the cargo regime must be adjusted at the depot. If unloading takes place at the first-served vertex, the change in the state at the depot is governed by this vertex. If there is no unloading at the first-served vertex, the change in the state in the depot is governed by the loading at the first-served vertex.

5. Discussion

The paper analysed the Vehicle Routing Problem for different types of goods, drawing from both literature and specialized software. It has been found that different modifications of heuristic algorithms or combinations of some types of metaheuristics involving different parameters and conditions are most often used to solve the Vehicle Routing Problem in practice. The modification of algorithms for solving a particular practical problem is usually tailored to the nature of the problem being addressed.

However, the possibility of simultaneous transport of goods with multiple temperature regimes in a vehicle has not been addressed yet. Therefore, this paper presents a potential solution to this problem. We proposed an additional restrictive condition based on the principle of identifying the states of the cargo temperature regime that can occur before loading or unloading the goods and subsequently determining the transitions between the states of the cargo regime after loading or unloading. Incorporating this condition into existing software would enhance the efficiency of solving the Vehicle Routing Problem and would lead to a reduction in overall transportation cost.

6. Conclusion

The Vehicle Routing Problem is a complex issue that involves numerous constraints in addition to the primary criterion. When dealing with similar complex tasks, a systematic approach should be applied that involves decomposing the problem into subtasks. One of these subtasks is solving the combination of transporting goods with different temperature regimes in a single vehicle. For a specified potential route of a vehicle, whose admissibility in terms of other constraints (capacity, time, etc.) has already been verified, its admissibility in terms of the combination of cargo temperature regimes at all points along the route must also be verified. The admissibility should be verified at the depot at the start of the route, at all served peaks of the route, and again at the depot at the end of the route.

The paper presents a possible solution to this task. During unloading and loading, the admissibility of the proposed route must always be verified at each of the vertices served. The solution involves determining the pre- and post-unloading conditions of the cargo temperature regime, with a similar procedure repeated for vehicle loading. Figures 1 and 2 illustrate the variants of cargo regime states before loading/unloading, describe the change of the state that occurs during loading/unloading, and the resulting state.

A considerable advantage of decomposing a complex problem and solving individual subtasks separately is the possibility of incorporating a subtask into different types of optimization algorithms. Furthermore, a subtask of combining transport of goods with different temperature regimes in a single vehicle can be analyzed and solved separately and then integrated into different types of optimization algorithms to solve the Vehicle Routing Problem, such as the Clark-Wright algorithm or different types of metaheuristic algorithms, including the nearest neighbor algorithm, simulated annealing, or other types of heuristics.

References

[1] Tillman, F.A. & Cain, T.M. (1972). An Upper bound Algorithm for the Single and Multiple Terminal Delivery Problem. Management Science 18(11), 589-721. DOI: 10.1287/mnsc.18.11.664.

[2] Cook, W.J. (2014). In Pursuit of the Traveling Salesman: Mathematics at the Limits of Computation. USA: Princeton University Press.

[3] Bulíček, J. & Mondek, N. (2018). Changes in the traffic situation on city roads after traffic diversion outside the city. In International conference on traffic and transport engineering, 27-28 September 2018 (pp.1064-1072). Belgrade. Serbia: City Net Scientific Research Center Ltd. Belgrade.

[4] Dvořák, Z., Řehák, D., Radimský, M. & Hromada, M. (2019). Dynamic Impact Modelling as a Road Transport Crisis Management Support Tool. Administrative Sciences 9(2), 1-16. DOI: 10.3390/admsci9020029.

[5] Clarke, G. & Wright, J.V. (1964). Scheduling of vehicles from a central depot to a number of delivery points. Operations Research 12(4), 568-581. DOI: 10.1287/opre.12.4.568.

[6] Nuriyev, U., Ugurlu, O. & Nuriyeva, F. (2018). A simple algorithm for the multi-depot multiple traveling salesman problem. In: 6Th International Conference on Control and Optimalization with Industrial Application, 11-13 Jul 2018. Baku, Azerbaijan.

[7] Russell, R., Chiang, W.Ch. & Zepeda, D. (2008). Integrating multi-product production and distribution in newspaper logistics. Computers & Operations Research 35(5), 1576-1588. DOI: 10.1016/j.cor.2006.09.002.

[8] Doyuran, T. & Catay, B. (2011). A robust enhancement to the Clarke-Wright savings algorithm. Journal of the Operational Research Society 62(1), 223-231. DOI: 10.1057/jors.2009.176.

[9] Nehezova, T.S. & Hlavaty, R. (2022). Robust Optimization Approach in Travelling Salesman Problem with Service Time. In: Proceedings of the 40Th International Conference Mathematical Methods in Economics, 07-09 September 2022. Jihlava, Czech Republic.

[10] Altinel, K. & Öncan, T.A. (2005). New Enhancement of the Clarke and Wright Savings Heuristic for the Capacitated Vehicle Routing Problem. The Journal of the Operational Research Society 56(8), 954-961. DOI:/10.1057/palgrave.jors.2601916.

[11] Juan, A.A., Faulin, J., Ruben, R., Barrios, B. & Caballe, S. (2010). The SR-GCWS hybrid algorithm for solving the capacitated vehicle routing problem. Applied Soft Computing Journal 10(1), 215-224. DOI: 10.1016/j.asoc.2009.07.003.

[12] Juan, A.A., Faulin, J., Jorba, D., Riera, D., Masip, D. & Barrios, B. (2011). On the use of Monte Carlo simulation, cache and splitting techniques to improve the Clarke and Wright savings heuristics. The Journal of the Operational Research Society 62(6), 1085-1097. DOI: 10.1057/jors.2010.29.

[13] Dorigo, M. & Stutzle, T. (2004). Ant Colony Optimization. A Bradford Book. Massachusetts Institute of Technology.

[14] Ji, Y., Yang, H. & Zhou, Y. (2015). Vehicle routing problem with simultaneous delivery and pickup for cold-chain logistics. In Proceedings of the 2015 International Conference on Modelling, Simulation and Applied Mathematics, 23-24 August 2015 (pp. 412-425). Phuket, Thailand: Atlantis Press.

[15] Huang, Z., Huang, W. & Guo, F. (2019). Integrated sustainable planning of self-pickup and door-to-door delivery service with multi-type stations. Computers & Industrial Engineering 135, 412-425. DOI: 10.1016/j.cie.2019.06.022.

[16] Berghida, M. & Boukra, A. (2015). Resolution of a vehicle routing problem with simultaneous pickup and delivery. International Journal of Applied Metaheuristic Computing 6(3), 53-68. DOI: 10.4018/ijamc.2015070103.

[17] Pan, X.Y., Wu, J., Zhang, W.Q., Lai, D. & Zhang, D. (2013). A hybrid algorithm for the scheduling of vehicles with simultaneous pickups and deliveries. Applied Mechanics and Materials 475-476, 733-736. DOI: 10.4028/www.scientific.net/amm.475-476.733.

[18] Struwing, C.B., Ruthven, G.A. & Leipzig, K. (2013). The application of design criteria for locating a hub configured supply chain for a restaurant cluster in the Stellenbosch Area. Journal of Transport and Supply Chain Management 7(1), 1-7. DOI: 10.4102/jtscm.v7i1.90.

[19] Gunawan, A., Widjaja, A.T., Vantseewengen, P. & Yu, V.F. (2021). Two-phase Metaheuristic for the vehicle routing problem with reverse cross docking. Annals of Mathematics and Artificial Intelligence 90, 915-949. DOI: 10.1007/s10472-021-09753-3.

[20] Ali, O., Côte, J.F. & Coelho, C.L. (2021). Models and algorithms for the delivery and installation routing problem. European Journal of Operational Research 291(1), 162-177. DOI: 10.1016/j.ejor.2020.09.011.

[21] Destyanto, A.R., Fajar, N.F., Mandhasiya, D.G., Mansur, F.A., Masyhur, M.Z., Aji, N.A. & Bramasta, R.R. (2019). Improving service level and utilization of distribution using discrete event simulation by comparing three vehicle routing problem algorithms: A case study of drugs distribution company. In: AIP Conference Proceedings, 22-24 July 2019. Padang, Indonesia. DOI:10.1063/5.0001058.

[22] Li, D., Cao, Q., Zuo, M. & Xu, F. (2020). Optimization of Green Fresh Food Logistics with Heterogeneous Fleet Vehicle Route Problem by Improved Genetic Algorithm. Sustainability 12(5). DOI: 10.3390/su12051946.

[23] Dvořák, Z., Řehák, D., David, A. & Cerekevac, Z. (2020). Qualitative Approach to Environmental Risk Assessment in Transport. International Journal of Environmental research and Public Health 17(15), 5494. DOI: 10.3390/ijerph17155494.

[24] UNECE. (2022). Agreement on the International Carriage of Perishable Foodstuffs and on the Special Equipment to be Used for such Carriage (ATP): As Amended on 1 June 2022. Retrieved October 7, 2023, from https://unece.org/sites/default/files/2022-05/2201321E_pdf_web%20with%20corrections_protected.pdf

[25] DIGITECH ČR. (2020) Plantour. Retrieved October 16, 2023, from https://www.digitech.cz

[26] Rinkai. (2023). We're the developers of optimisation tool RINKAI ROUTING. Retrieved November 3, 2023, from https://www.rinkai.cz/en

[27] Solvertech (2023). Tasha. Retrieved November 3, 2023, from https://solvertech.cz/produkty/tasha

[28] Solvertech. (2023). Kira. Retrieved November 3, 2023, from https://solvertech.cz/produkty/kira