UNIVERSITI PUTRA MALAYSIA

SUB-ROUTE REVERSAL REPAIR MECHANISM AND DIFFERENTIAL EVOLUTION FOR URBAN TRANSIT NETWORK DESIGN PROBLEM

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By

BUBA AHMED TARAJO

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

November 2017

DEDICATION

This work is dedicated to my late parents

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

SUB-ROUTE REVERSAL REPAIR MECHANISM AND DIFFERENTIAL EVOLUTION FOR URBAN TRANSIT NETWORK DESIGN PROBLEM

By

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November 2017

Chairman : Associate Professor Lee Lai Soon, PhD
Faculty : Science

This thesis considers the urban transit network design problem (UTNDP) focusing on the implementation of population-based metaheuristic approaches, specifically on differential evolution (DE) and particle swarm optimization (PSO). The main goal is to develop solution methods that can be used to determine optimal transit route configuration for urban public transportation systems, specifically for system based on buses. The UTNDP consists of determining the number and itinerary of urban public transportation lines and their associated frequencies, with a given infrastructure of streets and demand points. The problem is characterized by huge search space with multiobjective in nature, and it is considered as one of the most challenging combinatorial optimization problems.

Due to the NP-hard nature of the UTNDP, the evaluation of candidate solution is challenging and time consuming, in which many potential solutions are discarded on the grounds of infeasibility. A new repair mechanism that is governed by a sub-route reversal procedure is proposed and compared with existing repair mechanisms in terms of the efficiency. The proposed repair mechanism can either be used as a stand-alone or complement other existing repair mechanisms in the literature to deal with the infeasibility.

From the literature of UTNDP, the most widely used metaheuristic is the genetic algorithm, at the expense of other population-based metaheuristics. Hence, we focus on urban transit routing problem and develop a framework for tackling the problem. The problem is solved both as a single and multiobjective optimization problems based on small and large benchmark instances, as well as a real-world network.

In addition, the UTNDP, which comprise of the network design and the frequency setting problem is also modelled base on DE as a single objective optimization problem from the perspective of the passenger, in which simultaneous network design and frequency setting problem is tackled using a well-studied benchmark network.

As a further extension, a hybrid DE-PSO for the UTNDP is developed as a multiobjective combinatorial optimization that produces a set of routes that take into account the interest of users and operators for a given set of resource-and-service constraints. All proposed algorithms are executed using Python programming language, and the computational results show that the proposed algorithms improve the best-so-far results from the literature in most cases.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

MEKANISME PEMBAIKAN PEMBALIKAN SUB-LALUAN DAN EVOLUSI PEMBEZAAN UNTUK MASALAH REKA BENTUK RANGKAIAN TRANSIT BANDAR

Oleh

BUBA AHMED TARAJO

November 2017

Pengerusi : Profesor Madya Lee Lai Soon, PhD
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Tesis ini mempertimbangkan masalah reka bentuk rangkaian transit bandar (RBRTB) dengan mengaplikasikan metaheuristik berasaskan populasi khususnya evolusi pembezaan (EP) dan pengoptimuman rombongan zarah (PRZ). Matlamat utama tesis ini adalah untuk membangunkan kaedah penyelesaian untuk menentukan konfigurasi laluan transit yang optimum untuk sistem pengangkutan awam bandar, khususnya untuk sistem berasaskan bas. RBRTB ini dapat menetapkan jumlah dan jadual laluan pengangkutan awam bandar dan frekuensinya berdasarkan struktur jalan dan tempat permintaan yang diberikan. Masalah ini bercirikan ruang pencarian yang besar dengan sifat pelbagai objektif, dan ia dianggap sebagai salah satu masalah pengoptimuman kombinatorial yang paling mencabar.

Oleh kerana sifat RBRTB yang berunsurkan NP-keras, penyelesaian penilaian calon dari set penyelesaian adalah mencabar dan mengambil masa yang lama, yang mana banyak penyelesaian yang berpotensi dikeluarkan disebabkan ketidakupayaan. Mekanisme pembaikan baru yang dikendalikan oleh prosedur pembalikan sub-laluan telah dicadangkan dan dibandingkan dari segi kecekapan dengan mekanisme pembaikan yang sedia ada. Mekanisme pembaikan yang dicadangkan ini boleh digunakan secara berasingan atau digabungkan dengan mekanisme pembaikan yang sedia ada dalam literatur untuk menangani ketidakupayaan tersebut.

Daripada literatur RBRTB, metaheuristik yang paling banyak digunakan ialah algoritma genetik, dengan mengembangkan metaheuristik berasaskan populasi yang lain. Oleh itu, kami memberi tumpuan kepada masalah penghalaan transit bandar dan membuat rangkaan bagi kaedah EP untuk menangani masalah tersebut. Masalah itu

diselesaikan sebagai masalah pengoptimuman objektif tunggal dan pelbagai objektif berdasarkan contoh data penanda aras yang kecil dan besar, serta rangkaian dunia sebenar.

Tambahan pula, RBRTB yang terdiri daripada masalah reka bentuk rangkaian dan masalah penetapan frekuensi juga dimodelkan berdasarkan EP sebagai masalah pengoptimuman objektif tunggal dari segi perspektif penumpang, yang mana masalah reka bentuk rangkaian dan masalah penetapan frekuensi diatasi dengan serentak menggunakan rangkaian penanda aras yang dikaji dengan baik.

Bagi meneruskan perbincangan, kaedah hibrid EP-PRZ dibangunkan sebagai pengoptimuman gabungan pelbagai objektif yang menghasilkan satu set laluan dari segi kepentingan pengguna dan pengendali untuk set kekangan yang berkaitan dengan sumber dan perkhidmatan. Semua algoritma yang dicadangkan adalah diaplikasikan dengan menggunakan pengaturcaraan *Python* dan hasil komputasi menunjukkan bahawa kesemuanya dapat mempertingkatkan hasil terbaik sedia ada untuk kebanyakan kes.

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I certify that a Thesis Examination Committee has met on 30 November 2017 to conduct the final examination of Buba Ahmed Tarajo on his thesis entitled "Sub-Route Reversal Repair Mechanism and Differential Evolution for Urban Transit Network Design Problem" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This is to confirm that:

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LIST OF ABBREVIATIONS

ABC	Artificial Bee Colony
ACO	Ant Colony Optimization
BCO	Bee Colony Optimisation
CR	Combine Repair
CRO	Chemical Reaction Optimisation
DE	Differential Evolution
DE-PSO	Differential Evolution-Particle Swarm Optimization
DPSO	Discrete Particle Swarm Optimization
EA	Evolutionary Algorithm
GA	Genetic Algorithm
GRASP	Generalized Randomized Adaptive Search Procedure
HEABC	Hybrid Enhanced Artificial Bee Colony
iCR	Improved Combine Repair
iSRR	Improved Sub-Route Reversal Repair
MA	Memetic Algorithm
MSC	Make-Small-Change
PIA	Pair Insertion Algorithm
SA	Simulated Annealing
SAGA	Simulated Annealing-Genetic Algorithm
SRR	Sub-Route Reversal Repair
TR	Terminal Repair
TS	Tabu Search
UTNDP	Urban Transit Network Design Problem
UTRP	Urban Transit Routing Problem

UTSP	Urban Transit Scheduling Problem

CHAPTER 1

INTRODUCTION

1.1 Background

Nowadays public transportation system plays a significant role in daily lives of people in many cities of the world. With the rise in population and urbanization of many cities, especially in developing and emerging countries, have led to the increase in travel demand. As a result, there are significant increase of usage in private vehicles for daily commuting in urban and suburban areas. These issues had contributed to the problems including constant traffic congestion, excessive and unreliable travel times, stress, greenhouse gas emissions, noise, more traffic accidents and energy consumption among others. One of the most viable solution to handle these problems is to improve the public transport systems. This can be achieved through proper design of public transit networks that takes into account the interest of the users and the reduction of the transportation cost. In practice, improving the efficiency of public transport is an often-stated goal of transportation policy in big cities because only efficient public transport can successfully compete with private vehicles and thus help to reduce the traffic congestion.

One of the most important challenges confronting urban transit planners is to achieve suitable (viable) transportation systems that can accommodate these huge urban travel demands. With regard to the capacities of urban highways in many cities of the world, one can easily conclude that the use of private personal vehicles cannot handle the large numbers of urban travel demands. Rather, the most viable solution to address the demand in such cities is to utilize public transportation systems at different levels of operation (Amiripour et al., 2015). In addition, a number of benefits can be secured through the public transport usage including reduction of energy consumption, congestion, and carbon emissions among others. However, in many cities of the world, public transport has suffered under funding leading to low patronage with many transit users opting for private vehicle usage for comfortable and more convenient journey (John, 2016).

In real sense, some public transport modes are more flexible than others, and therefore can adapt more easily to changes in the community they served. For instance, it is far easier to adapt or change a set of bus routes relative to the fixed infrastructure of an underground system. As such, buses should constitute a core part of the urban transport system that must provide frequent, safe, and reliable services, minimize the waiting and in-vehicle travel time for passengers, and avoid the need to make many transfer between vehicles. This must be balanced with the cost of operation for the network operator (John et al., 2014). In other words, in order to provide better service to users and to increase operating efficiency, transit system planning should produce transit services that provide competitive travel time and require low operating costs. Beirao and Cabral (2007) highlighted the public transport barriers that need to be checked in order to increase public transport usage include, among others: lack of direct transport, long travel times, need for multiple journeys, and not frequent and enough information. Due to its complex transit travel time characteristics, which include in-vehicle travel time, waiting time, transfer time, and transfer penalties, it has been a difficult task to optimize transit networks (Lee & Vuchic, 2005).

Among the different existing technologies to construct and operate a public transportation system, this work is restricted to system based on buses. In this study, we focus on bus network design on existing infrastructure (street networks, stations). Therefore, we do not consider decisions related to building new infrastructure (e.g. exclusive bus corridors, trams or underground networks). As buses are the backbone of public transport systems, optimization of bus routes and associated service frequency would certainly contribute to improving the system efficiency. However, this problem is rarely tackled by transport planners. In most cases bus networks evolve incrementally: new services are being added as the city develops. Over the decades, many public transit networks in many cities have not been reappraised from anywhere between 20 to 50 years (Bagloe & Ceder, 2011). In recent times, land use has change considerably with the migration away from town centers into surrounding suburban areas; however public transport has been relatively slow to respond. It is timely to develop automated tools to aid public transport networks (John, 2016).

The design of public transportation system can be modeled as an optimization problem, in particular as a cost minimization problem. However, such a problem is intractable as a single individual unit, given the number of variables, relations among them and even conflicting objectives. For this reason, the problem is decomposed into a sequence of activities of smaller size: network design, frequency setting, timetable construction, bus scheduling, and driver scheduling (Ceder & Wilson, 1986) in such a way that the resulting problems can be tractable. In these problems, the main objective is to design a system which offers a better level of service, with the lowest possible cost. From the point of view of the users, such a system should satisfy the needs of travel for all the inhabitants of the city, with the lowest travel time, fare, and reasonable comfort conditions (Mauttone & Urquhart, 2010).

1.2 Problem Statement

The increase in population and the changes in land use faced by many cities of the world, indicate the need of an efficient public transport system to meet the huge travel demand. An efficient public transport system is capable of reducing the number of private vehicles and consequently lowering the level of traffic congestion on the road together with reduction in air pollution and energy consumption.

In the field of operations research, this public transport system can be defined as the urban transit network design problem (UTNDP). This problem is concerned with devising a set of routes and schedules according to the predefined demand points (bus stops or stations) and passengers' demand in each station for an urban public transport system. The UTNDP belongs to the class of NP-hard combinatorial optimization problem, which the optimal solution is unlikely to be found in polynomial time. It is regarded as a complex variant of the general network design problem, which is NP-hard in nature (Magnanti & Wong, 1984). Due to computational complexity of the UTNDP, many researchers resort to the development and use of various heuristic and metaheuristic algorithms. Metaheuristics have become dominant tools for solving hard combinatorial optimization problems (Nikolić & Teodorović, 2014). Several authors have also used hybrid metaheuristic approaches (e.g. Zhao & Zeng (2006), Liu et al. (2010), and Szeto & Wu (2011)).

In most cases, metaheuristics provide high-quality solutions within reasonable CPU time. However, most of the literature focused on the application of genetic algorithm (GA) with only a few studies based on simulated annealing (SA), tabu search (TS), ant colony optimization (ACO), bee colony optimization (BCO), and particle swarm optimization (PSO). In addition, some of the algorithms were found to produce efficient network design based on specific design parameters and passenger assignment procedures, with no attention given to the comparison of the study with other algorithms in the literature. Furthermore, some hybrid GAs have been developed for the UTNDP, but the hybridization with more recent population based metaheuristics such as differential evolution (DE), and PSO have not been explored. To the best of our knowledge, there is no application of DE on UTNDP. Finally, few research efforts have considered real-life transit networks of the UTNDP.

There are three stakeholders to consider while resolving the UTNDP: users, operators, and the planner (local authority). Users expect better level of service while the operator aims to reduce the cost. Thus, UTNDP must optimize many criteria in order to efficiently meet the needs of users, while at the same time minimizing the costs to the service provider. From the user's viewpoint, an ideal public transit system will provide frequent services and rapid travel times between the origin and the destination, with a minimum number of transfers between vehicles on the way. Operators, on the other hand, aim to minimize their costs, yet a low cost option may provide a poor service to the customer. Operator costs usually depend on the fleet size, transit vehicle size, transit vehicles miles and vehicle operation hours required for a particular route configuration. In addition, there are other stakeholders involved, including national and local government as well as taxpayers and local business. While many parties will benefit from an efficient public transit system, each one will evaluate its service from their own perspective (Fan & Mumford, 2010). It is usually difficult to find a solution that will satisfy both parties due to the conflicting objectives. In other words, the attempt to reduce the user cost will simultaneously increase the operator cost and vice versa.

1.3 Motivation of the Research

The main motivation of this research is the study of the transit route network optimization in public transportation systems, from an Operations Research viewpoint. The goals are to develop models and algorithms that can be applied to real cases related to public transportation systems based on buses. With the development of computer systems and computing methods, different problem-solving methods and optimization techniques have been utilized for designing urban transit networks, however, it is still a challenging issue for transit planners and practitioners (Chua (1984), Guihaire & Hao (2008), Kepaptsoglou & Karlaftis (2009), Farahani et al. (2013), Ibarra-Rojas et al. (2015)). Therefore, effective solution method(s) is/are needed that addresses the following challenges:

- dealing with infeasible route sets that may result: (i) in the course of constructing individual candidate route sets using either heuristics or standard shortest path algorithm at the initialization stage. (ii) due to the utilization of the operators of metaheuristic approaches.
- adapting more recent population-based metaheuristics to handle the UTNDP, in particular, DE and PSO which are considered simple, flexible, robust, and uses fewer parameters compared to GA.
- tackling the network design and frequency setting problem simultaneously using DE and hybrid DE-PSO so that the designed routes can support the define schedule. The NP-hardness of the network design and the frequency setting problem had forced earlier research efforts to tackle each separately.
- resolve the UTNDP through hybrid metaheuristics (i.e. hybrid DE-PSO), which are both population-based metaheuristics. Most hybridization approaches for UTNDP are GA combining with iterative search algorithms like SA and TS and a number of other metaheuristics.

1.4 Scope and Limitations

This study mainly focuses on the UTNDP, giving attention to the following:

- The public transport system is considered in isolation from other modes of transport, for example private cars. Moreover, we consider a single mode of public transportation, which is based on buses.
- The interactions between the public transportation systems and the land use dynamics of the city where it is embedded is not taken into account.
- The demand is considered inelastic. We assume a fixed set of users that do not have other alternative for travelling (captive clients).
- The modeling process does not consider the impact that might cause the fare charged for using the service of public transportation in the behavior of the users concerning the use of lines. It is known that different fare structures have consequences in such behavior (Zhou & Lam, 2003).

- The existence of advanced traveler information systems is not considered, which also have influence in the behavior of the user (Nuzzolo, 2003)
- It is assumed that users are sensitive to the waiting time and transfers. It is known that certain features of some systems, like special infrastructure (bus stops or stations) and operation schemes (high frequency, coordinated timetables,), contribute to decrease the negative perception that users have with regards to waiting time and transfers.

As mentioned earlier, with the advancement of computer systems and computing methods, different problem-solving methods and optimization techniques have been utilized for UTNDP. The problem has been well surveyed in several review papers: Chua (1984), Guihaire and Hao (2008), Kepaptsoglou and Karlaftis (2009), Farahani et al. (2013), and Ibarra-Rojas et al. (2015). However, tackling UTNDP is still a challenging issue for transit planners and practitioners. The difficulties faced are listed below:

- Defining and relating the decision variables to the objective function components. For instance, while the vehicle frequencies is reflected in the formulation of the UTNDP, without consideration of the number and nodal composition of the routes.
- The UTNDP formulation is characterized by non-linearities and non-convexities. Non-convexities represent the tendency such that as the transit designer deploy more vehicles in the transit network (thereby leading to increase in the operator's costs), there is higher chance that the total travel time can be high (worse user costs). Newell (1979) pointed that concavity is caused by the waiting time which takes place at the system entrance or at transfer points. The waiting time is not a cost associated with the links of the transit network.
- The route design problem is discrete in nature and hence experiences a significant combinatorial explosion as the network size grows. Thus, making the UTNDP a NP-hard problem.
- The passenger assignment model embedded as a sub-model of the UTNDP. From the perspective of users, a behavior model of passenger route choice and frequencies is required to evaluate a given solution. The assignment model of passengers to routes describes how demand is allocated among a given set of routes. Desaulniers and Hickman (2007) explained that its solution constitute a hard problem by itself, in this case posed as a sub-problem of the UTNDP.
- The characteristics of spatial layout of the routes is difficult to formally define and incorporate in a formal procedure, hence evaluation of the routes cannot be simply done. The aspect regarding what constitute a 'good' spatial layout of the routes has been to some extent addressed through design criteria including route coverage, route duplication, route length, and directness of service (circuitry) among others.
- The multiobjective nature of the UTNDP. Most past approaches have modeled the UTNDP as a single objective optimization problem by either minimizing user costs or operator costs. In real sense, important trade-offs among other

conflicting objectives need to be addressed in what is intrinsically a multiobjective problem. The total demand satisfied and its components (the total demand satisfied directly, one transfer, two transfer, or unsatisfied) are examined against the total travel time and its components (the total travel time i.e. in-vehicle, waiting, or transferring) and against the fleet size required to operate the transit system.

1.5 Research Objectives

The main goal of this study is to develop efficient solution methods using more recent population-based metaheuristics to address both urban transit routing problem (UTRP) and UTNDP. The specific objectives of this study are:

- to develop novel repair mechanisms that deal with infeasible route sets as a result of initialization procedure, as well as the operators of metaheuristic approaches in the proposed algorithms.
- to propose modified DE algorithm for solving discrete single and multiple objective UTRP and UTNDP.
- to validate the proposed algorithms using well-known benchmark Mandl's Swiss network and larger networks by Mumford.
- to carry out a case study of a real-life network of a transit operator.

1.6 Thesis Organization

The content of this thesis is organized in seven chapters in accordance with the objectives and the scope of the study. These chapters are structured so that the research objectives are apparent and are conducted in the sequence outlined. The present chapter comprises of the problem statement, the motivation for the study, the scope and limitations faced in solving the problem, and the research objectives.

Chapter 2: This chapter is the background research and literature review of the UTNDP with a comprehensive review on the diverse approaches employed to handle the problem including manual, mathematical, and heuristics or metaheuristic developments. The gaps and limitations of previous research are also highlighted.

Chapter 3: This chapter provides brief overview of the standard DE and PSO together with the algorithm parameters. Some literature on vehicle routing and scheduling as well as traffic and transportation engineering applications based on PSO are examined.

Chapter 4: This chapter discusses the initialization procedure for generating the initial candidate route set. New repair mechanisms for correcting infeasible route sets that may result from the initialization procedure, as well as the application of the operators of the metaheuristic approaches are also presented. Computational experiments of the proposed repair mechanism are reported in this chapter.

Chapter 5: This chapter presents the problem definition and formulation of the UTRP. The DE framework for single and multiobjective UTRP are outlined in terms of representation and initialization, fitness evaluation, mutation, crossover, and selection. The features of problem instances including small instance, large instances, and real data case are also presented. Extensive computational experiments are carried out to assess the performance of the proposed DE algorithms compared to other approaches from the literature.

Chapter 6: This chapter focuses in UTNDP on the problem definition and formulation as well as the determination of the bus line characteristics. The DE framework for the single objective UTNDP is presented. This is followed by the hybrid DE-PSO for multiobjective UTNDP. Computational experiments are carried out for all proposed algorithms for single and multiobjective UTNDP.

Chapter 7: Finally, conclusions based on the objectives stated in Chapter 1 are presented and future research are elaborated in this Chapter.

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LIST OF PUBLICATIONS

Buba, A. T. and Lee, L. S. (2016). Urban Transit Network Design Problems: A Review of Population-based Metaheuristics. *Pertanika Journal of Scholarly Research Reviews*, PJSRR (2016) 2(3): 86-99.

Buba, A. T. and Lee, L. S. (2016). Differential Evolution for Urban Transit Routing Problem. *Journal of Computer and Communications*, 2016, 4, 11-25.

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