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Solution approach to incompatibility of products in a multi-product and heterogeneous vehicle routing problem: An application in the 3PL industry

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Abstract **- Vehicle Routing Problem (VRP) is an extensively discussed area under supply chain literature, though it has variety of applications. Multi-product related VRP considers about optimizing the routes of vehicles distributing multiple commodities. Domestic distribution of goods of multiple clients from a third-party logistics distribution centre (DC) is one example of such an application. Compatibility of products is a major factor taken into consideration when consolidating and distributing multiple products in the same vehicle. From the literature, it was identified that, though compatibility is a major consideration, it has not been considered in the literature when developing vehicle routing models. Therefore, this study has been carried out with the objective of minimizing the cost of distribution in the multi-product VRP while considering the compatibility of the products distributed, using heterogeneous vehicle types. The extended mathematical model proposed has been validated using data obtained from a leading 3PL firm in Sri Lanka which has been simulated using the Supply Chain Guru software. The numerical results showcase that cost has been reduced when consolidating shipments in a 3PL DC. The study will contribute to literature with the finding that the compatibility factor of products can be considered when developing vehicle routing models for the multi-product related VRP.**

Keywords - compatibility of products, consolidation, simulation, third-party logistics, vehicle routing problem

I. INTRODUCTION

The Vehicle Routing Problem (VRP) is a well-known problem in the field of Operations Research, in which a set of geographically dispersed customers are served using a fleet of vehicles based in one or several warehouses [1]. This is an extension of the traveling salesman problem [2]. The objective of VRP is to find the optimal set of routes to deliver a set of customers with known demands at an optimized cost, where the vehicle routes are originated and terminated at a destination. Reference [3] states that VRP is an important problem in the fields of transportation, distribution, and logistics. Furthermore, it states that the context in VRP is to plan the routes to deliver goods from a central depot to customers who have placed orders for goods. VRP is an NP (non-deterministic polynomial-time) hard problem that has got a lot of attention in research work, and several techniques on exact methods and heuristics have been proposed and developed in solving the VRP [4].

There are many variants of VRP found in the literature such as Capacitated Vehicle Routing Problem (CVRP), Vehicle Routing Problem with Time Windows (VRPTW), Multiple Products, and Compartment related Vehicle Routing Problem and so on [5][6]. In CVRP, the capacity of the vehicle is imposed as a constraint while in VRPTW, the customer must be served within a specific time interval. In Multi-Product related VRP, multiple commodities are distributed to several customer locations.

One practical example where multi-product VRP can be applied is the domestic distribution of products of multiple clients from a 3PL DC. In this context, 3PL firms could consolidate the goods of multiple clients; thus, the problem can be treated as a multi-product related VRP. Consolidation is the coupling of shipments of different clients into the same vehicle. When considering the 3PL firms in Sri Lanka, most of them are currently not consolidating the shipments of different clients in the domestic distribution, whereas they separately distribute the shipments of those clients. Though consolidation can be identified as cost-effective, it has been challenging for them due to several reasons such as compatibility of different products, the unwillingness of clients to share the same vehicle with another client, and so on. Here the compatibility of the products is a major factor which should be considered when consolidating shipments. As an example, though a detergent product may be compatible with another chemical product, it is not compatible to transport in the same vehicle with a food product, because food items and detergent items are not compatible. Though, this compatibility factor has to be considered when developing the models in the multi-product related VRP, a gap in the existing literature was identified where the compatibility of products has not been considered when developing vehicle routing models. Therefore, this study has been carried out with the objective of considering the compatibility of products in a multi-product and heterogeneous vehicle routing problem where it has been applied to a real-world scenario in the 3PL industry.

II. LITERATURE REVIEW

In order to understand how the problem has been addressed in the previous studies, a thorough literature review was conducted in the areas of VRP where the detailed focus was given to multi-product related VRP and consolidation. It was noted that the compatibility of the products has not been taken into consideration when developing the vehicle routing models in the multi-product related VRP. This section will provide insights on few studies which were conducted on the areas considered in this study.

Reference [7] has considered the VRP with multi-compartments in which the authors have considered the problem, where customers can order several products, and the vehicles contain several compartments, but one compartment is dedicated to one product. The authors of that study have proposed a memetic algorithm and a tabu search algorithm. A study has been conducted by [8] on split VRP with capacity constraints for multi-product cross-docks. In VRP with split deliveries, customers can receive goods in multiple shipments, so the customer can be served by more than one vehicle. A mathematical model has been proposed to optimize the total operational and transportation cost. GAMS software has been used to obtain solutions for this problem in small-sized instances.

Reference [9] has conducted a study on multi-size compartment VRP with a split pattern where the distribution of multiple types of fluid products to customers has been considered. The authors have mainly focused on splitting the order quantities and loading each split demand to the compartments with different capacities and then determining the optimal routes. The paper has proposed three mathematical models and solution procedures of an optimization approach using CPLEX, 2-opt algorithm, and clustering technique. The study conducted by [10] on VRP in the frozen food distribution has proposed a model to optimize the total cost including transportation, refrigeration, penalty, and cargo damage cost. A heuristic-based Genetic Algorithm (GA) has been proposed to solve the model. The paper concludes that the proposed GA method can provide sound solutions in a reasonable time.

A study has been conducted by [3] on VRP for multiple product types, compartments, and trips with soft time windows. In soft time window, a penalty is being charged when the time windows are violated. The mathematical model proposed in the study has been developed in 3 cases: as in the first case, VRP for multiple product types, compartments, and trips is done without considering time windows. In the second case, time window is considered while in the final case, a soft time window is considered. The model proposed in this study contains a lot of constraints since the study deals with several aspects of VRP. A set of data obtained from literature was used to validate the model while AIMMS software has been used to obtain the solution.

The study conducted by [11] on a multi-compartment VRP with a heterogeneous fleet of vehicle has proposed a model to minimize total driving distance using a minimum number of vehicles. A heuristic algorithm has been proposed in the paper which had shown effective results in solving the model. A study conducted on Fuel Replenishment Problem by [12] has considered the multi-compartment VRP with multiple trips to determine the routing of vehicles and the allocation of multiple products to vehicle compartments. The proposed MILP model in the study has been solved using CPLEX and an Adaptive Large Neighborhood Search (ALNS) heuristic algorithm which had given optimal solutions much faster than the exact MILP model using CPLEX.

In conclusion, the authors were unable to locate any model which has considered the compatibility aspects of the product. Thus the study will focus on the compatibility of the product categories when consolidating multiple products.

III. Problem Definition and Mode Development

The problem addressed considers a domestic distribution, which consists of a central 3PL DC, distributing goods of multiple clients to different customer locations in the same region. These customer locations can be regional distributors or supermarkets that have ordered goods of different clients. It is considered that a fleet of heterogeneous vehicles is allocated to distribute the goods. Here the orders are assumed to be given in Cubic Meter (CBM) units and the truck capacities are also given in the same units. This study proposes a model where the goods of multiple clients are consolidated into vehicles considering the compatibility which depends on the nature of the products. However, the method of arranging the allocated orders in the vehicles is not considered in this study. Since the compatibility of products is considered, it is assumed that the products can be arranged in vehicles where there will be no requirement for separate compartments for the products.

Fig. 1, illustrates the problem with a situation where a central 3PL DC is distributing products of 5 different clients to 9 customer locations in a particular region. The products of these 5 clients may belong to 6 different product categories as shown in Fig. 1. The compatibility among the product categories may be different as shown in Table I. If the products are compatible, then shown in 1 if not 0. Currently, the 3PL providers do not consolidate shipments of different clients though they are compatible in nature. Therefore, it is required to build up a model which consolidates these goods considering the compatibility as given in Table I..

Model Assumptions

- Customers are divided into clusters/regions and there will be no movements between clusters.
- The location of the distribution center and customers are constant.
- Distribution centers can adequately satisfy the demands of the customers.

Notations

n	Number of customers
m	Number of product categories
l	Number of brands/clients
v	Number of delivery vehicles
Q_k	Load capacity of k^{th} truck (CBM
q_{igb}	Quantity demanded by i^{th} customer, for g^{th} product category of b^{th} brand (client)
OC_k	Fixed operating cost of kth vehicle
TC_k	Transportation cost per kilometer (delivery cost per distance unit of kth vehicle)
L_{ij}	Distance between client i and client

$$\min Z = \sum_{k=1}^{v} OC_k + \sum_{i=0}^{n}\sum_{j=0}^{n}\sum_{k=1}^{v}(L_{ij} * TC_k * x_{ijk}) \quad (1)$$

$$\sum_{i=0}^{n}\sum_{g=1}^{m}\sum_{b=1}^{l}\sum_{t=1}^{m}(q_{igb} * y_{ik} * z_{gk} * z_{tk}) \leq Q_k \ \forall_k \quad (2)$$

$$\sum_{i=0}^{n} x_{ijk} = y_{jk} \qquad \forall_{j,k} \quad (3)$$

$$y_{ik} = \begin{cases} 1 & i^{th}\ customer\ is\ served\ by\ k^{th}\ truck \\ 0 & otherwise \end{cases} \quad (4)$$

$$x_{ijk} = \begin{cases} 1 & k^{th}\ truck\ drives\ from\ i\ to\ j \\ 0 & otherwise \end{cases} \quad (5)$$

$$z_{gk} = \begin{cases} 1 & g^{th}\ product\ type\ is\ transported\ in\ truck\ k \\ 0 & otherwise \end{cases} \quad (6)$$

Note:

$$z_{gk} * z_{tk} \begin{cases} 1\ if\ 2\ product\ types\ are\ compatible\ t = 1 \dots m \\ 0\ if\ 2\ product\ types\ are\ incompatible\ t = 1 \dots m \end{cases}$$

Here the expression (1) is the objective of the model, which is to minimize the overall cost of transportation including the fixed operating cost of vehicles and delivery cost per distance unit of vehicle type. Expression (2) ensures that the vehicles are not overloaded in terms of capacity. Expression (3) ensures that the route for each vehicle is considered. Expressions (4), (5) and (6) reflect the integer constraints related to assigned truck k or product type is transported in kth truck. Note: ensures the compatibility constraint where only compatible product categories are transported in a vehicle.

TABLE I. COMPATIBILITY MATRIX

	Apparel	Chemical	Detergent	Food	Pharma	Stationary
Apparel	1	0	1	1	1	1
Chemical	0	1	1	0	0	1
Detergent	1	1	1	0	0	1
Food	1	0	0	1	1	1
Pharma	1	0	0	1	1	1
Stationary	1	1	1	1	1	1
Compatibility Matrix						

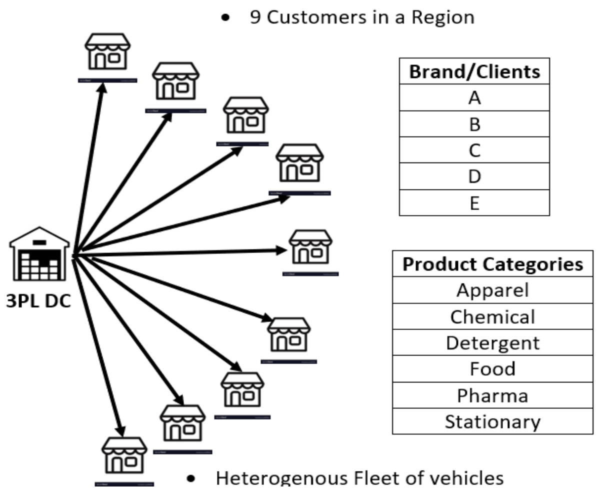

Fig. 1. Problem identification

Expressions (4), (5) and (6) reflect the integer constraints related to assigned truck k or product type is transported in kth truck. Note: Ensures that the route for each vehicle is considered.

IV. Data Analysis and Results Obtained

The extended mathematical model was validated using the data obtained from a leading 3PL provider in Sri Lanka. Customer locations were first divided into regions according to the distance. Then a particular region was selected, and the model was applied considering that region. Supply Chain Guru modelling and simulation software was used to simulate a real-world scenario taken from the 3PL provider. As mentioned earlier, since they are currently not consolidating the shipments of multiple clients, this current scenario was modelled as the baseline case and several other scenarios such as the consolidation scenario were created.

The real-world example considered here consists of a 3PL DC situated in Colombo, Sri Lanka, distributing sixdifferent categories of products to 9 different customers in the Southern region (same region). Fig. 1, shows the locations of the customers and the 3PL DC. It was assumed that a fleet of trucks with 10 vehicles of different capacities is available for the delivery process and their relevant delivery cost per km and the fixed costs were fed to the model. Geocode in Supply Chain Guru software was used to obtain the locations of the customers and the site. Data tables which were used include customers, sites, products, transport assets, asset availability, relationship constraints, rate, etc.

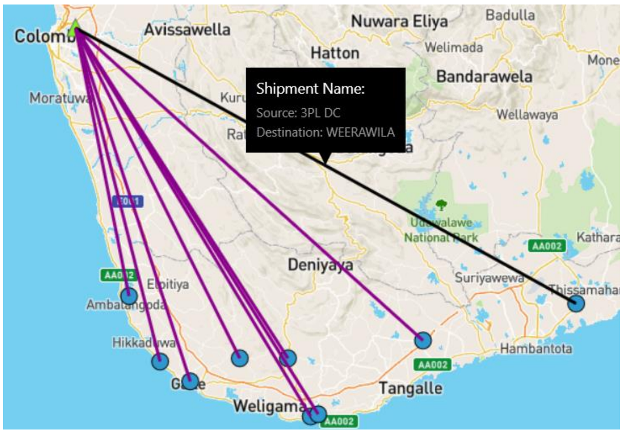

Fig. 2. Customer & 3PL DC Locations

The baseline case was compared with other scenarios based on the cost of travelling, travelling distance, use of vehicles, etc. Since the latitudes and longitudes of the locations are given as inputs here, the distance between locations is considered as the direct distance between locations. The results obtained from the simulated model using Supply Chain Guru software for the above scenario are discussed here.

The baseline model represents the situation where shipments of different clients are distributed separately, even to the same region though there are compatible shipments which can be distributed together. Fig. 3 depicts the aforementioned baseline scenario.

The consolidation scenario was created where compatible shipments are allowed to be shipped in the same vehicles. It was observed that the total transportation cost could be reduced. The route map of this scenario is shown in Fig. 4.

Fig. 3. Current scenario

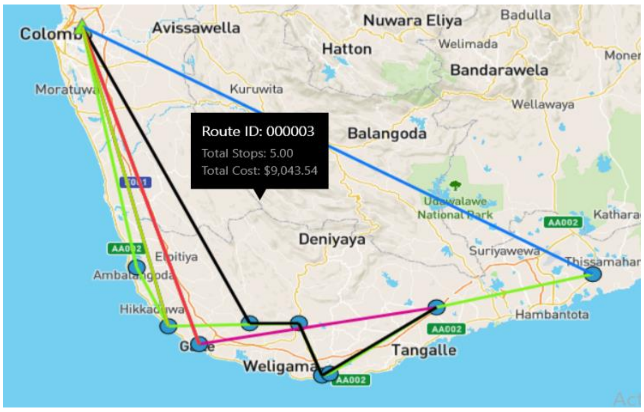

Fig 4. Consolidated scenario

Table II presents the comparison of the baseline model, where the shipment of different clients were not being consolidated with the consolidation scenario where compatible shipments are consolidated and distributed. It was evident from this model that, for the above example, a percentage cost reduction of 11% could be achieved when consolidating shipments of different clients. Further, the distance travelled could be reduced significantly. During the simulation of the proposed model using Supply Chain Guru software, it was experienced that the percentage of cost reduction varied between 10% and 18%.

TABLE II. COMPARISON OF CURRENT & CONSOLIDATION SCENARIOS

	Baseline		**Consolidation**
Total cost	79,360.08		70,488.38
# Trucks used	Truck 1	1	2
	Truck 2	0	1
	Truck 3	3	1
	Truck 4	2	2
	Truck 5	1	1
Total distance travelled	788.88		745.59

% Cost Reduction = (79,360.08-70,488.38) / 79,360.08
= 11.18%

% Distance Reduction = (788.88-745.59)/ 788.88
= 5.48%

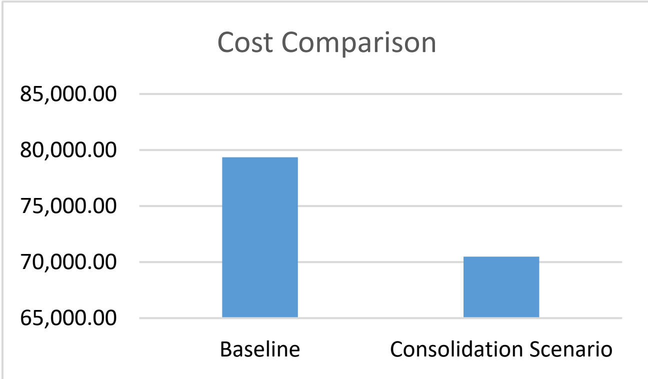

Fig. 5. Cost comparison

Fig. 5 depicts the comparison of the total costs in the baseline model and the consolidation model.

V. CONCLUSION

Multi-product related VRP is a variant of VRP which is a well-discussed problem in the literature. Since multi-product related VRP considers multiple commodities, a practical example for such a scenario could be identified as the domestic distribution of products of multiple clients from a 3PL DC. In Sri Lanka, most of the 3PL firms do not consolidate the shipments of multiple clients, though it could be found as cost-effective. One major factor which avoids 3PL firms from consolidation is the compatibility factor of products which should be definitely taken into consideration. From the referred literature, it was identified that a gap is existing where the compatibility of products has not been taken into account when developing models. Therefore, this study was conducted in order to address the above-mentioned gap. The extended mathematical model proposed in this study has been developed considering the compatibility of products. A real-world scenario taken from a leading 3PL provider in Sri Lanka has been used to validate the model which has been simulated using Supply Chain Guru modelling and simulation software. The numerical results have shown that the cost could be reduced nearly by 11% when consolidating the shipments, considering the compatibility. The study can be further expanded by adding more complexity to the model, considering different constraints such as order cutoff times, etc.

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