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Research Article

Comparative Analysis of New Solutions for the Capacitated Vehicle Routing Problem Against CVRPLIB Benchmark

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Abstract:

The capacitated vehicle routing (CVRP) is a combinatorial optimization problem (COP) which is belong to NP-hard problem category. This problem includes determining the best option for low-cargo vehicles to serve a number of clients. Every client is required to make a single journey, and the overall demand on each route cannot be greater than the vehicle's capacity. Numerous precise and heuristic approaches have been put out in the literature to address this problem. Specific methods such as branch-binding and branch-pruning assure the search for optimal solutions but are often impractical for large data sets due to their computational complexity heuristic and metaheuristic approaches like genetic algorithms (GAs), ant colony optimization (ACO), simulated annealing (SA), and tabu search (TS), provide optimal solutions in real time, making them more appropriate for bigger instances. Despite these advancements, most studies have not achieved new results compared to those in the standard CVRPLIB benchmark instances. Therefore, this study focused on exploring new results obtained by state-of-the-art approaches in the literature that have solved CVRP. In particular, our aim is to explore new algorithmic improvements designed to improve CVRP regarding to computational efficiency and quality of the solution.

1. Introduction

The CVRP considers the overall cost, total distance traveled, and a few more unique criteria based on demand [1]. To allow researchers to compare their algorithms using the same problem situations where either the best-known solution (BKS) or, in some cases, the optimal solution (OPT) is known, a number of datasets have been offered. The CVRP dataset is accessible online via the website at (http://vrp.galgos.inf.puc-rio.br/index.php/en/updates) under the name CVRPLIB. Regarding the applications of CVRP, there are numerous real-world uses, including services, transportation and distribution, and human transportation. Consequently, many studies have focused on CVRP applications. For example, research [2] investigated an application of selection of optimal fuel delivery method to ensure safe and timely delivery Study [3] proposed a routing method delivering waste disposal tracking that addresses strategic efficiency challenges in waste management along with strategies for providing quality fuels for e -commerce, CVRP has been demonstrated functions to reduce logistics costs and improve public transport systems by efficiently operating buses and shuttles These applications highlight the importance of CVRP and its functionality in many storage facilities to highlighting complex expatriation challenges in various sectors.

Exact methods such as branch-binding, branch-pruning assure to find the optimal solution but are generally not practical in large cases due to their computational complexity, on the other hand, heuristic and metaheuristic methods, resemble genetic algorithms (GAs), ant colony optimization (ACO), simulated annealing (SA), and tabu search (TS), delivers superior solutions in a reasonable amount of time, and builds to be more suitable for larger samples. These methods blend computational effectiveness with solution quality, enabling them to effectively overcome the scalability issues faced by specific approaches Although these advances have been important in the development of new approaches, significantly improved though, most studies did not yield results beyond the performance metrics established by standard CVRPLIB methods.

Achieving substantial improvements over these well-established benchmarks remains a significant challenge. Therefore, this study aims to investigate new results for CVRP instances specifically referred to as "CMT6, CMT7, CMT8, CMT9, CMT10, CMT13, CMT14, and M-n200-k17." These instances, introduced around 40 years ago in study [4], are available on the CVRPLIB website and provide a valuable foundation for evaluating recent advancements in solving the CVRP.

On other hand, ant colony system (ACS) algorithm which is one of the ACO family, through an updated transition rule, the ACO family has developed properties of its constituents, the introduction of a local update of the pheromone, and the only the best option is used for global pheromone updates. [5]. Moreover, the features of the CVRP, where ant nests can be viewed as depots, are compatible with elements of the ACS., artificial ants as cars, food as clients, and trails as paths, and the concentration of pheromones that will offer the most effective mode of distance optimization [6].

2. Literature review of CVRP

The CVRP is a model relevant to various important applications in the real world such as logistics, transportation, and distribution. However, CVRP belongs to NP-hard problem category, and thus computationally challenging. As problem sizes increase, these NP-hard problems become increasingly difficult to solve and require more effort to implement precise algorithms because large-scale issues have a high computational complexity [7] and [8]. This section presented by many subsections as following:

2.1 Defining Searching Terms

To identify relevant articles, searches were conducted using specific keywords such as ("Capacitated Vehicle Routing Problem" OR "Capacitated Vehicle Routing Problem" AND “Algorithms”) in titles, keywords, and abstracts. This approach ensured a thorough screening of relevant literature before beginning comprehensive searches across in Scopus database. The total number of articles obtained was 2825 articles from 1993 to 2024.

Table 1. *Details about the articles*

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	1993:2024
Sources (Journals, Books, etc)	491
Documents	1008
Annual Growth Rate %	11.83
Document Average Age	7.06
Average citations per doc	21.23
References	24675
DOCUMENT CONTENTS	
Keywords Plus (ID)	3950
Author's Keywords (DE)	1789
AUTHORS	
Authors	2200
Authors of single-authored docs	55
AUTHORS COLLABORATION	
Single-authored docs	65
Co-Authors per Doc	3.14
International co-authorships %	23.12
DOCUMENT TYPES	
article	525
book chapter	9
conference paper	471
conference review	1
note	1
review	1

By using R-studio software, Figure 1 illustrates the annual global output of articles addressing CVRP. The data indicates that in 1993, only one article was published on this topic. After this initial excitement, the number of publications began to increase steadily. This increase continued over the years, reflecting the increasing importance of the problem in combinatorial optimization and logistics with substantial growth in the quantity of sources, finally peaking in 2021 and 2022 Yesterday forever revealed that there is a significant increase in research activity and interest in CVRP.

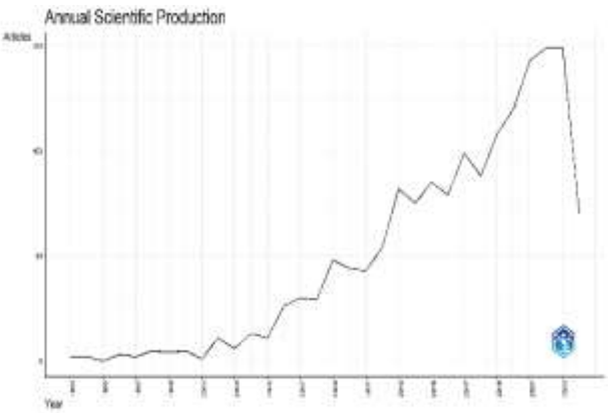

Figure 1. *Annual Scientific Production from 1993 to 2024*

2.2 Study Selection

Various criteria were used to include or exclude cases, with a particular focus on CVRP. This criterion is described in the table 2, which details the specific requirements and exceptions for filtering the relevant publications.

Table 2. *Selection criteria for studies: inclusion and exclusion*

Inclusion	Exclusion
Articles focus on CVRP and their solutions	Non-English articles
Articles published between 1993 to 2024	Un-related articles
Research articles, review, and survey	Books, book chapters, brief letters, and conference papers

2.3 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)

Four important steps in the systematic review process are defined through the “Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)” framework: description, review, evaluation, and inclusion. Illustrated in the PRISMA flowchart, this step assures a clear and structured process for selecting the required documents.

- **Identification**: In this first step, a thorough search is conducted for any potentially relevant research. Researchers search databases, references, and other sources to collect as many studies as there are.
- **Screening:** To determine the relevance of the research identified in the previous step, the researcher examines the titles and cross-references of those studies during the research phase This usually takes place in two stages - the first is a general examination and the second is a deep scan.

- **Eligibility:** The papers that made it beyond the screening phase are subjected to a full-text evaluation by researchers during this phase. to confirm that the studies are appropriate for inclusion in the systematic review and satisfy the established eligibility requirements.
- **Included:** The last step is to choose the research that satisfy all requirements to be part of the systematic review. to complete the collection of research that will be reviewed, evaluated, and summarized.

Figure 2 illustrates PRISMA steps based on data collected from the Scopus database as follows.

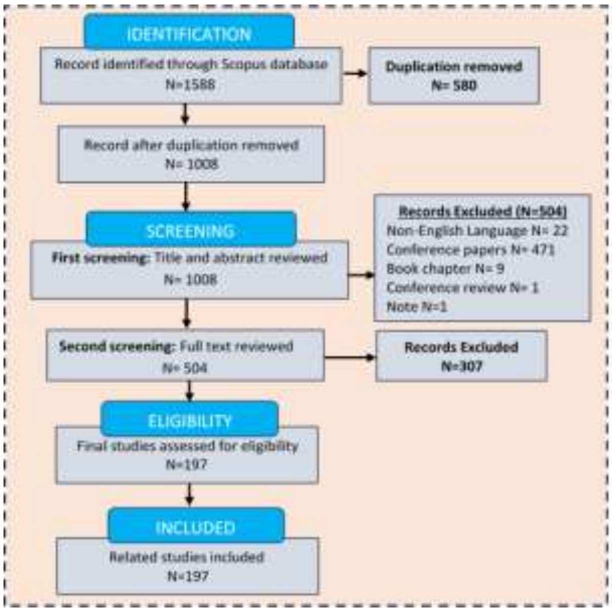

Figure 2. *Synopsis of the selection procedure framework by PRISMA*

2.4 CVRPLIB database

A well-known benchmark library for the CVRP is CVRPLIB. It acts as a comprehensive collection of CVRP cases, which researchers and practitioners utilize to create, evaluate, and contrast different methods and approaches to the problem. The table 3 shows the details of this database.

3. Result and Discussion

The outcomes of the previous 40 years' efforts to solve the CVRP are shown and discussed in this section. To give a thorough perspective, this study's main goal is to combine and evaluate various options. We used Mendeley and Excel for data

Table 3. *Database of CVRPLIB*

No.	Category Name	Reference	Number of Instances
1	Set A	[9]	27
2	Set B	[9]	23
3	Set E	[10]	13
4	Set F	[11]	3
5	Set M	[12]	5
6	Set P	[9]	23
7	Set CMT	[12]	14
8	Set Tai	[13]	13
9	Set Golen	[14]	20
10	Set Li	[15]	12
11	Set X	[16]	100
12	Set Amold	[17]	10

administration and visualization, as well as a number of well-known bibliometric analytic software programs, such as Bibliometric and R-Studio, to accomplish this.The subsections that follow go into more detail about the findings of the study and highlight important developments, perspectives, and trends in CVRP research. We examine the historical development of these solutions, highlighting key changes and fundamental revelations that have influenced the state of the field today. We examine several approaches and strategies for managing CVRP and seek to better understand the progress achieved and the obstacles that remain.

3.1 Article Citation Analysis

This section cites the ten most important issues affecting CVRP solutions. This review focuses on important contributions to the field, emerging trends and research implications. R-Studio was used to collate the citations and analyzed them using bibliometric tools to identify the most frequently cited articles. Table 4 shows this analysis. “Development of a fuel consumption optimization model for the capacitated vehicle routing problem” (2012) was the paper that ranked #1 with 509 citations. In this research, a novel optimization model for reducing fuel usage in CVRP solutions is presented. The suggested approach has received a lot of attention because it is pertinent to logistics cost-effectiveness and sustainability. **“**An artificial bee colony approach for the capacitated vehicle routing problem”, 2011, was the article that ranked second with 360 citations. This study demonstrates the efficiency of an artificial bee colony algorithm designed specifically for the CVRP in resolving challenging routing issues. The algorithm has received a lot of citations because of its creative approach and good performance.

Table 4. *Article Citation Analysis*

Paper Title and Reference	DOI	Total Citations (TC)	TC per Year
“Development of a fuel consumption optimization model for the capacitated vehicle routing problem”. [18]	10.1016/j.cor.2011.08.013	509	39.15
“An artificial bee colony algorithm for the capacitated vehicle routing problem”. [19]	10.1016/j.ejor.2011.06.006	360	25.71
“New Route Relaxation and Pricing Strategies for the Vehicle Routing Problem”. [20]	10.1287/opre.1110.0975	332	23.71
“The Two-Echelon Capacitated Vehicle Routing Problem: Models and Math-Based Heuristics”. [21]	10.1287/trsc.1110.0368	310	22.14
“Models, relaxations and exact approaches for the capacitated vehicle routing problem”. [22]	10.1016/S0166218X (01)00351-1	287	12.48
“Vehicle routing problem with drones”. [23]	10.1016/j.trb.2019.03.005	281	46.83
“New benchmark instances for the Capacitated Vehicle Routing Problem”. [24]	10.1016/j.ejor.2016.08.012	279	34.88
“Energy Minimizing Vehicle Routing Problem”. [25]	10.1007/978-3-540-73556-4_9	264	14.67
“The Vehicle Routing Problem with Occasional Drivers”. [26]	10.1016/j.ejor.2016.03.049	234	26.00
“An ant colony algorithm for the multi-compartment vehicle routing problem”. [27]	10.1016/j.asoc.2013.10.017	229	20.82

Although the article's title states: "An ant colony algorithm for the multi-compartment vehicle routing problem, 2014." Numerous people have acknowledged its methodological contributions in rank 10 with 229 citations. The versatility and efficacy of the ant colony optimization technique are demonstrated in this paper by applying it to the multi-compartment CVRP. Its contributions to methodology have received widespread recognition.

3.2 An analysis of countries' bibliographic couplings

The academic output linked to each nation's authors can be analyzed through bibliographic coupling to determine which countries have the produces the most documents. This analysis may be carried out in VOSviewer by using a set of articles that contain information about the affiliations of the authors. The visual aids that are produced provide insightful analyses of international research networks and aid in the mapping of the worldwide terrain of scientific cooperation.

According to the data, out of the 72 countries, 37 countries meet the assumptions that each country has at least 10 documents and that each document has at least five citations. Based on their research production, impact from citations, and scientific community network connection, eleven countries are compared in table 5. Documents, citations, and total link strength—the three main metrics—provide information about the productivity, impact, and international cooperation of each nation's research.

3.3 Advanced Solutions for CVRP

This section offers a fresh method for resolving the CVRP as it has been covered in the literature. According on the search results, a multi-objective ant colony optimization (ACO) technique was used to create these solutions, as described in [28]. The algorithm's performance was greatly improved by carefully adjusting its parameters using the well-known grid search method for parameter optimization. Grid search is a method for optimizing the parameters of other models, metaheuristics, and machine learning algorithms. To optimize a model or algorithm, the objective is to determine the optimal set of parameters that produces the best results. Achieving the stated improved outcomes was largely dependent on the careful manipulation of these factors. The following example is presented in table 6 in order to justify the method that was used in the analysis of the data of CVRP to discover those instances that can be reduced their number of vehicles. This instance has 51 nodes with the depot, 6 vehicles, the capacity of vehicle is 160, and the sum of the total demand is 777. When divided the total demand (777) on the capacity 160 the result is 4.856 round to 5, this means that one vehicle can be reduced from the current number of the vehicles in CVRP dataset. Furthermore, the new number of vehicles is multiplied by the capacity, and that in order to verify that the new number guarantees that all demands are covered, the result of this multiplied is 5*160 =800 which is more than all demands 777. The figure 3 shows the current solutions (Routes) of this instance (CMT6) on the CVRPLIB. The study's [28] contribution to lowering the number of automobiles is depicted in the figure 4. The current solutions of this instance in CVRPLIB by using **6** vehicles as follows:

Route #1: 32 11 16 29 21 50 34 30 9 38
Route #2: 1 22 31 28 3 36 35 20 2
Route #3: 14 25 13 41 40 19 42 17
Route #4: 12 37 44 15 45 33 39 10 49 5
Route #5: 27 48 8 26 7 43 24 23 6
Route #6: 18 4 47 46

Table 5. *Countries' bibliographic couplings*

Country	Documents	Citations	Total Link Strength
China	216	561	339
United States	76	743	132
Brazil	59	523	210
France	57	1763	121
Spain	55	45	113
India	49	99	73
Indonesia	46	4273	57
Canada	45	348	148
Italy	41	158	224
Germany	38	1946	97

Table 6. *Nodes and demands in ' CMT6 ' instance*

Node	Demand	Node	Demand	Node	Demand	Node	Demand
1	0	14	23	27	7	40	14
2	7	15	21	28	15	41	7
3	30	16	10	29	14	42	27
4	16	17	15	30	6	43	13
5	9	18	3	31	19	44	11
6	21	19	41	32	11	45	16
7	15	20	9	33	12	46	10
8	19	21	28	34	23	47	5
9	23	22	8	35	26	48	25
10	11	23	8	36	17	49	17
11	5	24	16	37	6	50	18
12	19	25	10	38	9	51	10
13	29	26	28	39	15	**Total**	**777**

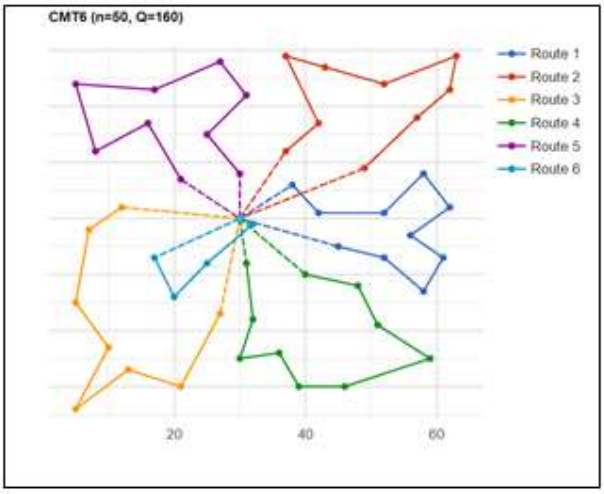

Figure 3. *Solution CMT6 in the CVRPLIB website by using 6 vehicles*

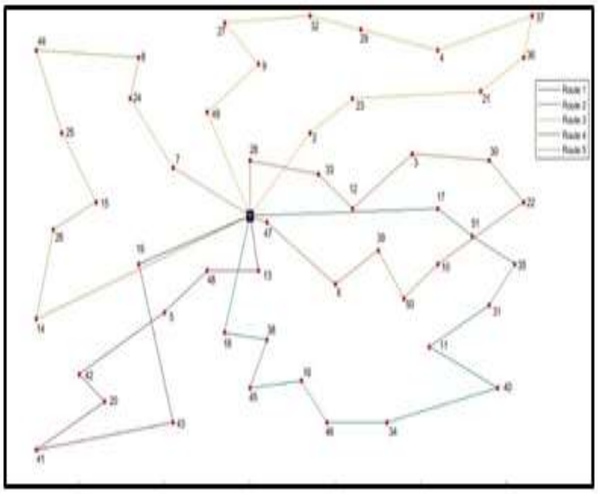

Figure 4. *Solutions of CMT instance by 5 vehicles by [28]*

While solution of this instance by using 5 vehicles which obtained by the study [28] as follows:

Route #1: 1 17 51 35 31 11 40 34 46 16 45 38 18 1
Route #2: 1 2 23 21 36 37 4 29 32 27 9 49 1
Route #3: 1 7 24 8 44 25 15 26 14 1
Route #4: 1 19 43 41 20 42 5 48 13 1
Route #5: 1 47 6 39 50 10 22 30 3 12 33 28 1

Table 7. *Comparison between solutions in CVRPLIB and our solutions by [28]*

Instances	Solutions on the CVRPLIB website		Solutions by [28]	
	Distance	Number of vehicles	Distance	Number of vehicles
CMT6	555.43	6	562.9	**5**
CMT7	909.68	11	911.68	**10**
CMT8	865.94	9	929.89	**8**
CMT9	1162.55	14	1265.84	**12**
CMT10	1395.85	18	1525.8	**17**
CMT13	1541.14	11	1541.16	**7**
CMT14	866.37	11	867.09	**10**
M-n200-k17	1275	17	1809	**16**

Table 7 records the results of some of those CVRP data which could reduce the number of its vehicles and be accompanied by a slight increase in distances. The study's [28] contribution to lowering the number of automobiles is depicted in the figure 5.

Contributing to reducing the number of vehicles helps:

- Reduces CO_2 emissions and thus reduces environmental pollution;
- Reduces the traffic;
- Reduces the number of drivers; and
- Reduces fuel cost.

4. Conclusions

There are many studies in the literature that have addressed the CVRP with the proposal of new

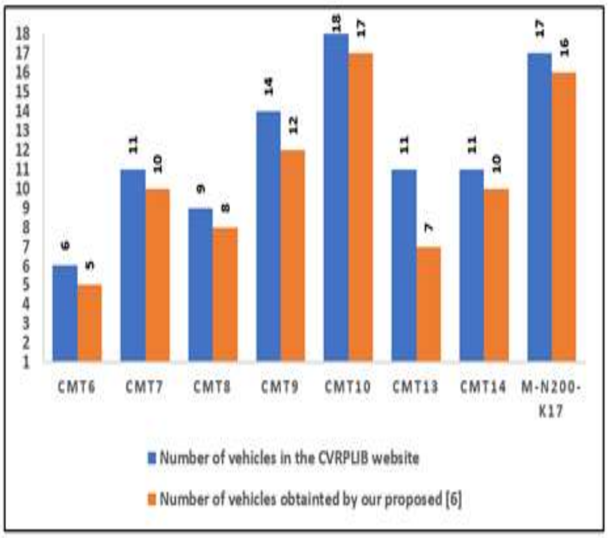

Figure 5. *Study's contribution [28] to lowering the number of vehicles in certain CVRP data instances*

methods, while others have represented the improvement of existing methods, and others have presented review studies of the CVRP and compared their results with the existing solutions to the CVRP instances available under the name CVRPLIB which include optimal solutions (OPT) and the best-known solutions (BKS) so far. However, all of these results are present in the CVRP standard and have not been improved. Therefore, the aim of this research is to search deeply and accurately in the literature in order to explore new solutions to the CVRP.
Using the Grid Search Technique in addition to the Pareto concept, the study [28] proposed an algorithm that utilized a new concept of sub-paths and parameter adjustment. These features combined have provided a new approach that contributed to reducing the number of vehicles in some CVRP instances with a slight increase in distance as discussed in the Table 7.

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- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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