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An Overview of Chinese Postman Problem

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Abstract

Routing problems can be divided into two main categories: node routing and arc routing. The purpose of arc routing problems,is to determine the shortest path and paths which is returning to the starting node by passing at least once from all the lines on a line. Chinese postman problem (CPP) which is one of arc routing problems was first investigated by Chinese mathematician Mei-Ko Kwan in 1962. The problem is defined that a postman pick up mails at the post office, delivers it, and then returns to the post office. He must cover each street in his area at least once. Subject to this situaiton, the CPP is referring to research how to cover every street and return to the post office under the least cost. Typical classification of CPP is as follows; undirected CPP, directed CPP, mixed CPP, windy CPP, k-CPP, Min-Max k-CPP, Capacitated CPP and hierchical CPP [1]. In reality, there are many situations in which CPP can be used. For example, a driver of patrol vehicle to increase safety or a garbage truck and snow plowing car, he desires to choose his route in such a way that traverses as little as possible [2]. There are many studies on CPP in the literature. In this paper, the studies that can be reached on this subject in the literature are invastigated.

1 INTRODUCTION

The purpose of arc routing problems is to determine the shortest route or routes returning to the starting vertex by traversing all arcs or edges on a graph at least once. Arc routing problems may be divided into two as rural postman problem (RPP) and Chinese postman problem (CPP). It is required to create the shortest path by traversing certain edges on a graph at least once in the rural postman problem, while it is required to create the shortest path by traversing all edges on a graph at least once in the CPP [3]. CPP is to create the shortest path by traversing each edge on a graph at least once starting from a certain starting vertex [4].

CPP may be used in several areas such as mail delivery, garbage collection, snow and ice controls on streets and highways, road gritting, snow removal and street cleaning operations, school bus and police patrol vehicles routing, water and newspaper distribution, effective web site determination [5]. Expenditures of public and private enterprises in these areas are increasing day by day and reach to high amounts. Due to insufficient planning and faulty investments, a significant amount of resources is extravagantly spent in these areas. Therefore, the importance of such problems is increasing and is being the subject of many researches. Studies of researchers in these areas help to increase the possibility of implementation by finding more effective solutions and thus to provide significant savings [6].

2 MATERIAL AND METHOD

In this study, CPP from arc routing problems is discussed. First of all, Eulerian path which has an important place in the solution of the CPP is discussed. Then, variations and solution methods of CPP are discussed. Finally, a literature research was conducted for CPP and its variations which are available and reachable in the literature. In the conclusion part, some suggestions are presented considering the deficiencies mentioned in the literature.

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2.1 Euler Tour

The arc routing problems (ARPs) entail determining a minimum-cost traversal of a specified subset of arcs on a graph. The earliest study related to the ARPs is the Königsberg Bridge Problem. The problem had been solved by the Swiss mathematician Leonhard Euler in 1736, who aimed to determine whether there exists a closed walk traversing each of the seven bridges given in Figure 1, once and exactly once [7]. For this reason, if a connected graph has a closed walk visiting each node at least once and each arc exactly once, that graph is named as Eulerian [8].

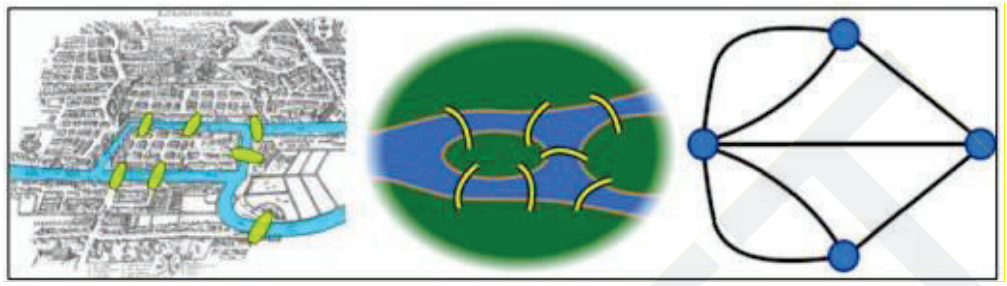

Figure 1. The seven bridges of königsberg

As can be seen from Figure 1, the bridges of Königsberg are represented as arcs and each arc joins a pair of the four junction points (nodes) which can be considered as islands and shores. The Königsberg Bridge Problem is only concerned with the existence and determination of a closed walk [3]. Euler has suggested that for such a tour to occur, each zone must be accessed from the other zones and each node must be dual-grade [9]. CPP takes its origin from the Königsberg Bridge Problem and deals with situations where such a solution does not exist [7].

2.2 Chinese Postman Problem

CPP first studied in 1962 by a Chinese mathematician called Mei-Ko Kwan, may be defined as the delivery of mails that a postman receives from the post office in the shortest possible path by traversing all streets/roads in the city and returning to the post office which is the starting vertex after the delivery is completed [4-10].
On a graph G = (V, E); where edge (i, j) establishes a connection between vertices i and j. Mathematical model, parameters and variables for CPP are given in Table 1. [11]

Table1. Mathematical model parameters and variables

Variables and parameters	
x_{ij}	The main decision variable which represents the number of times arc (i,j) is traversed in each cycle using vehicle starting from node i ending at node j. The variable is integer
x_{ji}	Decision variable which represents the number of times arc (j,i) is traversed in each cycle using vehicle starting from node j ending at node i. The variable is integer
C_{ij}	The length for traversing arc (i,j) starting from node i, ending at node j
V	Set including all nodes in the network
E	Set including all edges in the network
n	Total number of nodes in network

The entire formulation can be seen in the following,

$$\text{Min: } \sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij}\, x_{ij} \tag{1}$$

Subject to

$$\sum_{j=1}^{n} x_{ij} - \sum_{j=1}^{n} x_{ji} = 0 \quad ; \; i = 1,2,\dots,n \quad \forall_i \in V \tag{2}$$

$$x_{ij} + x_{ji} \geq 1 \qquad \forall (i,j) \in E \tag{3}$$

$$x_{ij}, x_{ji} \geq 0 \; and \; integer. \tag{4}$$

The objective function (1) minimizes the total length of route R that is covered by track inspection vehicle. Eq. (2) is flow conservation at each node constraint which guarantees the creation of a tour of the network for the

vehicle. Eq. (3) ensures that each arc that exists is covered at least once during each cycle regardless of its direction using the vehicle. Eq. (4) is restriction on the variables.

2.3 Variations and Solution Methods of Chinese Postman Problem

Considering the related literature, CPP is basically divided into three as directed, undirected and mixed CPP depending on the directions of the edges on a graph. Directed and undirected CPP can be solved by polynomial algorithms. Therefore, they belong to class P. In the mixed CPP, some of the paths are directed, others are undirected and this problem belongs to NP-hard problem class [12]. By adding other constraints to undirected, directed and mixed CPP, new CPP have arisen [13]. These can be given as Figure 2.

Figure 2. Variations of CPP

The solution methods of optimization problems are generally divided into two as exact and non-exact methods and non-exact methods are divided into two as approximate and heuristic methods. The best solutions are found with exact methods. Non-exact methods do not guarantee the best solution. However, it is clear how close the solutions obtained by the approximate methods are to the best solution (they approach the best solution by a certain percentage, such as x%). The approach rate of heuristic method to the best solution is unclear [14]. The solution methods of CPP can be summarized as in Figure 3:

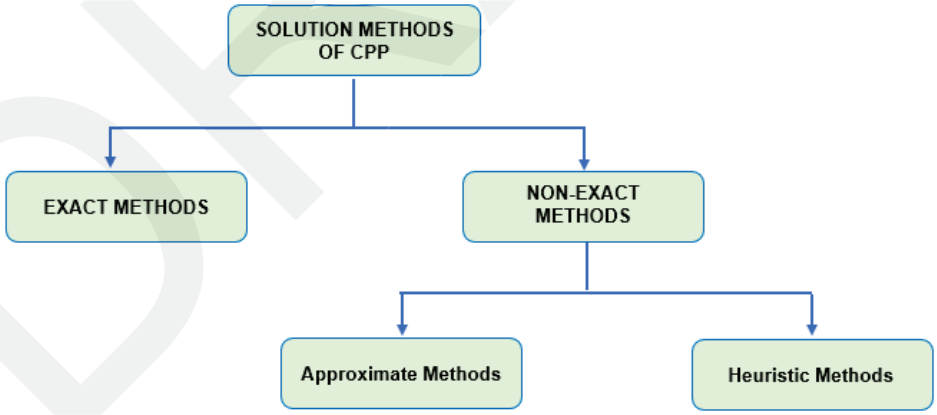

Figure 3. The solution methods of CPP

Metaheuristic algorithms are preferred for NP-hard problem types that cannot be solved in a reasonable time as the problem size increases. These algorithms are general algorithmic structures that have highly capable and effective methods in solving many complex optimization problems [15]. Metaheuristic methods are algorithms designed for the solution of complex optimization problems that cannot be solved in a reasonable time by exact solution methods by being inspired from events in the nature [7]. Metaheuristics contain a number of algorithms with different properties. In general, determination of an effective metaheuristic is an experience-dependent process that requires extensive analysis of different metaheuristics, their key parameters, and their operators. There are several studies in the literature where metaheuristic approaches are applied to arc routing problems [16]. In this study, studies using different solution methods are discussed and the deficiencies in the literature are mentioned

2.4. Literature Research

In this section, the studies related to CPP in the literature are presented in groups according to CPP types. CPP was first studied in 1962 by a Chinese mathematician called Mei-Ko Kwan. The problem arose when a postman wanted to deliver mails that he received from the post office by walking along all the streets in the city as short as possible [4].

In undirected CPP, it is aimed to find the shortest path by traversing each edge in a network of undirected edges at least once [16]. Authors developed a minimum matching algorithm that finds the optimum solution for undirected CPP [17]. They formulated the problem that can be solved as a matching problem, which aims to transform a graph G to a graph G' with all vertices being single degree [10]. Author suggested a new model for undirected CPP and showed that this model was solved efficiently by Cutting Plane Algorithm in his study [18]. Directed CPP requires to find the shortest path by returning to the starting vertex after traversed each edge on a directed graph at least once [4]. Algorithms and methods used to solve the problem can be considered as network flow methods and integer linear programming methods. In the study [5] complete and executable Java code is presented in order to solve directed version of the CPP.

In mixed CPP consisting of directed and undirected CPP convergence, it is required to find the shortest path by returning to the starting vertex and traversing all edges on a graph G = (V, E, A) consisting of both directed and undirected edges at least once [3]. Authors suggested an algorithm to select the most appropriate CPP solution method based on Bibliographic reference analysis (theoretical-conceptual research) in their study [19]. The suggested algorithm was used in two logistic problems cases (garbage collection service and post office mail delivery) with a population of 200,000 in Brazil. The purpose of the study [20] is to find a minimum cost closed walking along each edge and arc at least once, considering an edge-weighted mixed graph G. In the study [21] authors developed a formula used to determine CP optimal path length on a directed and undirected planar graph in their studies. In the study [22] authors aimed to determine a minimum cost tour by walking along each connection within predetermined limits, starting and ending in the warehouse for mixed CPP. In the study, solution algorithms are presented for directed and undirected networks. They considered CPP on edge-colored graphs (CPP-ECG). Polynomial time of CPP-ECG was proven to be soluble [23].

In the study [8] she considers a k-CPP with the objective of minimizing total squared workloads. The main objective of the study is to balance the workload among postmen, while keeping the total workload low. An effective subtour elimination method was developed and included in the model. Moreover, solution methods that find exact and approximate solutions, and work in exponential and polynomial time, respectively, were developed. Authors gave information about k-warehouse CP games in their studies [24]. They also found that global k-CP balanced graphs and locally k-CP balanced graphs were not equivalent to weak Eulerian graphs, unlike [25]. Authors studied k-CPP in their studies and proved that k-CPP is really detectable with a fixed parameter [26]. In study [27], different variations of K-CPP model under different assumptions were applied to the snow plough operations at Atatürk University campus and the results were compared.

Min-max k-CPP is almost the same as k-CPP. Again, k routes are determined. However, the longest route is to be minimized. The aim is to reach each edge as soon as possible. In order to make the routes more balanced, it is tried to create approximately equal length routes [28]. Authors develop a branch-price-and-cut algorithm to solve the MinMax k-WRPP in their study [30]. They use exact and heuristic column generation techniques incorporated in their branch and bound algorithm and get satisfactory results. The purpose of the study [29] is to provide a taboo search algorithm that performs better than all known heuristic methods for Min-max k-CPP.

Another class of CPP is hierarchical CPP (HCPP) . In this problem, priority relations are defined in directed edge set on G = (V, A) and it is predetermined in which order the service will be provided to which directed edges [31]. In their study, authors introduced HCPP for the first time and showed that it can be solved in polynomial time if the priority relationships are linear and all subgraphs are connected [32]. In their study [33], authors discussed a more realistic situation with sub-graphs that are not connected to each other. In their study, they presented a heuristic algorithm that solves the rural postman problem and then creates a giant tour that provides linear priority relationships. Authors [34] discussed the transformation of HCPP into an equivalent Rural Postman Problem (RPP) in their study They suggested a decomposition heuristic for undirected HCPP with linear priority relationships. HCPP was optimally solved for both purposes by applying a branch-price-and-cut algorithm to the transformed problem. In the study [31], a exact algorithm that requires a lower computational effort than previous processes for HCPP is presented and it is supported by examples. The algorithm they provided is the first algorithm that provides the exact solution for HCPP. In their study [35], authors suggested a different algorithm that finds the minimum cost route according to priority in networks classified by priority.

First, the minimum route of the highest priority subnet is found by the algorithm. The process is completed by calculating the minimum cost routes of each subnet separately, without ignoring the order of priority [11].In their study, they reduced the complexity of the original algorithm to $O(kn^4)$ with post-matching optimism techniques. In their study [36], authors developed a heuristic method that gave better lower limit values for HCPP compared to the solutions of CPP. They showed that the optimum solution was achieved in a shorter time by using exact search algorithms with these values. Various problem sizes were discussed with heuristics developed at the same time and better results were obtained from previous studies. In the study [37], authors suggested a basic model and two heuristic solution approaches for vehicle routing problem in snow ploughing operations in their study. This problem can be considered as multiple hcpp (m-HCPP). The suggested method produces more suitable routes than the existing routing plan that produces. In the study [38], is studied HCPP. Previously, is suggested an algorithm that eliminates the time complexity of O (kn^5) [32]. CPP is considered as a lower limit of HCCP. In this study [38], alternative approaches are given by using Kruskal method to reduce the number of O (k^2 n^2) edges.In the study [39], the determination of the shortest length route of a maintenance vehicle used on the roads in the assigned area of 12th Regional Directorate of Highways was discussed. The problem discussed is large and a nearest neighbor search based heuristic algorithm was developed for its solution.

In recent years, the availability of travel time or travel speed information at different times of the day led researchers to develop different routing models using this additional information. Modeling of time-dependent travel times has become an important subject in the literature of moment-dependent routing [16]. In the study [40], authors suggested two different models to solve CPP with Time Window (CPPTW) in their study. The first is constraint programming, and the second is the transformation to an equivalent time-window vehicle routing problem. The results show that optimal solutions can be achieved quickly when time windows are tight. Authors investigate The Time Dependent CPP (TDCPP) in their paper [41]. They prove that the CPP defined on the time dependent network is *NP*−Hard even if it verifies the Eulerian and First-In-First-Out properties. In their study [42], authors deal with a generalization of the CPPTW involving the added complexity of time dependent service times and travel times, which is motivated from hybrid system testing. This paper focus on an exact method, transforming the TDCPPTW to a generalized Rural Postman Problem (GRPP) equivalently, and the latter problem can be formulated as a linear integer programming without any timing constraints. In their study[43], they presented a new linear integer programming formulation for time-dependent travel time CPP. There is no unrealistic assumption in this formulation and it can be considered as an extended version of the formulation research [1]. The cutting plane algorithm was used in the study. The study [16], a mathematical model was developed for the solution of the problem and two metaheuristic algorithms including Genetic Algorithm and Hybrid Annealing Simulation were suggested for solving large-scale problems. In the study [44], authors first discussed time-dependent transport times for TSP and CPP. They suggested a branch boundary algorithm to solve the maximum useful CPP and stated that small size problems could be solved with this algorithm.

In their study [45], authors examined maximum benefit CPP (MBCPP) on undirected graph. They showed that the problem is NP-hard class type. They suggested a heuristic based on minimum spanning tree algorithm and minimum cost matching for the solution. In the study [46], an IP formulation for MBCPP for the first time and valid families of inequality were introduced. Moreover, a branch cutting algorithm was suggested for MBCPP in the study. In their study [47], authors discussed the problem of guiding patrol vehicles in MBCPP studies and presented a new mathematical model that could be used to find the most suitable routes based on different situations. The primary purpose of the model is to realize the tour with the shortest distance, and the secondary aim is to minimize the difference in distance between vehicles.

In the undirected capacity constrained CPP, it was aimed to find the shortest distance tour by considering the capacity constraints of the vehicles [48]. In their study [49], authors discussed CPP under the postman's load capacity and working time constraints. GA structure was designed without transforming the arc routing problem into a vertex routing problem and a priority-based chromosome coding technique was developed.

In Windy CPP, the length of the edges on a undirected graph may vary according to the direction of passage from these edges. The aim is to find the shortest tour by passing through each arc in the graph at least once [10]. Windy postman problem (WPP), which was firstly introduced in study [50], consists of finding a minimum cost closed walk passing through every arc of G at least once. It is shown that the WPP is NPhard [51]. When the graph is unicursal, he shows that the problem can be solved in polynomial time in his study [52]. In the study [53], authors also describe the cutting plane algorithm to solve the WPP, which is considered to be the best known exact method up to now.

In the study [54], authors have been discussed CPP in stochastic networks. they proposed an algorithm for solving the problem. Authors present an algorithm to solve a multi objective problem and implements the same on a biobjective CPP in their study [55]. In the study [56], he propose a technique to obtain the route plan of a test droplet for the purpose of structural testing of biochips. The methodology is formulated using the CPP. In their study [57], authors aimed to eliminate the lack of adequate patrol path design procedures by providing a taboo search algorithm that can create multiple patrol routes for site security officers. The algorithm presented was tested on a real problem in South Africa, and as a result a significant improvement was shown compared to the past.

Authors suggested a new map transformation framework (MTF) in their study [58]. MTF, the bridge between CPP and multi-target search, makes it possible to use algorithms that conform to CPP to perform route planning in multi-target search with a mobile robot. Both simulation results and experiments show that MTF-based algorithm is better than several other target search algorithms. In the study [59], they focused on the security detection problem that deals with the effects of geographic locations on mutual game-based defense strategy. In the study; a game-based model was suggested to determine the best patrol strategy of security assets on the network in the case of a strategic enemy presence aiming at creating a nuclear threat on the edges of the network. They solved the model with rural CPP.

Authors examined CPP and showed that the integration between an advanced mathematical model and Geographic Information System (GIS) technology could be useful by providing a powerful tool for developing, testing and implementing advanced heuristic methods for arc routing problems in their study [60]. In the study [61], authors have proposed an optimization method to solve the CPP problem using Fleury's algorithm under real-time weighting. The results show that the proposed method is efficient and effective in solving the CPP in real-time. In their study [62], they present a road network search path planning algorithm in which more than one autonomous vehicle can efficiently visit each path defined on the map in the context of CPP. In the study, multi-choice multi-period knapsack problem was formulated in order to find an optimal solution that minimizes flight time, and then it was solved with mixed integer linear programming. In the study [63], a new algorithm filled with random barriers and based on cellular separation technique to effectively cover a known environment. In this hierarchical approach, first, the field is fragmented, then CPP is solved to calculate a Eulerian circuit circulating these cells.

Authors focused on bimodal CPP. In this "binary search game", the search for a small or well-hidden object (explosive device, predator net, etc.) is modeled in their study [64]. In dual mode CP Tour, it is aimed to complete the tour in minimum time by traversing each point of arc at least once in slow mode. In the study [65], the task of designing parking permit inspection routes was modeled as revenue collection CPP. In the study; it was shown that the designed inspection route maximized expected revenue.

He discussed multi-purpose CPP in his study [7]. A branch and bound algorithm that produces all effective solutions according to total cost and total distance criteria is defined. The algorithm uses effective lower and upper limits produced using linear programming relaxation methods. In their study [66], authors suggested a new strategy for robotic discovery in order to find a specific object in a certain static environment. In this study, the problem of directing the robot to search for the object at the calculated search points is modeled as an CPP. In their study [67], authors developed a software that graphically shows the additional production process. They presented a graphical model of 3D printing process and used CPP solution to optimize the movement of an extrusion machine on a particular weave.

Authors examined the performance of Random CP Tour (RCPT) for Gal's (1979) find-and-bring game on a network in their study [68]. Since the time for calculating RCPT in the number of vertices of the network is polynomial, this study generally concludes that it is easily applicable to games with complex solutions. In their study [11], they used CPP to find the optimal route of the machines that periodically inspect the railway. As a result, this method was proved to perform better compared to the existing manual application based on expert knowledge. In this study [69], they have proposed an non- exact multi-objective CPP (UMCPP) under the framework of uncertainty theory, for an undirected connected network. The proposed model determines a postman tour by simultaneously maximizing total profit and minimizing total travel time.

He developed a practical approach for accurate contour deformation in his study [70]. This is the first time CPP in graph theory has been used for contour deformation. In their study [71], authors use the strand displacement technology in their paper to solve the CPP. The model calculation shows that the complexity of the problem can be reduced by using the molecular beacon strand displacement reaction to solve the CPP. In the study [72], is presented a mathematical formulation for the postman problem with variable service costs. It is assumed that the

travel costs of the edges depend on the number of passes and they tend to decrease with each pass. The authors consider CPP with variable service costs (CPPVSC), and windy postman problem .with variable service costs (WPPVSC). Besides they propose two heuristics for the solution of problems.

3 RESULTS

In this section, the results obtained by literature research are discussed. When the studies included in the research are examined, it is seen that the application areas of CPP are gradually increasing (garbage collection, snow and ice controls on streets and highways, road gritting, snow removal and street cleaning operations, school bus and police patrol vehicles, water and newspaper distribution, robotic discoverydesigning parking permit, mutual game-based defense strategy, guiding patrol vehicles). Researchers are especially interested in capacity-limited CPP, time-dependent CPP, and hierarchical CPPs. Because these problems are easier to implement in real life.

In the literature, it is seen that heuristic methods are mainly used for CPP solution. In recent years, exact solution methods have been applied. The problem is commonly solved by integer linear programming, the exact solution method, and branch-bound and branch-cut methods. In NP-hard problems (problems that cannot be solved by precise mathematical methods in polynomial time), it has been observed that as the problem size increases, it is difficult to obtain the best results and heuristic methods are used. Several heuristic algorithms are developed for CPPs and related computational results. When the literature is examined, it is seen that these methods, both alone and in combination with other heuristic methods, have achieved very successful results.

According to the results obtained from literature research, CPP types according to problem classes are as follows: Undirected CPP, Directed CPP belong to class P. Mixed CPP, Min-Max k CPP and Capacitated CPP are known to be NP-hard. And Windy CPP and HCPP belong to NP-hard (some conditions P) class.

4 CONCLUSION

In this study literature research was conducted for CPP and its variations which are available and reachable in the literature. Besides some suggestions are presented considering the deficiencies mentioned in the literature.

In future studies, CPP can be solved with different models considering the deficiencies mentioned in the literature research. Types of CPPs that overlap with real-life problems can be developed. Studies in the literature can be solved with different heuristic methods and methods that provide faster and higher quality solutions can be obtained.

When the studies in the literature are examined, it is seen that travel times are ignored and the distances covered are considered in most of the problems. In future studies, CPP can be applied by considering travel times in real life problems. And CPP can be presented with fuzzy modeling solutions that can be expressed in linguistic variables. Besides, it was seen that there is no study about open CPP and stochastic CPP. CPP considering these deficiencies mentioned in the literature can be solved with different models to overlap with real life problems.

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