Journal of Service Science and Management, 2022, 15, 308-322
https://www.scirp.org/journal/jssm
ISSN Online: 1940-9907
ISSN Print: 1940-9893

A Model for Minimizing the Cost of Distributing Metallic Coins in Mexico

Mariana Gómez-Vargas, Aida Huerta-Barrientos*

Operational Research Department, Faculty of Engineering, National University of Mexico, Mexico City, Mexico
Email: marianaggvv@gmail.com, *aida.huerta@comunidad.unam.mx

How to cite this paper: Gómez-Vargas, M., & Huerta-Barrientos, A. (2022). A Model for Minimizing the Cost of Distributing Metallic Coins in Mexico. *Journal of Service Science and Management, 15,* 308-322.
https://doi.org/10.4236/jssm.2022.153018

Received: April 20, 2022
Accepted: June 27, 2022
Published: June 30, 2022

Abstract

Currently, cash distribution experts know the importance of supporting decisions in an optimization model. Different enterprises and institutions design their distribution routes in an empirical way, without using robust theoretical tools that minimize transport costs and maximize levels of customer satisfaction. Particularly, considering the case of the Bank of Mexico, the distribution of metallic coins is a fundamental process. However, there are areas of opportunity in planning and scheduling distribution routes, which could lead to coin shortage, and delays in deliveries to end-users generating high costs for the institution. The objective of this study is to propose the use of an optimization model for minimizing the cost of distributing metallic coins in Mexico, which has different delivery points all over the country. The number of the required origin warehouses is determined, as well as the routes for each vehicle, minimizing the distribution costs. Based on the results, this research is also considered relevant for other banking institutions to help in their making-decision process.

Keywords

Optimization Model, Bank of Mexico, Metallic Coins, Distribution

1. Introduction

Cash plays an important role considering that it is still the most common way of payment despite the appearance and spread of other payment methods. In the US cash circulation increased by 76% between 1990 and 2005 and according to projections made at the time, by 2010 the stock of cash circulating in the economy would reach 1000 billion USD. In the UK, 66% of household consumption was forecasted to be still paid for in cash in 2011 (Rajamani, et al., 2009). Around the world, despite their misgivings, most consumers see the future of money as less cash and more card-based. Only 27% think that, in 10 years, people will use a mix of payment types not very different from what we use today (Oxford Economics, 2017). In fact, a third of consumers globally think e-money will be the dominant payment method. Similarly, in Mexico, the payment methods that people use for their daily expenses in 2018 were: 91% uses cash, 12% uses debit cards, 4% uses credit cards, and only 3% uses electronic transfers (SPEI) (Banxico, 2018a).

Nowadays, a central bank is a public financial institution, considered the highest monetary authority, which exists in most countries of the world. Generally, it is an entity with autonomy and independence from the government in turn. The functions and objectives of the Central Banks depend on each country (Warjiyo & Juhro, 2019). Among the main objectives are the following: to maintain price stability through inflation control, to maintain exchange rate stability relative to other currencies, to achieve positive and sustainable economic growth, to moderate interest rates, to provide money to the national economy, to be the bank of banks and governments, to regulate and inspect payment systems, to design monetary policy.

The functions and objectives of the Mints depend on each country. Among the main objectives are the following: to design and produce coinage for circulation, to design, produce and commercialize numismatic items, to distribute coins, to disburse gold and silver for authorized purposes, to safeguard and control the movement of bullion, the coin recycling, and alloy recovery class of record.

As in any supply chain, the velocity or frequency of cash handling, the cost of circulating cash, and the quality (fitness) of cash indicate the efficiency, resilience, and robustness of the cash supply chain. The structure of a cash supply chain is largely dictated by the policy of the central bank in that country. Traditionally, central banks are viewed as being responsible for all aspects of cash circulation: produce, issue, move, store, receive, sort, authenticate, and destroy. In response to the increase in Automated Teller Machines (ATMs), the rising demand for fit cash by businesses, and the overall increased use of cash within economies, the central banks of many countries have increased their capacities, and the cost of providing currency services has risen as well. This has led governments to promote various cash supply chain business models. These models are differentiated by the currency services offered by the central bank. Cash circulation is mainly driven by the demand for cash by customers for transaction purposes. The various business models adopted by different countries can be classified into three as shown in **Table 1**. Banks face the usual dilemma when setting their cash inventory level: they must hold an enough amount to meet customer demand at all times, but they also want to minimize the amount held, since cash in inventory generates a cost of lost opportunity. The demand for cash varies considerably within a week, within a month, and within a year, as well as varying between branch locations for a particular bank and between main

Table 1. Three types of banknote supply chains (Blacketer & Evetts, 2004).

Type	Level of privatization		
	Privatized	**Semi-privatized**	**Centralized**
Additional services	Production and destruction of currency	Balance sheet relief but no deposit facility	Recirculation, fit-sorting
Countries	Australia, South Africa	Canada, UK, Mexico	Germany, Poland, France

offices of different banks. Some bank branch offices are net cash recipients, while others are net cash suppliers (Rajamani et al., 2009).

Considering the case of the Mexican Central Bank, the methodology used for delivering the metallic coins is cluster first, route second. Firstly, it is necessary to generate groups of clients, also called clusters, that will be on the same route in the final solution. Secondly, for each cluster, a route is created that visits all its clients. Additionally, capacity restrictions are considered in the first stage, ensuring that the total demand of each cluster does not exceed the truck's capacity. Therefore, building the delivery routes for each cluster is very similar to the Travel Salesman Problem (TSP), very used in Operations Research. Finally, to create the clusters it is necessary to join all the bank's requests by place of delivery and fill the trucks taking care of the capacity restriction, the rest should be used to make the routes. The tool currently used is excel, it is created by human specialized resources and it takes 8 hours to develop the monthly plan. The big problem with this way of calculation is, on the one hand, the probable human error that can be induced, and on the other hand, the human resources learn to generate the groups of clients by expertise, through trial and error technique. The main implication in this way is that the delivery cost is incremented and the Mexican Central Bank and the commercial banks assume such variability. This research aims to minimize the cost of distributing metallic coins, generating the efficient use of the economic and human resources destined for it and satisfying the demand for national currency, with the times and quality required by the society.

The innovative aspect of this article is the way in which the Vehicle Routing Problem (VRP) in the version Capacitated Multi Depot Vehicle Routing Problem with Heterogeneous Fleet is used to support the decision process for minimizing the cost of distributing metallic coins, using to solve its Constraint Programming (CP), Large Neighbourhood Search (LNS) and Feature-based Insertion algorithms. This model can be used to optimize a variety of delivery processes and design anticipatory scenarios to improve response.

The rest of the paper is organized as follows. The literature review about money supply and routing models and algorithms is addressed in Section 2. In Section 3 the mathematical model to determine feasible distribution paths in Mexico between Regional Cashiers and the locations of the Commercial Banks where they need coins is discussed, followed by the solution procedure using the INDIGO™

solver in Section 4. Finally, Section 5 concludes the paper.

2. Literature Review

2.1. Money Supply

Geismar et al. (2016) presented a survey of research on currency supply chains. The classification of problems from the perspective of commercial banks (demand-side) and from the perspective of the central bank (supply-side) is presented. Most of the demand-side studies develop models to manage commercial banks' inventory and logistics under the U.S. Federal Reserve's (FED) new guidelines, which were designed to encourage banks to be less dependent on the FED to provide currency services (Rajamani et al., 2009). From the demand perspective, Mehrotra et al. (2010) considered how large banks should respond to the more advanced features of the FED's new guidelines. Zhu et al. (2011) analyzed the problem as it applies to medium-sized banks. In the literature, we find some works that considered supply perspective. Dawande et al. (2010) proposed coordination mechanisms for the U.S. cash supply chain. Zhu et al. (2015) focused on the security concerns of a central bank in a developing country. In contrast, Huang et al. (2016) address the Central Banks' supply and logistics network nationwide.

On the other hand, inventory-location models are another important stream of research related to location selection. Significant papers on this topic include Nozick and Turnquist (1998), Nozick and Turnquist (2001a), Nozick and Turnquist (2001b), Daskin et al. (2002), Shen et al. (2003), Yao et al. (2010) and Tancrez et al. (2012).

2.2. Vehicle Routing Problem (VRP)

The VRP calls for the determination of the optimal set of routes to be performed by a fleet of vehicles to serve a given set of costumers, and it is one of the most important and studied combinatorial optimization problems. It is known to be an NP-hard problem. The CVRP is an extension of the well-known Traveling Salesman Problem, TSP, calling for the determination of a Hamiltonian circuit with minimum cost visiting exactly once a given set of points. In 1959, Dantzig and Ramser introduced the VRP problem describing a real-world application concerning the delivery of gasoline to service stations and proposed the first mathematical programming formulation and algorithm approach. A few years later, in 1964, Clarke and Wright proposed an effective greedy heuristic that improved on the Dantzig and Ramser (1959) approach. As Toth and Vigo (2014) suggested, multiple models, algorithms, packages were proposed for the optimal and approximate solution of the different versions of the VRP. Toth and Vigo (2014) proposed the following generic verbal definition of the family of vehicle routing problems:

Given: A set of transportation requests and a fleet of vehicles. The problem is then to find a plan for the following:

Task: Determine a set of vehicle routes to perform all (or some) transportation requests with the given fleet at minimum cost; in particular, decide which vehicle handles which requests in which sequence so that all vehicle routes can be feasibly executed.

The first classification of VRP was adapted from Jaegere et al. (2013) and Eksioglu and Vural (2009). They distinguished five main topics each with its own detailed categories and sub-categories: type of study, scenario characteristics, problem physical characteristics, information characteristics, and data characteristics. Also Jaegere et al. (2013) considered that in the last years the most used models in literature are:

- CVRP (Capacitated).
- VRPTW (Time Window).
- HVRP (Heterogeneous).
- MDVRP (Multi Depot).
- VRPPB (Backhauls).
- SDVRP (Split Deliveries).
- DVRP (Dynamic).
- PVRP (Periodic).
- VRPSD (Stochastic Demands).
- VRRSPD (Simultaneous Pickup and Delivery).
- OVRP (Open).
- TDVRP (Time Dependent).
- MCVRP (Multi-Compartment).
- CCVRP (Cumulative).

The second classification was proposed by Toth and Vigo (2014), which may help in identifying the specific characteristics of a VRP that one wants to model and solve, as follows: the (road) network structure, the type of transportation requests, the constraints that affect each route individually, the fleet composition and location, the inter-route constraints, and the optimization objectives.

2.3. Some Algorithms to Solve the VRP

Jaegere, et al. (2013) showed that in the last years the most used algorithms to solve the VRP are the following:

- Metaheuristics. Current metaheuristics for the VRP can broadly be classified into local search methods and population-based heuristics. Local search methods explore the solution space by moving at each iteration from a solution to another solution in its neighborhood (Toth & Vigo, 2014). These include:
    - Local Search Algorithms.
    - Population-Based Algorithms.
    - Hybridizations.
    - Unified Algorithms.
- Heuristics. The history of VRP heuristics is as old as the problem itself, the evolution of VRP heuristics over the past 10 years has taken place, almost ex-

clusively, within the context of metaheuristics. Some of the principal are:

- The Clarke and Wright Savings Heuristic.
- Petal Algorithms.
- λ−OPT exchanges.
- Relocate.
- Swap.
- Adaptative Large Neighborhood Search (ALNS).

- Exact Methods. The main approaches used are:
  - Branch-and-Bound Algorithms.
  - Early Set Partitioning Algorithms.
  - Branch-and-Cut Algorithms.

3. Materials and Methods

3.1. The Context for Distributing Metallic Coins in Mexico

One of the aims of Mexican Central Bank is to supply domestic currency to the economy (Banxico, 2018b). In addition to printing banknotes and ordering the minting of coins by Casa de Moneda de Mexico (Mexican Mint), an entity that is subordinate to the Ministry of Finance and Public Credit (SHCP, for its acronym in Spanish). To achieve this goal, a money supply system must be in place to guarantee the availability of cash (money) wherever and whenever, in the denominations and with the quality required by people. Mexican Central Bank, jointly with commercial banks and cash carrier companies, is responsible for the proper functioning of this distribution system. Coinage distribution begins at the Mexican Mint located in San Luis Potosi, Mexico. From this location, coins are delivered to the Regional Cashiers Hermosillo, Monterrey, Guadalajara, Ciudad de Mexico, Veracruz and Merida (see **Figure 1**). Cash carrier companies then transport by land the coins to their destination. It is the lawful duty of Mexican Central Bank to order coinage to the Mexican Mint and pay for this service. Since bank correspondents are not involved in the distribution of coins, coin requirements at the sites that do not have Regional Cashiers are met directly by Mexican Central Bank head offices through cash carrier companies that transport the coins to the requesting local banks. Bank requests are also handled directly by the Regional Cashiers (Banxico, 2018c).

The Central Mexican Bank has the responsibility for providing the currency in 86 destinations. The distribution is initially taken to 6 destinations, the Regional Cashiers: Guadalajara, Hermosillo, Monterrey, Merida, Veracruz and Mexico City. At these locations is where the commercial banks are directly attended, or, taking them the currency where they request it, within the 80 destinations located in all the country. The currency is divided into 8 denominations: 20, 10, 5, 2, 1, 0.50, 0.20 and 0.10 Mexican pesos; each one has a different demand and behavior. The Credit Institutions that use the cash services: withdrawals and requests for metallic currencies in the Regional Cashiers or places where there are

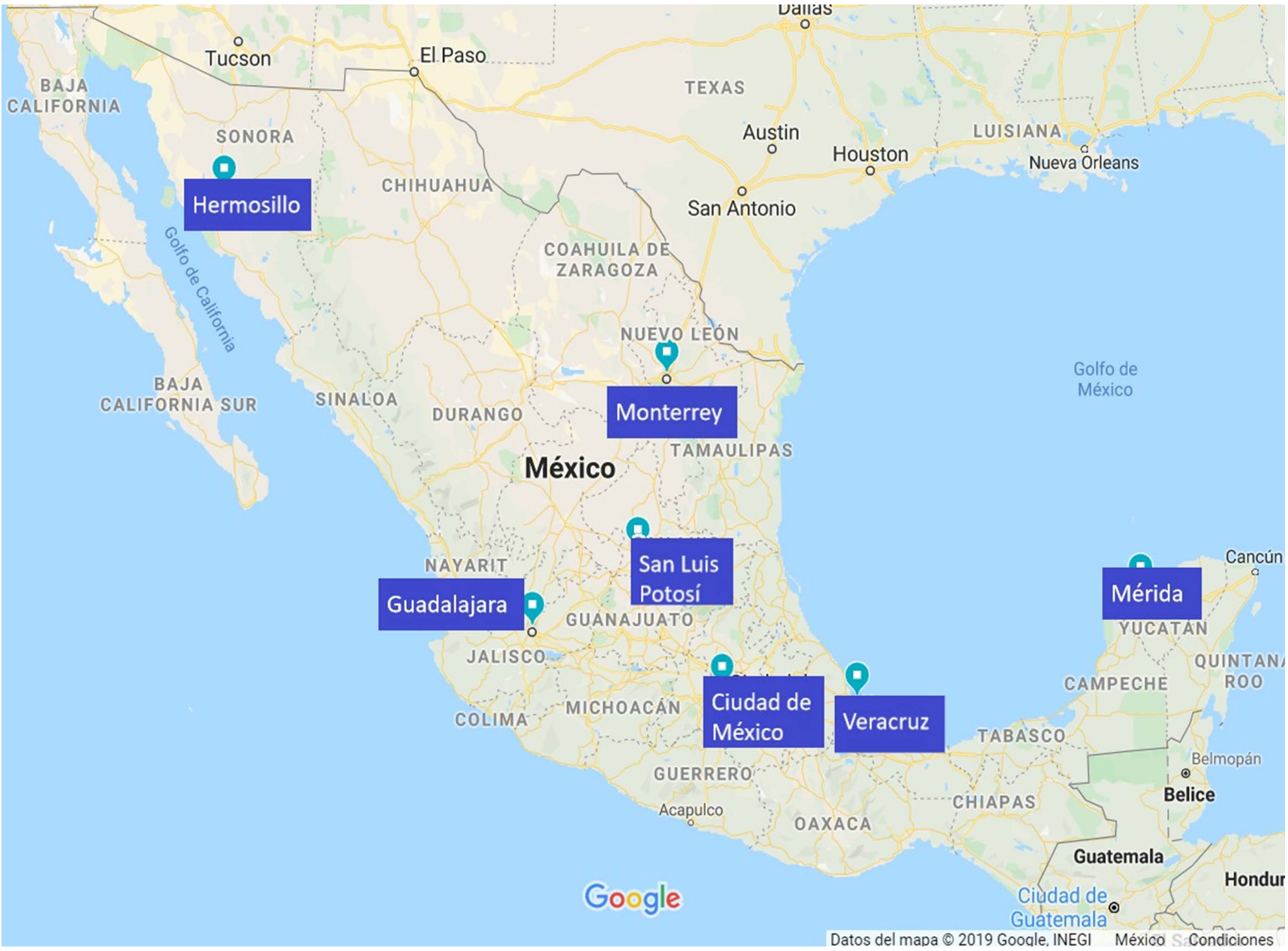

Figure 1. Location of Regional Cashiers and Mexican Mint. Source: all spatial data was collected by authors based on Banxico (2018d).

no one, from the Cash Operations Circular, must first make sure that no credit institution located in the same place has surpluses. For all requests for metallic coins, the applications must be registered in the computer systems provided.

The Central Mexican Bank allocates an important part of its budget in determining the amount of metallic currency that must be minted each year and for distribution. For distribution in 2018, the total cost was $54515353.28 Mexican pesos of which $30771540.54 Mexican pesos corresponded to the distribution services from Casa de Moneda de Mexico to the Regional Cashiers, and $23743812.74 Mexican pesos were charged to Credit institutions for their request of metallic coins, it means that when the Credit Institutions request the Mexican Central Bank to deliver metallic coins in places where there are no Regional Cashiers, the costs incurred for transporting and delivering will be payed by them (see **Figure 2**). The distribution is carried out by adjusting the quantities to be sent depending on various aspects, among which we can mention: the seasonal behavior in each region and the variations in its demand, circulation policies established by the central bank, warehouse vault capabilities, and limited number of trucks per region.

Figure 2. Location of peer-to-peer and banking places where the Mexican Central Bank directly deliver the needs of metallic coins. Source: Source: all spatial data was collected by authors based on Banxico (2018d).

3.2. VRP Model

The model proposed is Capacitated Multi Depot Vehicle Routing Problem with Heterogeneous Fleet based on the papers by Ropke and Pisinger (2006) and Kilby and Verden (2011). It is needed the coins supply to n commercial banks (customers). Each customer i specifies the location for service l_i, and the quantity of coins required q^i. A fleet of m vehicles are available to perform deliveries. Each vehicle k has capacity Q_k. We have the cost of travel between each pair of customer c_{ij}. In the most basic form of the problem, it is desirable to find a set of routes, one for each vehicle, such that customer requests are satisfied at minimum total cost, subject to the constraint that the total quantity of deliveries assigned to each truck does not exceed the truck capacity.

The VRP model proposed by NICTA (2013) to solve the problem heuristically is the following:

- n customers (fixed in this model).
- m routes (fixed in this model).
- Fixed locations.
    - o Where things happen, one for each customer and one for each depot.
- c commodities (weight).

- Known demand from each customer for each commodity.
- Known distance between each location pair.
- Known cost between each location pair.
  - Both obey triangle inequality.

It has been considered the following:

- A solution is made up of routes (one for each vehicle).
- A route is made up of a sequence of visits.
- Some visits serve a customer (customer visit).
- Each route has a "start visit" and an "end visit".
- Start visit is first visit on a route—location is depot.
  End visit is last visit on a route—location is depot.
- Also have an additional route—the unassigned route (where visits live that cannot be assigned).

Customers:

- Each customer has an index in $N = \{1.n\}$.
- Customers are "named" in CP by their index.

Routes:

- Each route has an index in $M = \{1.m\}$—Unassigned route has index 0.
- Routes are "named" in CP by their index.

Visits:

- Customer visit index same as customer index.
- Start visit for route k has index $n + k$; as start_k.
- End visit for route k has index $n + m + k$; as end_k.

Sets:

$N = \{1.n\}$—customers.

$M = \{1.m\}$—routes.

$R = M \cup \{0\}$ —includes "unassigned" route.

$S = \{n + 1.n + m\}$—startvisits.

$E = \{n + m + 1.n + 2m\}$—end visits.

$V = N \cup S \cup E$ —all visits.

$V^S = N \cup S$ —visits that have a sensible successor.

$V^E = N \cup E$ —visits that have a sensible predecessor.

Input Data:

V_i, the 'value' of customer i.

D_{ik}, demand by customer i for commodity k.

E_i, earliest time to start service at i.

L_i, latest time to start service at i

Q_{jk}, Capacity of vehicle j for commodity k.

T_{ij}, Travel time from visit i to visit j.

C_{ij}, Cost of travel from i to j.

Successor variables: s_i.

s_i gives direct successor of i.

$s_i \in V^E$ for i *in* V^S $s_i = 0$ for i in E.

Predecessor variables p_i.

p_i gives the index of the previous visit in the route.

$p_i \in V^S$ for i in V^E $p_i = 0$ for i in S.

Redundant—but empirical evidence for its use:

Route variables r_i.

r_i gives the index of the route (vehicle) that visits i.

$$r_i \in R$$

Accumulation variables:

q_{ik} Quantity of commodity k after visit i.

c_i Objective cost getting to i.

For problems with time constraints:

a_i Arrival time at i.

t_i Start time at i (time service starts).

d_i Departure time at i.

$$\text{Minimize } \sum_{i \in E} c_i + \sum_{i \mid r_{i=0}} v_i$$

Path $\left(S, E, \{S_i \mid i \in V\}\right)$.

All diferent $\left(\{p_i \mid i \in V^E\}\right)$.

Accumulate obj. $c_{S_i} = c_i + C_{i,S_i}, \ \forall i \in V^S$.

Accumulate time $a_{S_i} = d_i + T_{i,S_i}, \ \forall i \in V^S$.

Time windows $t_i \ge a_i, \ \forall i \in V$.

$$t_i \le L_i, \ \forall i \in V$$

$$t_i \ge E_i, \ \forall i \in V$$

$$t_i = 0, \ \forall i \in S$$

Load $q_{S_{ik}} = q_i k + Q_{S_{ik}}, \ \forall i \in V^S, \ k \in C$

$$q_i k \le Q_{r_{ik}}, \ \forall i \in V, \ k \in C$$

$$q_i k \ge 0, \ \forall i \in V, \ k \in C$$

$$q_i k = 0, \ \forall i \in S, \ k \in C$$

consistency $S_{p_i} = i, \ \forall i \in V^S$

$$p_{S_i} = i, \ \forall i \in V^E$$

$$r_i = rS_i, \ \forall i \in V^S$$

$$r_{n+k} = k, \ \forall k \in M$$

$$r_{n+m+k} = k, \ \forall k \in M$$

3.3. INDIGO™ Software

To solve the VRP model, the software INDIGO™ was used, which is a VRP solver and it was developed at NICTA (National ICT Australia Ltd, Australia's Information and Communications Technology Research Centre of Excellence). INDIGO™ builds the solution in two phases. During phase one, a feasible solution is constructed using the Clarke's Savings Method and during phase two a Local Search Algorithm is used to improve on the solution. The improvement phase uses the Large Neighborhood Search (LNS) metaheuristic and insertion methods that build a solution by inserting one visit at a time into an emerging route set. INDIGO™ internally uses a Constraint Programming (CP) framework to model the problem as a variable assignment problem. Combining this CP representation allows INDIGO™ to effectively prune large sections of the unfeasible search space. Using CP as the underlying model allows INDIGO™ to be very flexible in modeling the side constraints of the classical VRP. One can easily extend INDIGO™ to handle much more expressive VRP variants. The input for INDIGO solver is a VRX ASCII file format document, which is used for encapsulate the instance of the VRP problem to solve. The VRX ASCII file is an extension of the VRPLIB library used in some VRP benchmarks.

4. Results and Discussion

Results from INDIGO™ Solver

Finding the solution to the VRP model using INDIGO™ solver we obtained the results showed in Figure 3 in terms of best profit obtained through the assignment of vehicles to routes, total cost, wait time, and the total distance that vehicles travel.

First of all, we observed that several requests were not assigned to available vehicles and routes. This means that the truck configuration is not enough, and an adjustment must be made. It is important to note that Mexico has an extensive territory, and in consequence the road network is very large. The problem here is that some coverage zones of warehouses for the delivery are overlap. The coverage zones where is considered as an ideal circle with a radium but when the coverage zones are overlapping the model present a warning. To solve this detail, each time the VRP model is executed it is important to do some adjustments to the maximum radium allowed for the coverage zones of the warehouses, following the terminology of the VRP. Similarly, we noted that no requests were assigned

```
Solution COIN
                   Solver ./indigo Version 2.0  Build 30 08:27 4 Jul 2019 at Fri 13/03/2020 02:44:26
                 Run date Fri 13/03/2020 02:44:26
         Reportable cost 5.53381e+06
          Num Unassigned 55
                  Profit 2.46619e+06
              Obj Metric 33814
               Penalties 0
    Additional obj terms 0
  Value of assigned reqs 8e+06
Value of unassigned reqs 5.5e+06
     Vehicle Fixed Costs 0
               Wait time 0
              Total cost 5.53381e+06
           All Penalties 0

Metric totals:
  Dist: 33814
```

Figure 3. First solution from INDIGO™ solver. Source: data was collected by authors.

because the capacity of some of the trucks were exceeded, so also it is necessary to adjust them before executing the model. After doing the adjustment on the limits of coverage zones for each warehouse and on the capacity of the trucks, and executing again the VRP model on INDIGO solver, we obtained the results showed in Figure 4.

In the last case, the total distance for delivering the metallic coins requested from warehouses to 55 cities was 65452 kilometers.

The main advantages of using the VRP model proposed are the following.

- Advantage 1: In terms of time to prepare the distribution plan exists a saving on time and resources.
- Advantage 2: In terms of associated costs, the system allows us to obtain the minimum number of kilometers between cities and warehouses, and therefore the cost of the kilometer decreases.
- Advantage 3: In terms of reliability in the system, the elaboration of the distribution plan does not depend on the experience of the analysts.

In contrast, the main disadvantages of not using the VRP model are as follows.

- Disadvantage 1: It is necessary to automate the process of entering data into the model and its subsequent analysis for each of the runs.
- Disadvantage 2: It is necessary to create a flexible interface to interact with the analyst.
- Disadvantage 3: The system is executed externally, which means the distribution plan is carried out by the analysts without tools for the decision support.

```
Solution COIN
                   Solver ./indigo Version 2.0  Build 30 08:27 4 Jul 2019 at Mon
29/06/2020 03:02:33
                 Run date Mon 29/06/2020 03:02:33
         Reportable cost 65452
          Num Unassigned 0
                  Profit 1.53345e+07
              Obj Metric 65452
               Penalties 0
    Additional obj terms 0
  Value of assigned reqs 1.54e+07
Value of unassigned reqs 0
     Vehicle Fixed Costs 0
               Wait time 0
              Total cost 65452
           All Penalties 0

Metric totals:
  Dist: 65452
```

Figure 4. Second solution from INDIGO™ solver. Source: data was collected by authors.

5. Conclusion

The Vehicle Routing Problem is a well-studied combinatorial optimization problem with many real practical applications. In this research, the Capacitated Multi Depot Vehicle Routing Problem with Heterogeneous Fleet using Constraint Programming (CP), Large Neighbourhood Search (LNS), and Feature-based Insertion was addressed.

One of the main contributions of this work is to express this task as an optimization problem and to propose a model to solve it. Different types of models and algorithms have been presented, and also were shown other software tools, these tools were not completely compatible with the characteristics of the problem presented, so this is the reason why these programs were not used to solve it. The usefulness of the model proposed was saving on time and resources in the delivery planning of metallic coins. Using the model will eliminate the risk of human errors so the results are more accurate and reliable. It is known that computer programs make calculations faster than humans, and using them we can process more data and adjust results to new conditions almost instantaneously.

The route optimization solution will allow to taking the quality of the delivery services to the next level and boost customer satisfaction. To demonstrate this, data on the current situation were first collected, then experiments were made, and finally the comparisons with the current routing method in the Mexican Central Bank. The computational time was surprisingly less than one minute (Tc < 1 minute) so these results can lead to the conclusion that this model can be very convenient in practice and also because there is flexibility for various variants of VRP. So, it could be used as a decision support tool that allows to improving the planning of delivery of metallic coins and the allocation of optimal resources. Throughout the development of the model, it was necessary to thoroughly validate each of the input data, parameters, and output data to guarantee a realistic solution, consistent with the routes previously used by the Mexican Central Bank.

There are a number of gaps in our knowledge around delivering planning of metallic coins that follow from our findings and would benefit from further research.

- The use of time windows: There are important reasons to use time windows, for example, that the banks do not work all day and that the trucks should not circulate at night.
- Cluster: The idea of clustering as a means to help reduce the size of the search neighborhood.
- Use a Mixed Integer Programming (MIP) model: Literature says that exact methods for solving VRPs with optimality are based on MIP and are only capable of solving instances with no more than 100 requests because are NP-complete.
- Consider the inventory: In this work, it is assumed that all the stock is available in each warehouse.
- Implementation with Mexican Central Bank resources: Means to program this model internally so that the databases necessary for the execution of the model interact, since for this work it was tried to execute externally.

Acknowledgements

The authors are grateful to the Faculty of Engineering, the National Autonomous University of Mexico for partially funding this research. Also, the authors greatly appreciate the contribution of reviewers who have dedicated their valuable time and efforts to improving the quality of this paper.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Banxico (2018a). *Resultados de estudios cuantitativos y cualitativos sobre efectivo 2018.* http://www.banxico.org.mx/billetes-y-monedas/estudios-e-indicadores/%7BE78EA1C4-B511-2E4D-2935-5DA0EA60AC0F%7D.pdf

Banxico (2018b). *The History of Coins and Banknotes in Mexico.* http://www.banxico.org.mx/banknotes-and-coins/d/%7BB8C0D87B-F55F-792A-A6C6-FC0F58CF2EA3%7D.pdf

Banxico (2018c). *Money Supply.* https://www.banxico.org.mx/banknotes-and-coins/d/%7B09D38FAE-DF96-4F8C-F75D-0DAF9E4668BD%7D.pdf

Banxico (2018d). *Circular de operaciones de caja.* http://www.anterior.banxico.org.mx/disposiciones/normativa/circular-operaciones-de-caja/%7B79DA3F88-917D-F447-867B-2053E121E378%7D.pdf

Blacketer, B., & Evetts, B. (2004). *Forging Your Bank's Link in the New Currency Supply Chain.*

Dantzig, G. B., & Ramser, J. H. (1959). The Truck Dispatching Problem. *Management Science, 6,* 80-91. https://doi.org/10.1287/mnsc.6.1.80

Daskin, M. S., Coullar, C. R., & Shen, Z. J. M. (2002). An Inventory-Location Model: Formulation, Solution Algorithm and Computational Results. *Annals of Operations Research, 110,* 83-106. https://doi.org/10.1023/A:1020763400324

Dawande, M., Mehrotra, M., Mookerjee, V., & Sriskandarajah, C. (2010). An Analysis of Coordination Mechanisms for the U.S. Cash Supply Chain. *Management Science, 56,* 553-570. https://doi.org/10.1287/mnsc.1090.1106

Eksioglu, B., & Vural, A. (2009). The Vehicle Routing Problem: A Taxonomic Review. *Computers & Industrial Engineering, 57,* 1472-1483. https://doi.org/10.1016/j.cie.2009.05.009

Geismar, H. N., Sriskandarajah, C., & Zhu, Y. X. (2016). A Review of Operational Issues in Managing Physical Currency Supply Chains. *Production and Operation Management, 26,* 976-996. https://doi.org/10.1111/poms.12593

Huang, Y., Geismar, H. N., Rajamani, D., Sethi, S., Sriskandarajah, C., & Carlos, M. (2016). Optimizing Logistics Operations in a Country's Currency Supply Network. *IISE Transactions, 49,* 223-237. https://doi.org/10.1080/0740817X.2016.1224958

Jaegere, N. D., Defraeye, M., & Nieuwenhuyse, I. V. I. (2013). *The Vehicle Routing Problem: State of the Art Classification and Review.* FEB Research Report KBI1415.

Kilby, P., & Verden, A. (2011). *Flexible Routing Combing Constraint Programming, Large Neighbourhood Search, and Feature-Based Insertion.* ANU Research Publications.

Mehrotra, M., Dawande, M., & Sriskandarajah, C. (2010). A Depository Institution's Optimal Currency Supply Network under the Fed's New Guidelines: Operating Policies, Logistics, and Impact. *Production and Operations Management, 19,* 709-724. https://doi.org/10.1111/j.1937-5956.2010.01153.x

NICTA (2013). *Solving Real-World Vehicle Routing Problems.*

Nozick, L. K., & Turnquist, M. A. (1998). Integrating Inventory Impacts into a Fixed-Charge Model for Locating Distribution Centers. *Transportation Research Part E: Logistics and Transportation Review, 34,* 173-186. https://doi.org/10.1016/S1366-5545(98)00010-6

Nozick, L. K., & Turnquist, M. A. (2001a). Inventory, Transportation, Service Quality and the Location of Distribution Centers. *European Journal of Operational Research, 129,* 362-371. https://doi.org/10.1016/S0377-2217(00)00234-4

Nozick, L. K., & Turnquist, M. A. (2001b). A Two-Echelon Inventory Allocation and Distribution Center Location Analysis. *Transportation Research Part E: Logistics and Transportation Review, 37,* 425-441. https://doi.org/10.1016/S1366-5545(01)00007-2

Oxford Economics (2017). *The Future of Money: How Digital Payments Are Changing Global Commerce.* https://d1iydh3qrygeij.cloudfront.net/Media/Default/landing-pages/recent-releases/2017/Future_of_Money_Report_V12%20FINAL%20WEB.pdf

Rajamani, D., Geismar, H. N., & Sriskandarajah, C. (2009). A Framework to Analyze Cash Supply Chains. *Production and Operations Management, 15,* 544-552. https://doi.org/10.1111/j.1937-5956.2006.tb00162.x

Ropke, S., & Pisinger, D. (2006). An Adaptive Large Neighborhood Search Heuristic for the Pickup and Delivery Problem with Time Windows. *Transportation Science, 40,* 455-472. https://doi.org/10.1287/trsc.1050.0135

Shen, Z. J. M., Coullard, C., & Daskin, M. S. (2003). A Joint Location-Inventory Model. *Transportation Science, 37,* 40-55. https://doi.org/10.1287/trsc.37.1.40.12823

Tancrez, J. S., Lange, J. C., & Semal, P. (2012). A Location-Inventory Model for Large Three-Level Supply Chains. *Transportation Research Part E: Logistics and Transportation Review, 48,* 485-502. https://doi.org/10.1016/j.tre.2011.10.005

Toth, P., & Vigo, D. (2014). *Vehicle Routing: Problems, Methods, and Applications.* Society for Industrial and Applied Mathematics. https://doi.org/10.1137/1.9781611973594

Warjiyo, P., & Juhro, S. M. (2019). *Central Bank Policy: Theory and Practice.* Emerald Publishing. https://doi.org/10.1108/9781789737516

Yao, Z., Lee, L. H., Jaruphongsa, W., Tan, V., & Hui, C. F. (2010). Multi-Source Facility Location-Allocation and Inventory Problem. *European Journal of Operational Research, 207,* 750-762. https://doi.org/10.1016/j.ejor.2010.06.006

Zhu, Y., Dawande, M., & Sriskandarajah, C. (2011). Value of Local Cash Reuse: Inventory Models for Medium-Size Depository Institutions under the New Federal Policy. *Manufacturing & Service Operations Research, 13,* 508-524. https://doi.org/10.1287/msom.1110.0336

Zhu, Y., Kumar, S., Rodríguez-Sánchez, S., & Sriskandarajah, C. (2015). Managing Logistics in Regional Banknote Supply Chain under Security Concerns. *Production and Operations Management, 24,* 1966-1983. https://doi.org/10.1111/poms.12378