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Transit Network Design using GIS and Metaheuristics in Sanandaj, IRAN

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Abstract

The public transit system in Sanandaj has been under review and modification for the last several years. The goal is to reduce the traffic congestion and the share of private car usage in the city and increase the very low share of the public transit. The bus routes in Sanandaj are not connected. There is no connected transit network with the ability to transfer between the routes in locations outside of the downtown terminal. The routes mostly connect the downtown core directly to the peripheries without providing travel options for passengers between peripheries. Although there has been some improvement in the transit system, but lack of service in many populated districts of Sanandaj and town nearby makes the transit system unpopular and unreliable.

This research is an attempt to provide solutions for the transit network design (TND) problem in Sanandaj using the capabilities of GIS and artificial intelligence methods. GIS offers several tools that enables the decision-makers to investigate the spatial correlations between different features. One of the contributions of this research is developing a transit network design with utilizing a spectrum of GIS software modeling functionalities. The visual ability of GIS is used to generate TNDs. Many studies focus on artificial intelligence as the main method to generate the TNDs, but the focus of this research is to combine GIS and artificial intelligence capabilities in order to generate a multi-objective GIS-based procedure to construct different bus network designs and explore and evaluate them to find the suitable transit network alternative.

The GIS-based procedure results will be assessed and compared with the results of metaheuristic approaches. Metaheuristic methods are partial search procedures that may provide sufficiently good solutions to an optimization problem characterized by incomplete information or limited computation capacity (Talbi, 2009). Yang, Cui, Xiao, Gandomi, and Karamanoglu (2013) classified metaheuristic methods into two groups: single-agent procedures (e.g., simulated annealing algorithm involves one agent navigating in the environment), and multiple agents (e.g., population-based genetic algorithm, and swarm intelligence methods). This study focuses on swarm intelligence methods, such as ant colony optimization and honeybee algorithm. These methods provide a multi-objective assessment of the TND scenarios generated by GIS applications. The outcome of this study will help us to find the optimal solutions for the TND in Sanandaj.

Keywords

Transit Network Design (TND), Metaheuristics, GIS, Ant Colony Optimization, Honeybee Algorithm

Summary for lay audience

Public transit systems such as bus play a crucial role in reducing the traffic and transport people with low-income to their destinations in the cities and suburbs. In this research, we propose and evaluate several transit network designs in order to improve the access to buses in the city of Sanandaj and reduce the usage of the private vehicles to travel to downtown or other towns and districts in the outskirts of Sanandaj. Several maps for the future bus network have been proposed and analyzed to find the suitable transit network layout for Sanandaj, based on the objectives such as better access to the bus system, minimum travel distance and daily cost of operation of the public transportation.

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Chapter 1

Introduction

1_1 Problem Statement

The rapid growth of cities and higher car ownership have caused air pollution and traffic congestion. As a result, a rapid and efficient transit system is recommended to tackle those issues. In addition, the higher car ownership is causing health and safety problems, such as injuries, deaths, air pollution and noise which can be reduced by introducing an efficient transit system (Cipriani, Gori, & Petrelli, 2012).

Public transit planning is a user-oriented problem, respectful of financial issues and involves different stakeholders such as the general public, the transportation provider and the local government. One of the main components of public transit planning is the transit network design (TND) problem. The TND is a strategic planning problem aiming at maximizing service quality under budgetary restrictions. It is a method of finding a set of routes with specific schedules for a transit fleet (Fan & Mumford, 2010). Because of the large number of the bus stops, it is difficult to find a set of routes using the traditional approaches (Zhu, Guo, Zeng, & Zhang, 2017). There are two main approaches to TND: the route level design and the network level design (Ceder, 2016). Route level design focuses on a small part of the network or a single transit route to manage new travel demand and reduce the number of transfers and circuity. The network approach is to design the transit network as a set of routes to serve the current travel demand efficiently.

Visualization helps to find patterns in the data and understand the data and its attributes. Martin and Higgs (1996) describe two main applications of visualization in planning procedure as 1) representing the real world and 2) abstract statistical relationships. GIS offers several tools to enable a decision-maker to investigate spatial correlations between different features. One of the contributions of this research is development of a transit network design with utilizing a spectrum of GIS software modeling functionalities. The visual ability of GIS is used to the full extent in order to construct and modify the network alternatives using the interactive environment of GIS application. The transit network alternatives are constructed based on the location of attractive and major destinations in the city. Several steps are designed in the GIS-based procedure in order to construct efficient transit networks to be examined later.

Also, access to the network is analyzed based on the coverage of major destinations and population centers. Accessibility for the population with limited access to the private transportation is a major objective of the public transit system (Murray & Wu, 2003). Accessibility is "the ease with which activities at one place may be reached from another via a particular travel mode" (S. Liu & Zhu, 2004). Spatial accessibility includes access and geographic coverage (Murray & Wu, 2003). Lower walking distance from the transit network to the attractive destinations, such as shopping malls, or population centers generates a higher level of accessibility (S. Liu & Zhu, 2004). GIS will help to find the level of access and coverage of the designed transit network alternatives based on the distance to population centers and attractive locations.

Many studies focus on artificial intelligence as the main method to generate the TNDs. The focus of this research is to combine the GIS and artificial intelligence capabilities together in order to use their power to design better transit network designs. In previous studies, metaheuristic or heuristic methods must do all of the analysis of network deign. But in the proposed procedure, the burden of analysis is distributed to GIS and metaheuristic methods because GIS applications have higher spatial analysis capabilities compared to the metaheuristic methods.

This research focus is on the public transportation network of Sanandaj, Iran. The share of travel using public transit system is very low (two percent) compared to other modes of travel (Kurdistan, 2011). This is due to the lack of an efficient and connected bus system. The current bus system has a very limited number of stops in the peripheries. Further, the system offers almost no transfer and connection options between radial lines except in the downtown terminal. Radial bus lines connect the downtown area to the outskirts of the city. There are not any beltway bus lines in the bus network that could connect the peripheral towns and districts. Beltway bus lines connect the districts and towns outside or on the boundary of the city together without the need to travel to the downtown area. Radial bus lines connect the central terminals in downtown to the peripheral stations outside of the downtown area. Beltway lines connect the peripheral bus station outside the downtown area. Peripheral stations are major bus stops located in the towns and districts outside of the downtown area and close to the boundary of the city.

The necessity of comprehensive planning of transit system in Sanandaj is clear due to the several issues as follows. First, traffic congestion in the peak hours of morning and afternoon creates a heavy traffic congestion in Sanandaj. The congestion can be addressed by implementing the fast bus routes in a connected network with transfer options between the routes. Second, the current bus system does not provide any service to several areas in the peripheries. Lack of enough coverage and low level of bus service has reduced the share of traveling using public transit system to only two percent of the daily trips. The current transit system offers a limited service between the central business district (CBD) to other districts of the city and surrounding towns. There are only few routes. Designing a better transit system by increasing the service coverage of the bus system and routes from CBD to the peripheral areas of Sanandaj is a goal of the network design in this research. Also, reducing the travel distance between the main travel destinations and populated areas of the city is important. Many bus lines in Sanandaj have not been designed based on the minimum travel distance from the origin to the destination (Kurdistan, 2011).

1-2 Research Objectives

The main goal of this research is to develop a multi-objective GIS-based procedure for the TND problem and apply the proposed approach to construct and to evaluate several bus network alternatives in Sanandaj. For the stated goal, the following three main research objectives of this study must be accomplished:

(i) To formulate a multi-objective model of the TND problem.

(ii) To develop a GIS-based procedure for solving the TND problem.

(iii) To examine the solutions (alternative transit networks) using metaheuristic methods such as ant colony optimization, and honeybee algorithm.

The multi-objective model proposed consists of three objectives including the walking distance to the network, total travel distance and number of stops for the proposed bus networks. First objective is proposed based on the passengers' preference to minimize the total walking distance to the transit station. An acceptable walking distance within a certain limit is crucial in order to persuade the user to take a trip using the transit system (Ceder, 2016; Fletterman, 2008). There is an inverse relationship between walking distance to the stop and accessibility of transit system (Fletterman, 2008). Also, optimal number of stops minimizes the long-run cost of transit system and provides suitable coverage in the operation area (Jahani, 2013).

Travel distance between two stops on the shortest path is the minimum (Ceder, 2016). It is necessary to consider travel distance in TND because of its influence on the user's satisfaction. Some TNDs might not be designed based on the shortest travel distance in order to provide better coverage for the population blocks far from downtown or other population centers.

The GIS-based procedure proposed is an innovative approach in designing and evaluation of the network. Using the visual and analytical capabilities of GIS several transit network solutions have been generated, and later, the coverage of the TND scenarios has been determined. In this study combination of GIS and metaheuristic will provide an efficient multi-objective procedure to design, explore and examine variable solutions in order to achieve a more optimal result than existing bus network.

1.3 Thesis structure

The manuscript consists of six chapters as follows. The first chapter is the Introduction that consists of problem statement, research objectives and thesis structure sections. Second chapter is a semi-systematic literature review of scholarly work produced about transit network design using heuristic and metaheuristic methods. In this chapter, research papers are selected using certain keywords and criteria. The articles retrieved are categorized based on the objective, decision variables, travel demand model, methodology and network structure and conclusion. In the second chapter, objectives used in transit network design is discussed and grouped based on the different views expressed by the selected research papers, such as operator and user points of view. Also, variables used in the TND procedures in the literature are discussed. Moreover, different types of travel demand such as fixed, variable, and elastic that have been proposed in the literature are discussed in relevance to the transit network design procedure. Different types of methods proposed to solve the TND problem is discussed in the literature review. Major metaheuristic methods implemented for TND consist of genetic algorithm, ant colony, honeybee, and particle swarm methods. The network structure proposed in the literature is also explained. Transit network structures consist of irregular and grid network layouts. In addition, the gaps in previous research is discussed at the end of the literature review chapter.

In Chapter 3, city of Sanandaj in Iran, as the study area, and its characteristics such as traffic congestion and built environment are presented in detail. Traffic congestion is considered as a real problem in Sanandaj, especially in the downtown core. Designing and implementing a transit system that could reduce the burden of the traffic by taking higher share of daily trips is necessary.

The Methodology chapter focuses on the GIS-based procedure proposed to solve the TND problem in Sanandaj. First, the multi-objective decision-making approach is explained. Afterwards, the TND model based on the objectives proposed is described. Also, the evaluation of results using GIS is discussed. Coverage of the proposed TNDs is analyzed in GIS based on different walking distance scenarios from the transit network to the destinations and population centers. combination of spatial capabilities of GIS and metaheuristics can provide a powerful design and evaluation tool in the transit network design process.

In chapter 5, TNDs are designed using ArcGIS. Proposed transit networks are based on different type of network such as star, cartwheel and radial designs. These TNDs are assessed in GIS for the coverage of population in Sanandaj and travel distance and number of stops. In the next step, metaheuristic methods analyze the TNDs and evaluate their efficiency regarding travel distance and number of stops, based of the TND model provided.

In the Conclusion chapter, the contributions and outcomes of this research are highlighted. Importance of TND in Sanandaj and how the results of the study can contribute to decision making for public transit planning is explained. Also, it is discussed how this research can contribute to the general knowledge of GIS and artificial intelligence. Also, limitations of the research and existing problem in this study are discussed. Moreover, recommendations in order to improve the research results in future and how to add to the knowledge in this field of study are provided.

Chapter 2

Reviewed literature

2-1 Review Objectives

The goal of this chapter is to review methods, objectives and parameters used for the construction of transit networks and for the modification of existing networks. Four objectives of the review are followings:

1- To discuss how demand is modeled in different case studies, the main characteristics of demand patterns will be discussed.

2- To find out the extent to which metaheuristic methods have been used in transit network optimization and what type of metaheuristic methods are more suitable in the network design procedure.

3- To describe what network structures and layouts have been generated in the reviewed literature.

4- To study the objectives (or costs) considered in the case studies and how they are implemented in designing the network.

2-2 Search Criteria

To identify research directions and approaches in the transit network design literature, specifically in studies that implemented metaheuristic methods, an article search procedure is designed. Using the search criteria, relevant research papers on available journal databases and online libraries are retrieved. Several keywords are used for the search process including followings: “transit network design”, “multi-objective, optimization" and "metaheuristics". The keywords are used to search the abstract and title of the peer-reviewed research papers in the online journal databases. Using the proposed keywords, research articles from different subjects including transportation, geography, engineering, management, policy and planning, computer and applied sciences are retrieved, investigated and examined. The online databases and journals that have been included are ProQuest, ScienceDirect, Springer, Elsevier, Taylor & Francis, PlOS One, Wiley. The following term is used to search the title and abstract of the articles in selected databases and journals: *("public transportation" OR "public transport") AND ("transit network design" OR "transportation network design" OR "bus network design" OR "transit routing") AND (optimization) AND (multi-criteria OR multi-objective OR multi-criteria OR multi-objective OR "multiple criteria" OR "multiple objective") AND (heuristic OR metaheuristic OR meta-heuristic)*. Search terms are combined using Boolean operators. First, Boolean operator OR is used to consider the synonyms of frequently used keywords in TND literature. In the next step, search terms are joined using AND Boolean operator, to reduce the number of irrelevant papers retrieved from each database.

2-3 Study selection and review process

After applying provided search terms 106 articles are retrieved from journal databases and another 23 papers are identified from other sources. Therefore, a group of 129 articles it total is been selected for further investigation. After that, by screening the abstract of the articles, regarding *transit network design using multi-objective* *metaheuristics*, irrelevant studies are removed from the set of 129 papers. The number of relevant research papers is reduced to 91, considering relevance of their abstract and title to multi-objective transit network design. At the end, each article's full text is investigated, and 41 studies are selected as suitable case studies to be examined further and included in the review paper. Half of the research papers have been removed after reading the full text due to lack of relevance to the subject of this research. The final set of articles, that consists 41 research papers that have been discussed here.

2-4 General Characteristics of Reviewed Studies

2-4-1 Objectives and costs in the network design literature

Optimization is a normative approach to identifying the best solution for a given decision/management problem (Thomas & Haggett, 1980). The solution determines the values of decision variables, subject to a set of constraints. If a decision/management problem involves a single objective function, then the problem is represented by a single criterion or objective optimization model. When two or more objective functions are to be optimized simultaneously, then the decision situation is described by a multi-objective optimization model (Cohon, 1978; Mora, García-Sánchez, Merelo, & Castillo, 2013).

The transit network design problem has changed from a single objective problem to a multi-objective complex problem in recent years (Álvarez, Casado, Velarde, & Pacheco, 2010; Fan & Mumford, 2010; Sun, Lu, & Chu, 2013). In the literature, objectives such as higher service level and ridership, shorter walking distance and travel time and maximizing coverage and access are used to design transit networks The number of research articles that implemented objectives such as demand, travel time and frequency as in the transit network design procedure is displayed in figure 2. Obviously, travel time and travel related costs of passengers is regarded as one of the main objectives in the case studies.

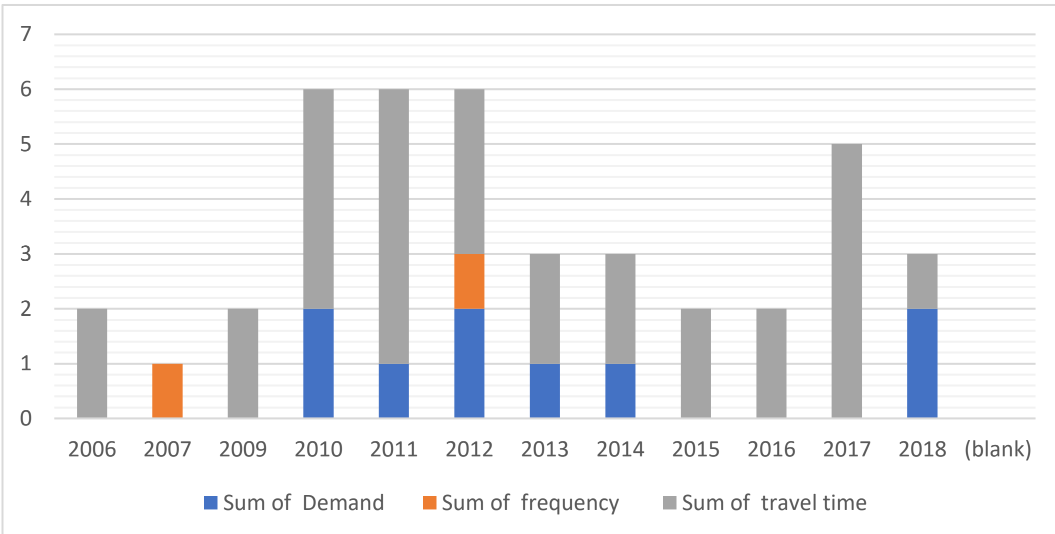


Figure 1: Number of studies used each objective in the transit network optimization

2-4-2 Decision variables

Several variables are used in modelling the transit system in the reviewed studies, such as Fan and Mumford (2010), who model the network based on average travel time as the main variable. Also, several multi-objective TND research use transit routes as a binary variable in the decision-making procedure. A route is a binary variable that means if a route is taken by the transit vehicle the variable value is one, otherwise it is zero (table 1). Moreover, demand-related variables such as unserved or unsatisfied demand, covered demand and service demand are mentioned in different case studies of multi-objective TND using heuristic and metaheuristic methods (see Table 1).

Several case studies focus on stops as one of their main decision variables. When the stop is not selected the variable value is zero. At the end of the TND procedure transit routes are designed between the selected stops. Furthermore, various variables such as headways, service frequency, fare, travel mode, number of transfers, number of passengers, fleet size and traffic flow have been considered in modeling the transit network.

In the figure 3, the case studies that use specific decision variables such as number of stops, route layout, or number of transfers in their analysis are displayed. As you can see, during several years the routes are considered as major variable in modeling networks. These decision variables are mixed of spatial and non-spatial variables. For instance, route layout is a spatial variable based on the direction of routes in the network.

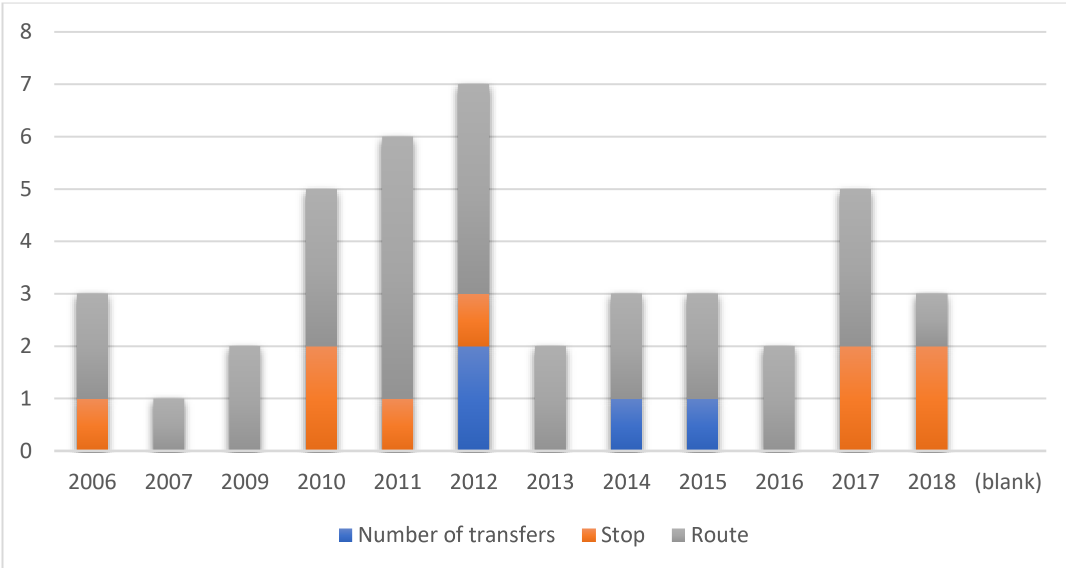


Figure 2: Decision variables used in reviewed studies by the year of publication

2-4-3 Travel Demand

There are two main categories of demand pointed out in the literature, fixed and elastic. In the fixed demand model, the demand for each mode is unchanged. On the other hand, elastic demand is defined in such a way that considers several factors such as variability of demand during different times of day or travel time using different travel modes. Elastic demand is also divided to two types. In the first type, demand between each O-D pair is fixed but the share of travel demand for each mode is variable. In The second type, the demand between each O-D pair is elastic. The first type only considers travel mode changes, but the traveler does not give up traveling due to high cost of the trip cost. In the second model, traveler might cancel the trip or change the destination due to high travel cost (Farahani, Miandoabchi, Szeto, & Rashidi, 2013). In the figure below, a year by year summary of publications presented to investigate the elasticity of demand in the reviewed literature. Based on the year of publication, many of the older studies ignored the fact that introducing new transportation modes will affect the demand for other modes of travel.

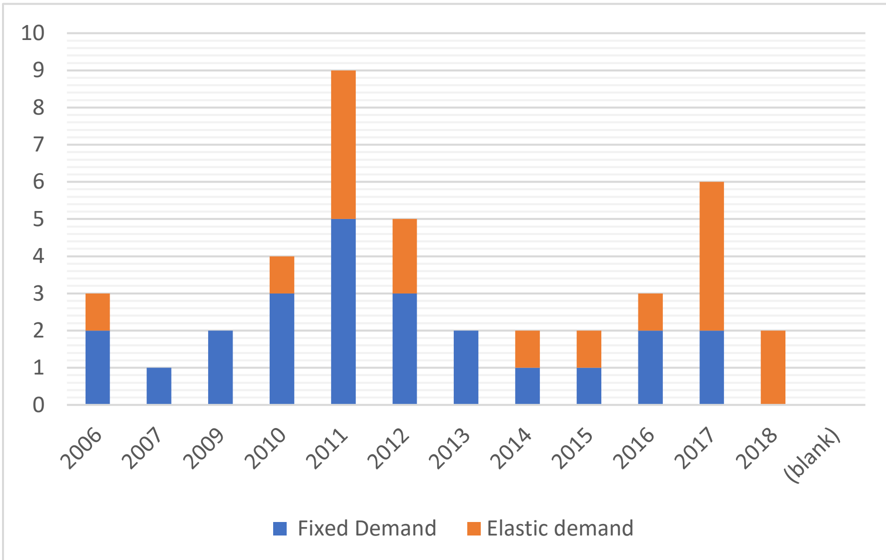


Figure 3: Demand pattern in the publications reviewed based on the year of study

2-4-3-1 Main characteristics of demand models

Several studies predict the demand based on the attractiveness destinations and socioeconomic properties of the origin. Based on the literature variables such as access and travel time affect the transit demand. Also, traffic analysis zones (TAZs) are proposed in some case studies to generate an aggregated travel demand estimation. In the reviewed literature, many have focused on generating network layouts with several origins and destinations, based on the existing demand pattern in the study area (many-to-many travel demand pattern). Also, another model of travel demand for transit service, proposed in several studies, considers the transit service demand to be elastic. That means that the travel demand of each travel mode changes when another mode is added to the transportation system. For instance, introducing private car, bicycle, rail transit or underground can affect the bus service demand. Travel demand for a transportation mode can be calculated using the utility function (Gallo, Montella, & D'Acierno, 2011). The utility functions use parameters such as driving time, walking time and waiting time for the public transit and private car mode to calculate their utility. Each mode with higher utility obtains higher travel demand. Also, lower waiting time at bus stations generates higher utility and desirability for the bus transit (Klier & Haase, 2015).

Lu, Han, and Zhou (2018) discuss that in off-peak hours a heterogeneous travel forecasting model is a better approach in modeling the travel demand, because spatial and temporal distribution of passengers and route choice are more diverse in off-peak hours than peak. Torabi and Salari (2018) also discussed the heterogeneous demand pattern and the solution to address that. They proposed a limited-stop service to solve the TND problem and reduce the unused capacity of the fleet. Moreover, other studies mention the importance of real-time information available using routing applications that affects the route choice and demand for public transportation (Lu et al., 2018).

2_4_4 Proposed methods in the literature

Methods used to provide transit network layouts in the reviewed literature can be classified into three classes. First class of methods consists of traditional approaches such as mathematical programming that offers deterministic solution to the problem. The second class is heuristic methods and third, meta-heuristic methods.

Guihaire and Hao (2008) classify transit network design methods to four categories which except for first category the rest of them include metaheuristic methods:

1- Ad-hoc heuristics that generally use greedy construction procedure.
2- Neighborhood search approaches such as: Tabu search and Simulated annealing
3- Evolutionary methods, with Genetic algorithm is the main example
4- Hybrid approaches that use several methods in different stages of construction and modification of the network.

Various methods have been implemented to provide a set of solutions for TND problem. The first class of methods proposed is the exact methods. Several exact approaches such as line planning procedure and TRANSMAX have been proposed in the reviewed studies along with heuristic or metaheuristic methods (Borndörfer, Grötschel, & Pfetsch, 2007; Schöbel, 2012). Curtin and Biba (2011) transform the TNDP to an integer programming problem referred to as Transit Route Arc-Node Service Maximization (TRANSMAX) problem. In this approach, the problem is to find a set of arcs and nodes that provides the best transit service for the study area. They discuss that the TNDP can be altered to a modified version of travel salesman problem (TSP).

Second class of methods implemented for solving TNDP is called heuristics. Bruno and Laporte (2002) classify heuristics as single alignment and multi-alignment heuristics. Single alignment method constructs a transit line with several stations while satisfying minimum and maximum constraints (number of stations). In multi-alignment heuristics the planner should select a network configuration from a set of available scenarios before designing the network, For example, cartwheel, star, radial, half-radial, half-wheel, triangle network models (Bruno & Laporte, 2002).

Another major class of algorithms used to solve TND problem is metaheuristics. Metaheuristic methods have gained more popularity in recent years. They are developed based on traditional heuristics and include probabilistic property of heuristic methods in the process of finding solutions (Talbi, 2009). A meta-heuristic method is a partial search procedure (algorithm) that may provide a sufficiently good solution to an optimization problem characterized by incomplete information or limited computation capacity. Meta-heuristic methods in TND can be classified into two groups: single agent procedures (e.g., simulated annealing algorithm), and multiple agents (e.g., genetic algorithm and swarm intelligence). One of major differences between metaheuristics and traditional heuristics is that heuristic approaches are designed to solve specific problems such as route construction, while metaheuristic methods are more advanced and can be easily modified to solve different optimization problems.

In the figure 5, number of reviewed articles that implemented metaheuristics approaches, for multi-objective transit network design is provided. Based on the publication statistics, we can argue that genetic algorithm is the most popular multi-objective metaheuristics implemented to design the transit networks.

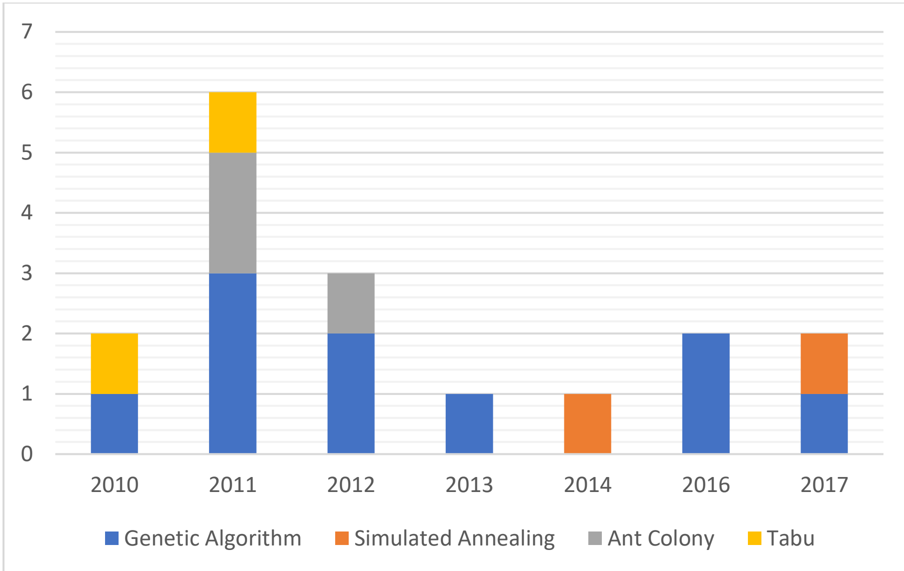


Figure 5: Metaheuristic methods proposed in the reviewed literature

Passenger perspective: Time cost of passengers and walking distance to bus stop are related to the **passenger's point of view** in transit network design. Time cost of passengers includes items such as in-vehicle cost, waiting cost, and arrival time cost ahead of schedule, and transfer time (Ma et al., 2017). Several user-related costs can be expressed in distance and time terms, interchangeably. For example, walking and in-vehicle epochs have been expressed in both time and distance. Access can be defined as physical proximity to stops (Murray & Wu, 2003). While more stops means better access to transit systems, adding to the number of stops reduces the speed (Murray, 2001). Transit planners generally have to deal with a tradeoff between increasing accessibility by using more stops in the design and having routes with reasonable travel time (Delmelle, Li, & Murray, 2012). Also, availability of different transportation modes increases the level of accessibility (S. Liu & Zhu, 2004).

Operator perspective: operational cost or income, and ridership are related to the **operator's point of view**. Operational income is generated by transit fare (Mauttone & Urquhart, 2009b). The fare might be distance-based or a flat rate. Operational costs are related to fleet maintenance, crew wages and welfare, fuel, and cost of deprecation of the fleet (Ma et al., 2017). Moreover, operator costs that have been proposed to be minimized in the TND include: the total number of routes, the fleet size, and the service time. Also, maximizing ridership considered in several case studies as one of main objectives of TND. Maximizing coverage of the transportation network are used as an operator-related objective to be satisfied in the reviewed articles.

Environmental and social perspective: In the literature , environmental and social costs are considered in TND to reduce problems such as pollution and traffic (Cipriani et al., 2012; Gallo et al., 2011; Ma et al., 2017; Sun et al., 2013). Social welfare is considered as an objective of TND to increase the social benefits of public transportation by reducing the traffic congestion. An environmental cost is based on the increase or decrease of air pollution when a public transit mode is added, considering the fact that introducing public transit can reduce private car use (Ma et al., 2017).

Diversity in objective space: multi-objective optimization models include conflicting and often non-commensurate criteria, the multi-objective problem involves finding a set of Pareto optimal solutions (also known as a set of efficient, non-dominated, and non-inferior solutions). A vector, of decision variables $\boldsymbol{x}^*$ is said to be Pareto optimal if there exist no other feasible vector $\boldsymbol{x}$ such that $f_k(\boldsymbol{x}) \geq f_k(\boldsymbol{x}^*)$ for all $k = 1, 2, \ldots, n$

and $f_k(\boldsymbol{x}) < f_k(\boldsymbol{x}^*)$ for at least one k. This implies that $\boldsymbol{x}^*$ is Pareto optimal if there is no feasible vector that would improve an objective without causing a simultaneous deterioration of at least one other objective (Cohon, 1978; Malczewski & Rinner, 2015). The non-dominated set in the objective space is referred to as the Pareto front.

In the absence of any preference regarding the objectives, all non-dominated solutions are assumed equivalent or indifferent. However, the multi-objective decision problems often require that a single non-dominated alternative is selected from the set of Pareto optimal solutions. This type of problems has traditionally been handled by combining the objectives into a scalar function and then solving the equivalent single-optimization problem to identify a best-compromise alternative (or a set of non-dominated alternatives).

Deb (2014) considers the purpose of non-exact search algorithms as closeness and diversity. Closeness is to generate solutions which are close to the optimal Pareto front. Diversity is to find a set of solutions with different trade-offs between the conflicting interests and objectives of decision makers. Metaheuristic algorithms such as Ant colony optimization, artificial bee algorithm, genetic algorithm, GRASP and scatter search can provide a set of diverse solutions (Gallo et al., 2011; Santana-Quintero, Ramírez, & Coello, 2006; Shrivastava & O'Mahony, 2006).

2-4_5 Network structures and layouts

Several types of transit network layouts have been discussed in the literature such as grid, irregular and irregular grid. The transit network layouts proposed, generally, follow the corresponding road network pattern. For example, when the road structure is a grid, then the transit network will have a grid pattern. As another example, feeder bus networks are designed following the railway or trunk lines for which they provide service. Moreover, hierarchical TNDs such as hub-and-spoke networks in the literature are proposed in few studies considering the main stations already designed in downtown, hub nodes or trunk lines. Here, in the next figure, we provided a summary of transit network layouts in the reviewed case studies, considering different factor such as road network structure, stop locations and other affecting parameters.

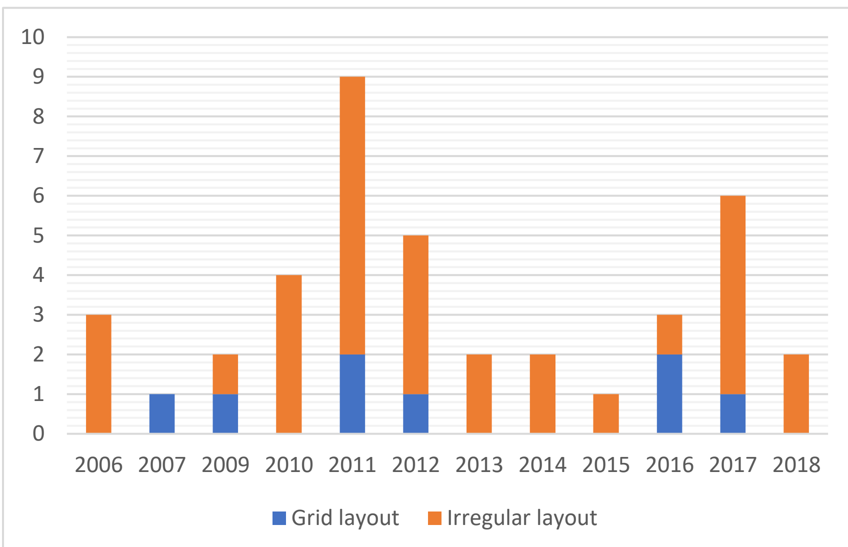


Figure 6: Studies that have implemented grid or irregular transit network layout

Different case studies proposed various network layouts such as grid and irregular (radial, cartwheel, star) to optimize service for the user. Grid network designs with parallel routes that reduce the traffic burden (by distributing passengers on the transit lines), maximize the coverage, and minimize walking time, travel time and transfer time have been implemented in the reviewed research. On one hand, grid networks satisfy the user objectives. On the other hand, hub-and-spoke or radial transit network satisfies the operator's objectives, which results in reduction of transit service level. Hub-and-spoke design provides transfer only at main stations as a dispersed network with less density and more direct routes compared to grid network. Miandoabchi, Farahani, and Szeto (2012) point to a gap in the literature in finding the best network configuration with lane allocated for public transit. They mention a lack of sufficient studies with allocation of specific lanes for high occupancy vehicles (HOV), bicycles and buses.

2-5 Discussion and conclusion

2-5-1 TND publication trend

An interesting trend in multi-objective meta-heuristics research in TND is that a significant number of reviewed articles (90 percent) are published after year 2000. More than two-third of these studies are implemented in the current decade. This trend displays a growth in popularity of multi-objective meta-heuristics. Similarly, a significant portion of the studies in multi-objective TND using exact methods, traditional heuristics or modern metaheuristics are published in 2000's. Also, as much as 80 percent of the multi-objective approaches that use metaheuristics as their main method in transit network design have been published since 2012. This trend of publication implies the growth in popularity of using meta-heuristic methods in TND.

Considering the study area of the reviewed publications, more than one-fourth of the case studies have focused on the geographic regions in China. Three studies are implemented in Canada and a similar number are using Iranian cities as their main study area. These case studies have used metaheuristics to design the transit network and they conduct their research considering the multi-objective nature of TNDP. Finally, the outcome of the article search displays that China is the leading country in TND research when it comes to using advanced artificial intelligence approaches.

2-5-2 Major metaheuristic methods

More than half of the peer reviewed articles in multi-objective TND use genetic algorithm (GA) as the main method for problem solving. GA is proposed by Holland (1975) to solve non-convex optimization functions. Decision variables are represented by chromosomes in GA. When there are several decision variables, each variable forms a sub-string (chromosome) that join other sub-strings to form a string (chromosome). GA has several shortcomings. For instance, premature convergence. It means, before reaching an optimal solution it generates a final TND that does not satisfy the objectives of the study. Another issue is that GA does not have the local search ability (Ma et al., 2017).

A few metaheuristic methods proposed in literature are swarm intelligence methods. Swarm methods include ant, artificial bee, bird and other nature-inspired algorithms which have been designed based on the swarming behavior of animals in nature (Yu & Yang, 2011). Characteristics of social behavior of fish, birds, ants and bees are their communication system, parallel search and warning method (Teodorović, 2008).

Ant colony optimization (ACO) is a type of swarm intelligence with simple agents and low level of complexity (Kazharov & Kureichik, 2010). ACO consists of a collection of ants searching for food in nature. Ants try to find the shortest route to the food source by following the path created by pheromones on the ground from previous ants. ACO originally has been proposed in two main types: Ant System (AS) and Ant Colony System (ACS), but now it has different variants developed based on these two approaches (Mora et al., 2013). ACO has been developed to solve single objective problems, but recently multi-objective ant colony optimization (MOACO) algorithms have been proposed to solve problems with several conflicting objectives (Mora et al., 2013). For complex optimization problems, the distribution or parallelization of the algorithm reduces the time to generate solutions. ACO is a distributed method because ants are relatively independent. Moreover, ants in ACO are equipped with memory of former decisions and knowledge of important locations in their geographic area (Bell & McMullen, 2004; Kazharov & Kureichik, 2010; Mohaymany & Gholami, 2010).

2-5-3 Gaps in the reviewed research

Considering methodology of the research papers, many of case studies ignored the possibility of solving the transit network design problem using exact methods. They have tried to design complex procedures using heuristic and metaheuristic methods. Multi-level approaches have been used widely in the reviewed studies. Also, many studies have not considered transit network design using GIS. Although adding to the complexity of the TND is a problem but if there is a GIS-based approach that can visualize and model the TND alternatives and examine and evaluate the TNDs using spatial analysis methods, it will be helpful in the decision making process. A GIS-based methodology will use the visual and analytic capabilities of the GIS combined with the ability of heuristic or metaheuristic methods and provides a powerful tool for construction and evaluation of TND alternatives. Approaches that only use heuristic or metaheuristic methods offer limited spatial analysis ability to evaluate and modify the network designs. The visual capabilities of GIS help the decision makers in making informed decision about the final TND for a study area.

Moreover, most of the studies have focused on designing only one final transit network without providing alternative network designs. In this case, the planners or design makers in the study area will have no option other than the proposed network design if they want to explore other network configurations for the transit system. For instance, if the research only generates a network design without any ring lines, the experts do not have the ability to see how adding a ring line or beltway in the bus network would affect coverage or accessibility.

Many studies Using capabilities of GIS and various spatial analysis tools available in GIS with the multi-objective meta-heuristic approaches, a procedure can be designed that generates and evaluates TNDs using the abilities of GIS and meta-heuristic methods. In this procedure GIS is not only used to visualize input and output data, but also its abilities are used to analyze the transit network with help of meta-heuristics.

Chapter 3

Study Area

Kurdistan province with an area of 28,203 square kilometer located between 34.44’N and 36.30’N latitudes, and 45.31’E and 48.16’E longitudes which makes up 1.7 percent of country’s land. The province mainly consists of plains and valleys in Zagros mountains. To the north, the province is neighboring Azarbaijan, to the east Hamedan and Zanjan, and to the south Kermanshah provinces. Kurdistan province is also on the Iraqi border, it is connected to Iraq from West.

The City of Sanandaj is the capital of the Kurdistan province in Iran. The city’s population was 432,330 in 2011 (Kurdistan, 2011). Sanandaj lies between two mountain ridges in Zagros mountains. Its distance from Tehran (capital city) is 520 kilometers. Historically, due to green and fertile land and numerous rivers, it has attracted people from different regions in the western IRAN to settle in Sanandaj and other towns near the city.

Several datasets including census data, street network, land-use are used in this study to provide a transit network design. Census data consist of several excel files. These excel sheets provide population by age and gender in each block, household size, number of workers and employed people in the block who must commute daily and their job category such as government employees, retail sector, different industries in the city and agriculture. Sanandaj working class in the private sectors are mostly hired in retail and agricultural businesses. With only few small industries, the city is not an industrial hub. Also, residents of rural areas or towns in proximity travel to Sanandaj during weekdays to visit the provincial government's offices and for shopping and delivering their agricultural and dairy products. This travel behavior leads to traffic congestion in the city. The figure 7 displays the location of Sanandaj in the province and country.

Figure 7: Iran Map. Image credit to: www.maps.com

3-1 Geographical data

Geographic datasets that are used in TND include ArcGIS shapefiles of the road network, attractive destinations, and census blocks. Road network of Sanandaj consists of different classes of paved roads in the city and unpaved roads in rural areas. Roads are classified as major highway, arterial streets, collector streets and residential roads and alleys. There are only a limited number of highways in Sanandaj which mostly consist of beltways around the city. In the following map highways, arterial roads, collectors and residential roads of Sanandaj are displayed. An arterial road is a high-capacity street and its main function is to deliver traffic from collector roads to freeways or expressways, and major between urban areas. Collector road or distributor road is a low-to-moderate-capacity road that moves traffic from local streets to arterial roads. The road network has hierarchical structure with residential roads serving as the lowest level of the hierarchy that connects most of population centers to main roads.

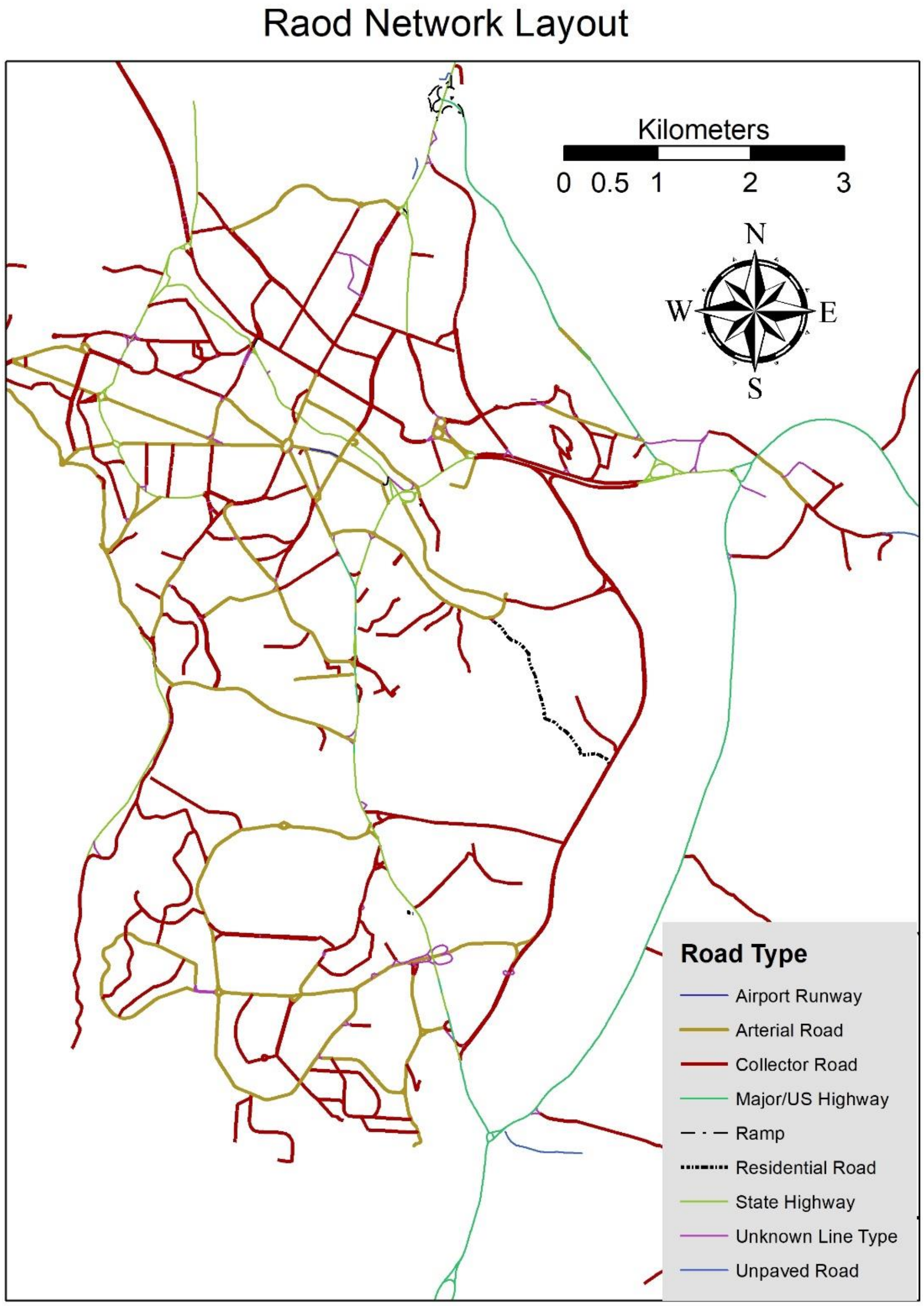


Figure 4: Road map of Sanandaj

Several attributes of census blocks of the city have been collected and classified in excel files by urban planning and housing ministry of IRAN. Also, each excel file includes information such as labor force, migration, household structure and size, population, education. Maps displaying the kernel density of the population are generated and used as a base to find important locations for peripheral terminal.

We can consider high population census blocks in our research as the points which generate trips toward CBD or popular destinations outside of the downtown core. Following map presents several popular destinations that usually people in Sanandaj go to visit, work or shop during the day. They include hospitals, parks, movies theaters, Bazaar, government offices, retail market, industrial sites and other popular locations in the city. Also, next figure displays Kernel population density of Sanandaj. Based on the maps provided, high population densities are mostly located around CBD, specially the old districts of the city. Also, Baharan town in southern suburb of Sanandaj contains several districts with high population that could be considered in designing the bus network scenarios. Baharan town covers a large part of Sanandaj and a significant number of people commute from there to downtown during morning and afternoon peak hours of traffic. Residents of Baharan and other peripheral districts go to CBD for different purposes such as shopping, cinema, café, social events.

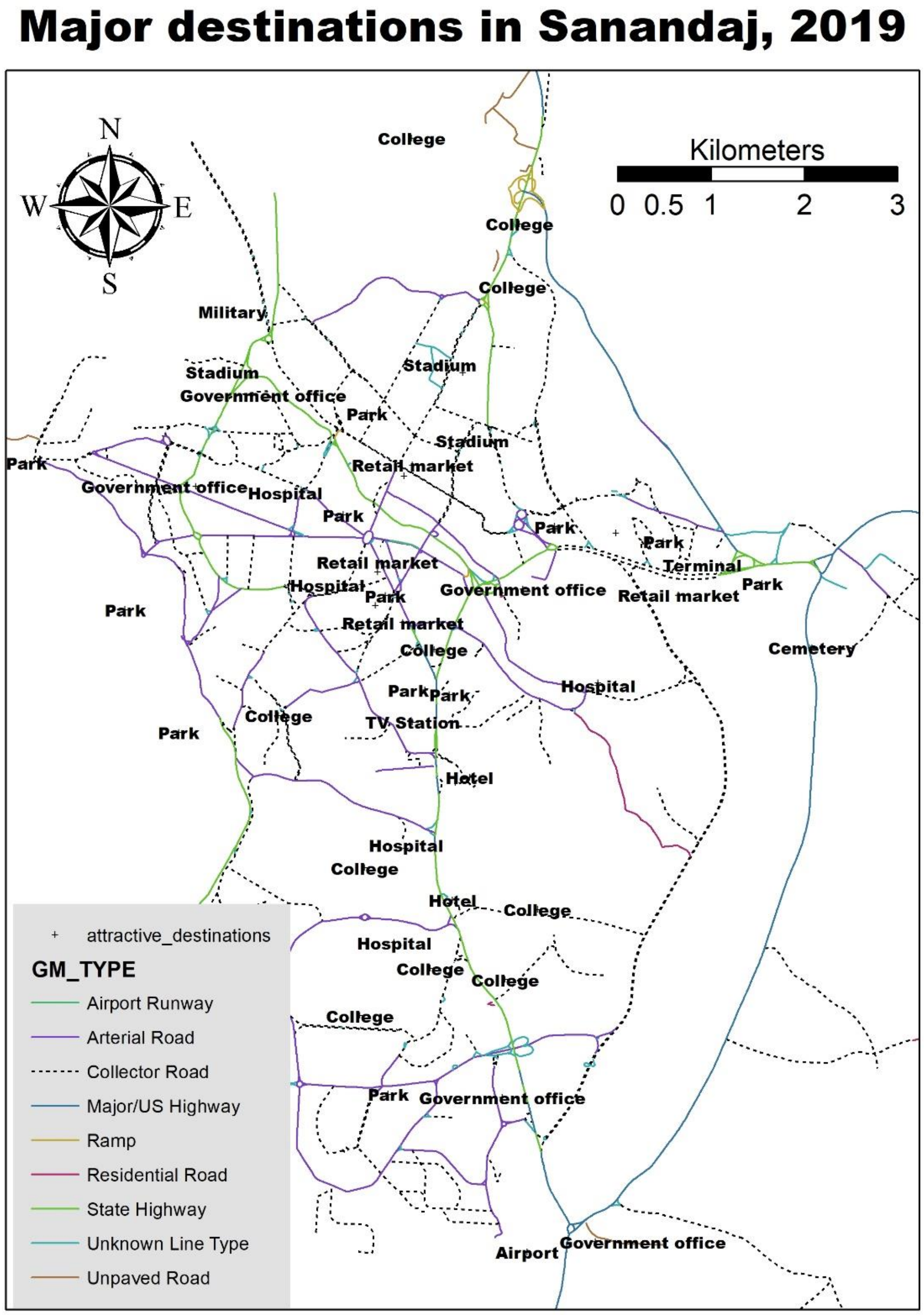


Figure 5: location of major destinations in Sanandaj

3-2 Built environment characteristics of downtown core

Sanandaj has a highly populated downtown core. Also, several peripheral cores are existing around which has been developed in last 20 years. Many attractive destinations such Bazaar, groceries shops, shopping centers, movie theaters and restaurants are around the central business district (CBD). CBD is a part of old downtown core that the city started expanding from during 20th century. Enghelab and Azadi squares that have been connected by Ferdowsi Street, with less than one-kilometer length, and the area surrounding these squares are considered the CBD. Old Bazaar is connected to Enghelab square which is one of the busiest locations in Sanandaj during the day.

Following map displays the downtown core that includes CBD. As mentioned, this area consists of several squares and streets and has a high density of commercial land-use and several retail markets. In the official plan of Sanandaj, several attributes of the downtown core area including commercial area, total population, and population of students and work force is described. Also, an estimation of the future values for these attributes in 2030 is provided. In the next table, the attribute values are provided. Based on the official plan, administration is planning to reduce the density and area allocated to commercial use in downtown core. It is due to their decision to reduce the traffic burden in CBD and promote peripheral cores and towns such as Baharan, Hasan-Abad.

Sanandaj current transit plan is a part of the ‘official’ plan provided by the city administration. Official plan includes the comprehensive plan, the general plan and the tourist plan (Kurdistan, 2011). Main goal of the transit plan is to reduce the congestion in the city core of Sanandaj. In the current local government reports of the public transit development in Sanandaj, changing the usage of specialized taxi routes to bus routes is proposed (Kurdistan, 2011). Several new bus routes and taxi routes have been proposed to increase the accessibility to downtown core of the city. Bus routes are designed in north-south (three lines) and east-west (five routes) directions and along one of the major streets (two routes) (Kurdistan, 2011). There is no transit network in the city. It is only bus lines that serve the main towns or districts with high population and they are not connected by any beltways.

3-3 Traffic congestion and public transit planning in Sanandaj

Traffic can be attributed to the process of migration from smaller population centers, insufficient transportation infrastructure development, the compact structure of road/street network (Kain & Fauth, 1976; Kurdistan, 2011), and the structure of trips by transportation mode (a very low share of bus system of trips and very high share of private car trips) (Kurdistan, 2011) (see next figure). Transportation policies such as construction of fast and competitive public transit system can facilitate movement and reduce congestion in cities with radial pattern similar to Sanandaj (Badia, Estrada, & Robusté, 2014).

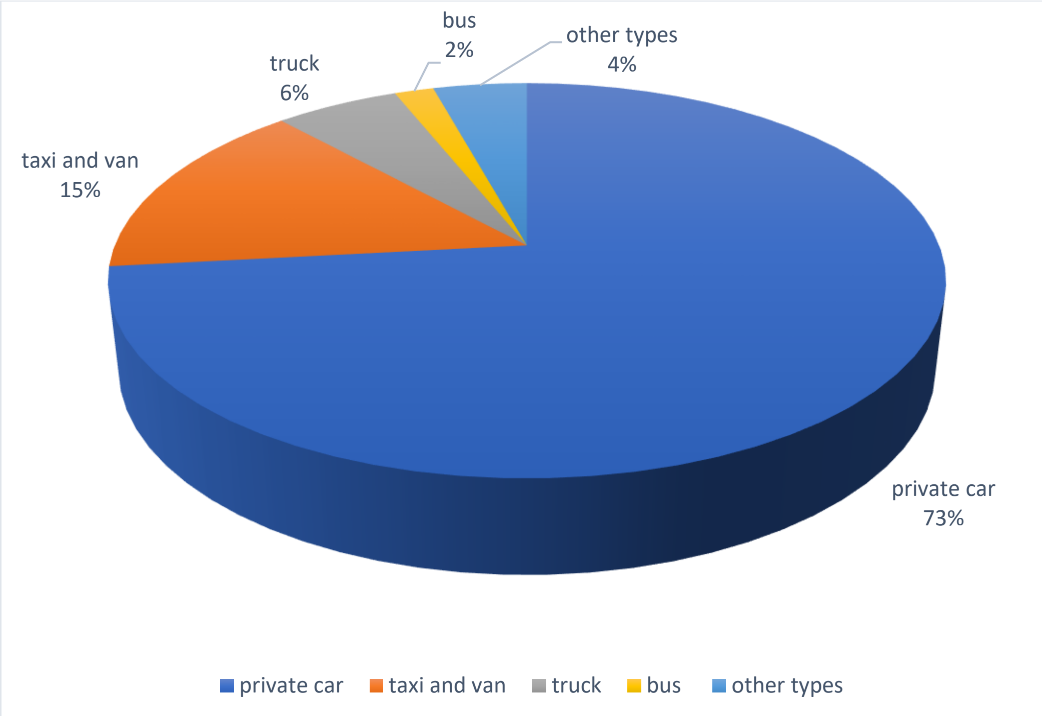


Figure 6: Percentage Share of Transportation Modes in Sanandaj (Kurdistan, 2011)

The total number of buses operating in the city is 98 and the number of passengers they transfer is 23400 (Kurdistan, 2011). Also, a survey in comprehensive traffic plan displays that the number of people arrived at the main bus terminal of Sanandaj (Naser-Khosrow terminal) is the highest during 9 to 11 AM and 5 to 7 PM. The total travel distance of the buses for one tour of the network in the current transit system in Sanandaj is 252 kilometers. The travel time on the routes are between 30 to 70 minutes per route. The total number of stops for the current transit system is 729 bus stops.

Based on the data provided by local administration, a large portion of trip to destinations in downtown area in peak hours of morning is commuting to workplaces in CBD. Also, in peak hour of afternoon most of the trips to downtown is to leisure and shopping destinations such as shopping malls or Bazaar, retail markets and the movie theaters on Ferdowsi street. Following map is the google traffic map of Sanandaj for different hours of a weekday which the traffic is higher than weekend in the city.

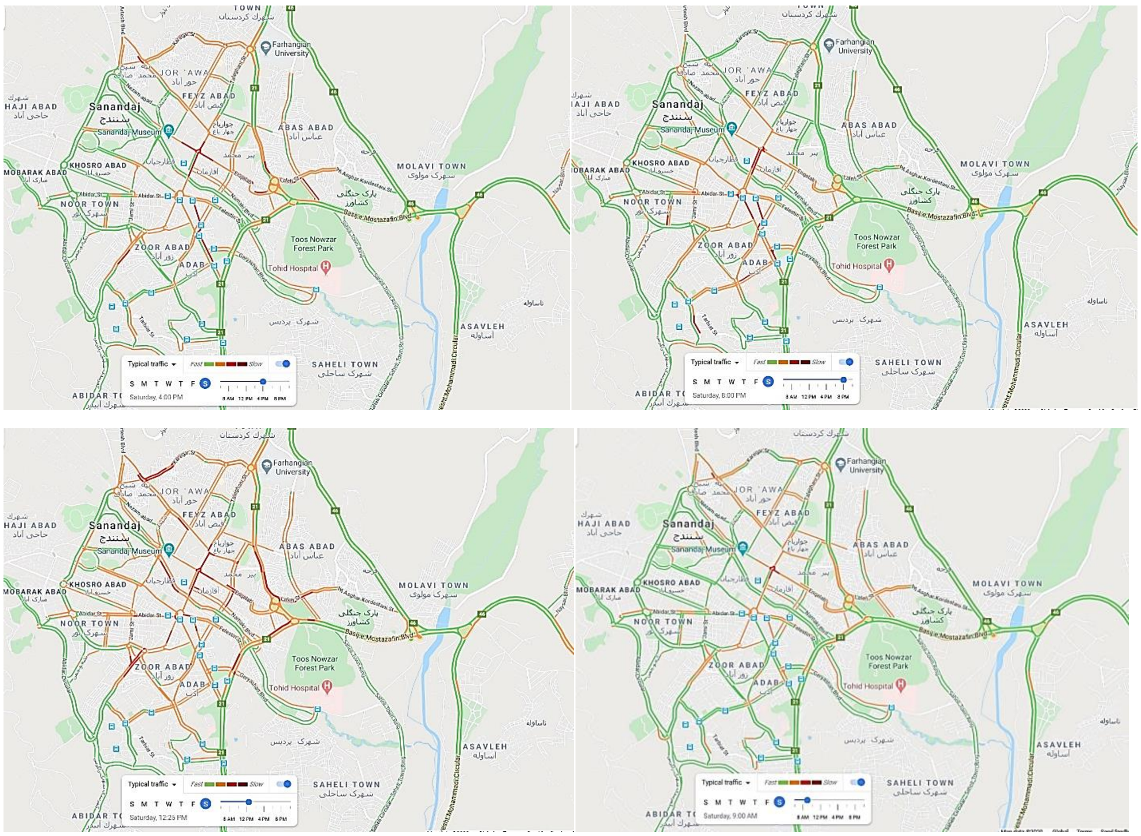


Figure 7: *Traffic congestion google maps of Sanandaj based on 8 AM, 12 PM, 4 PM and 8 PM traffic of weekdays.*

Based on the O-D matrix collected by the city administration, peak hours of traffic are at 7AM, 12 PM, and 17 PM (Kurdistan, 2011). Reducing the traffic in the peak hours is one of the main tasks of the public transit system in Sanandaj, but only two percent of the trips are currently done by using public transit system in Sanandaj (Kurdistan, 2011).

Chapter 4

Methodology

4-1 Multi-Objective Decision Analysis

Multi-criteria decision analysis (MCDA) is a set of methods and procedures for tackling decision problems involving a set of decision alternatives and multiple, conflicting and incommensurable evaluation criteria (Roy, 1996; Yoon & Hwang, 1995). One can distinguish two types of MCDA methods: multi-attribute decision analysis (MADA) and multi-objective decision analysis (MODA) (Goicoechea, Hansen, & Duckstein, 1982; Yoon & Hwang, 1995). Table 1 shows the main characteristics of these two groups of approaches. Multi-attribute decision problems involve a predetermined, limited number of alternatives. In multi-attribute problems, the alternatives are given explicitly rather than defined implicitly as in the case of multi-objective decision. Solving this type of decision problem is an outcome-oriented evaluation and choice process. The MODA approach is a process-oriented design and search. Unlike MADA procedures, MODA makes a distinction between the concept of decision variables and decision criteria. These two elements are related to one another by a set of objective functions. Although the multi-attribute and multi-objective decision methods are sometimes referred to as discrete and continuous decision problems, respectively, it is important to indicate that the multi-objective decision problems can be defined in terms of a set of continuous and/or discrete decision variables and be solved using methods of mathematical programming (Ceder, 2016; Guihaire & Hao, 2008) and heuristic/metaheuristic algorithms (Ceder, 2016; Fusco, Gori, & Petrelli, 2002; Talbi, 2009). This study focuses on MODA, which is also referred to as multi-objective optimization approach.

4-1-1 Multi-Objective Optimization Problem

Optimization is a normative approach for identifying the best solution for a given decision/management problem (Thomas & Haggett, 1980). The solution determines the values of decision variables subject to a set of constraints. If a decision/management problem involves a single objective function, then the problem is represented by a single criterion or objective optimization model. When two or more objective functions are to be optimized simultaneously, then the decision situation is described by a multi-objective optimization model (Cohon, 1978; Mora et al., 2013). Formally, multi-objective optimization problem can be defined as follows:

$$Minimize \text{ or } Maximize\ F(x) = \{f_1(x), f_2\ (x), \ldots\ldots\ , f_n\ (x)\}, \quad (1)$$

$$\text{subject to: } \boldsymbol{x} \in \boldsymbol{X}, \quad (2)$$

Where $F(\boldsymbol{x})$ is the objective function with n-dimensions; $f_k(\boldsymbol{x})$ is an objective function $(k = 1,2, \ldots\ldots, n)$; $\boldsymbol{X}$ is the set of feasible decision alternatives, which is typically defined by constraints imposed on the values of decision variables (alternatives that satisfy all constraints are referred to as feasible or acceptable alternatives); and $x_i \geq 0$ is a vector of decision variables $(i = 1,2, \ldots\ldots, m)$. In modelling spatial systems, there is at least one set of spatially explicit decision variables. The variables can be used in many ways to define spatial decision alternatives. For example, the concept of location-allocation is often employed for defining a set of spatial alternatives in transportation planning (Cohon, 1978; Diaz Gonzalez, 2016). Specifically, any locational alternative can be defined as a binary vector, $\boldsymbol{x} = (x_1, x_2, \ldots, x_m)$, where a decision variable, x_j, is defined as follows: $x_j = 1$, if an activity (e.g., bus stop) is located at the *i*-th site; and $x_j = 0$, otherwise. Also, a vector of allocation variables associated with the *j*-th location can be defined in terms of a binary variable as follows: $x_{ij} = 1$, if a population of demand nodes at the *i*-th location is 'allocated' to the *j*-th bus stop; and $x_{ij} = 0$, otherwise.

Given that the multi-objective optimization models (1)-(2) include conflicting and often non-commensurate criteria, the multi-objective problem involves finding a set of Pareto optimal solutions (which is also known as a set of efficient, non-dominated, and non-inferior solutions). A vector of decision variables $\boldsymbol{x}^*$ is said to be Pareto optimal if there exist no other feasible vector $\boldsymbol{x}$ such that $f_k(\boldsymbol{x}) \geq f_k(\boldsymbol{x}^*)$ for all $k = 1, 2, \ldots, n$ and $f_k(\boldsymbol{x}) > f_k(\boldsymbol{x}^*)$ for at least one k. This implies that $\boldsymbol{x}^*$ is Pareto optimal if there is no feasible vector that would improve some objective without causing a simultaneous deterioration of at least one other objective (Cohon, 1978; Malczewski & Rinner, 2015). The non-dominated set in the objective space is referred to as the Pareto front. In the absence of any preference regarding the objectives, all non-dominated solutions are assumed equivalent or indifferent. However, the multi-objective decision problems often require that a single non-dominated alternative is selected from the set of Pareto optimal solutions. This type of problems has traditionally been handled by combining the objectives into a scalar function and then solving the equivalent single-optimization problem to identify a best-compromise alternative (or a set of non-dominated alternatives). Once the multi-objective problem is specified in terms of single-objective model, it can be solved using conventional mathematical programming methods, and heuristic/metaheuristic algorithms (Cohon, 1978; Goicoechea et al., 1982; Huang & Lin, 2010; Malczewski & Rinner, 2015).

4-1-2 Decision makers and decision-making agents

Public transit planning research is conducted with the aid of decision makers (DM) who are individuals or entities with the responsibility of making decisions (Massam, 1993). DMs can be individuals, a group of experts, community, private or government organizations (Yoon & Hwang, 1995). In GIS, decisions involve several entities and stakeholders, and public participation in making decisions have started from 1970s and 1980s (Voinov et al., 2016). For simple problems, GIS functions such as overlay can solve the problem, but when stakeholders have different preferences GIS lacks the tools to solve the problem. Therefore, multi-criteria or multi-objective methods are needed to help GIS solve the conflict of interest between different stakeholders. Massam (1993) defines three types of them: experts who suggest a decision, stakeholders who will be affected by the result of the decision, and those who solve the conflict of interest between experts and stakeholders. These three types of interest group may be involved in assessing decision alternatives (e.g., alternative transits network designs) with respect to a set of evaluation criteria/objectives.

While the conventional decision analysis focuses on the human decision maker, recent approaches to computer-based modeling provide a broader description of decision maker to include the concept of decision making agent (Parker, Manson, Janssen, Hoffmann, & Deadman, 2003; Raja Sengupta & Bennett, 2003). An agent is a computer program characterized by such properties as: autonomy (i.e., the capability of taking independent action such as taking a certain path in the road network), reactivity (i.e., the capability of sensing and reacting to its environment and other agents, such an ant using solutions found by other ants) (Sengupta and Bennett, 2003). These characteristics make it possible to represent decision makers as agents acting in a simulated real-world environment (road or bus network). Intelligent agents designed specifically for using geographic data and tackling spatial problems are referred to as geospatial agents. Raja Sengupta and Sieber (2007) identify two general uses of the geospatial agent concept in GIScience/Geo-computation. First, the term is used in the context of modeling an individual's action in a social world. Second, the agents are autonomous software designed for supporting interaction among software components to aid users. Both perspectives are relevant for GIS-based multi-objective modeling of transportation systems. Specifically, the concept of decision-making agent is typically used in the agent-based modelling (ABM) approaches including multi-objective optimization using swarm intelligence metaheuristics (Sengupta & Bennett, 2003).

4-2 Swarm Metaheuristics

Mauttone and Urquhart (2009b) define the TND problem as a hard problem that can be solved using different methods of approximating the solutions. They classify the methods as heuristic and metaheuristic methods. Heuristic methods are classic approximation methods with local or global search ability. Metaheuristic methods are modern approximation approaches that efficiently search the solution space. Flexible metaheuristic algorithms can display a good performance in solving the transit network design problem.

Swarm intelligence methods are based on swarming behavior of animals in nature (Yu & Yang, 2011). One characteristic of social behavior of animals such as fish, birds, ants and bees is their communication system and warning method (Teodorović, 2008). These methods evaluate the transit network scenarios based on multiple agents moving from a node to all other nodes in the network.

Swarm methods due to using multiple agents can calculate are superior compared to single agent algorithms and heuristic methods such as greedy algorithm Ant colony optimization, bee optimization method, and particle swarm optimization are the best known swarm intelligence methods (Zhan, Zhang, Li, & Chung, 2009). Network based swarm methods are multi-objective routing algorithms which have the ability to implement the desired transportation network design based on policies and objectives of planners and stakeholders (Farahani et al., 2013).

There has recently been a considerable increase in the number of swarm intelligence algorithms for tackling TND problem (Bell & McMullen, 2004; Mohaymany & Gholami, 2010; Nikolić & Teodorović, 2013b; Poole & Kotsialos, 2016; Yu & Yang, 2011). Different versions of swarm intelligence methods have been proposed in order to achieve high level of 'optimality' in generated solutions. The proposed methods have focused on creating computationally efficient algorithms by improving the abilities of searching for the 'best' solutions, increasing the interactions between agents (e.g., particles, ants, bees), reducing the probability of algorithms being trapped in the local optima.

Ant, bee and particle swarm intelligence methods have the ability of finding an optimum transit network design by using several agents which search different areas of the network and exchange information with each other about their path (Bell & McMullen, 2004; Mohaymany & Gholami, 2010; Teodorović, 2008; Yu & Yang, 2011). The probability of generating a well-designed network by using these algorithms is higher than heuristic methods because the population of agents will not be trapped in the local optimum or certain areas of the network. Because of their communication throughout the search, a collective behavior emerges (Dehuri, Jagadev, & Panda, 2015). Moreover, in ant, bee and particle methods preferences of stakeholders can be considered by applying a weight to each objective function value provided by these individuals or entities (Akbari, Hedayatzadeh, Ziarati, & Hassanizadeh, 2012; Diaz Gonzalez, 2016).

4-2-1 Ant Colony Optimization

Ant Colony Optimization (ACO) is a type of swarm intelligence with simple agents and lower level of complexity compared to ABM (Kazharov & Kureichik, 2010). ACO originally has been proposed in two main types: Ant System (AS) and Ant Colony System (ACS); however currently it has different variants developed based on these two approaches (Mora et al., 2013). ACO consists of a collection of ants searching for food in nature. Ants try to find the shortest route to the food source by following the path created by pheromones on the ground from previous ants.

Computational steps for ACO involves the followings (Dehuri et al., 2015): (i) Representing the optimization problem by means of a weighted graph (network) on which ants (agents) can build their solutions. (ii) Modeling pheromone trails. Pheromone is laid on ground by an ant to help other ants follow the previous ant’s path and find the shortest path on the ground. (iii) Selecting an ACO algorithm and implement it to solve the problem. (iv) Tuning ACO parameters. Ants in ACO are equipped with memory of former decisions and knowledge of important locations in their geographic area (Bell & McMullen, 2004; Kazharov & Kureichik, 2010; Mohaymany & Gholami, 2010).

Although one ant is unable to communicate and solve complex problems, but interaction with other ants will enable them to solve complex optimization problems. In nature, ants travel randomly on the surface of the earth until encountering pheromone from another ant which can follow and leave their pheromone behind to reinforce the path. More ants choose one path; probability of next ant taking the similar path is higher.

After a period of time, solutions with lower level of pheromone due to pheromone evaporation lose their attraction (Bell & McMullen, 2004). There are studies which propose improved versions of ant colony optimization to solve the traveling salesman problem by using a centralized system that receives solutions produced by each agent (i.e., ants) and evaluates them, and also other studies that use a distributed system in which every ant builds its solution separately without a centralized system to assess them (Aggarwal & Saroj, 2012; Joshi & Kaur, 2015; Mouhcine, Mansouri, & Mohamed, 2016).

ACO has been developed to solve single objective problems but recently multi-objective ant colony optimization methods have been proposed to solve problems with several conflicting objectives (Mora et al., 2013). For complex optimization problems, the distribution or parallelization of the methods reduces the time to generate solutions. ACO is a distributed method because ants are relatively independent. Combination of distributed computation and multi-objective ACO is a new topic of research in swarm intelligence.

Multi-objective ACO method is used to evaluate the transit networks proposed. Several ants starting from random locations find the tour with lowest objective functions values. Because, several objectives have been proposed in the TND model section, each ant has to find the optimal tour with lower objective values with regard to the proposed objective functions.

4-2-2 Honeybee Optimization

Karaboga (2005) proposed a swarm intelligence method based on the honeybee's search for food in nature and information exchange between bees for minimal forage selection that leads to a collective behavior of the swarm. The model consists of several components: food source, employed forager (i.e., recruiter bee) and unemployed forager (i.e., uncommitted bee), and the model that determines the two behavior modes.

Honeybee optimization methods are based on the concept of a population of agents searching to find the optimal solution . The methods aim at generating a solution set in a predetermined number of iterations and search for the best solution is terminated when certain criteria are satisfied (Nikolić & Teodorović, 2013b). Honeybees use two operations to find the best solution: forward pass and backward pass (Nikolić & Teodorović, 2013a; Yang et al., 2013).

In the first step of this method bees search the solution space with a predefined number of moves and construct or improve a partial path (i.e. forward pass); afterwards they go back to the hive (i.e., backward pass). In the second step, bees interact and exchange information to know each other's objective function values. With a probability, each bee either picks a new solution and discards its uncompleted solution to be an uncommitted follower of other bees, or dances to recruit others to follow its partial solution. Followers use the partial solution as a base to build their path from its end point (Nikolić & Teodorović, 2013a, 2013b). Two phases of forward pass and backward pass are performed several times to provide a complete solution and the algorithm continues to operate until a stopping condition such as predefined number of iterations, or iterations with no improvement in the value of objective function is satisfied.

4-3 TND Model

Modelling TND problem involves a process of searching for efficient transit routes based on the preferences of transportation firms and users (Bagloee & Ceder, 2011; Ceder, 2016; Ceder & Israeli, 1998; Fusco et al., 2002; Petrelli, 2004). In the multi-objective network design, one would define several objectives in order to operationalize the operator's and user's preferences. A weight is assigned to each objective that represents the importance of the objective for the decision maker. Each decision maker, based on his/her preference, assigns different values to objectives' weights. After weights have been determined, a distinct solution is generated. Solutions generated in this way by experts and stakeholders create a set of non-dominated or Pareto optimal solutions that construct a Pareto frontier in the solution space (see section 3.1). This study focuses on following objectives:

1- Number of stops in the transit network
2- Walking distance to the transit stop
3- Travel distance of passengers in the transit system.

First objective is based on the operator's perspective to minimize the number of stops in the transit network. The objective objective's formulation is as follows:

$$f_2(N_{rn}) \ = \sum_{r=1}^{k} \sum_{n=1}^{m} N_{rn} \qquad (5)$$

where N_{rn} is a decision variable, and N_{rn} = 1 if a stop *n* is located on the *r*-th route, otherwise N_{rn} = 0. n is the stop number and k are the route number. The objective function is subject to some constraints. In order to limit the minimum and maximum number of stops, a distance constraint between two stops should be considered. The minimum and maximum distances between two stops is set to 300 and 600 meters, respectively; these are based on the observed pattern of stops of radial transit networks (Badia et al., 2014). Also, the number of stops on each bus route should be greater than zero. The objective function takes the following form:

$$f_2(WD_{rn}) = \sum_{r=1}^{k} \sum_{n=1}^{m} WD_{rn} \qquad (6)$$

Where WD_{rn} is a decision variable of walking distance to the stop *n* on the *r*-th route, $0 \leq WD_{rn} \leq 300$ meters. In order to minimize the total travel distance or time of passengers in the transit system (i.e., the total cost for user) another objective is proposed. The objective is to minimize the difference of travel time between two stops and the shortest path time. The objective function is expressed as follows:

$$f_3(t_{rnl}) = \sum_{r=1}^{k} \sum_{n=1}^{m} \sum_{l=1}^{o} d_{rnl}(td_{rnl} - spd_{rnl}) \qquad (7)$$

Where t_{rnl} is the difference between tt_{rnl} (travel time between stops *l* and *n* on the *r*-th route that includes waiting time, in-vehicle time and transfer time) and spt_{rnl} (the shortest path between stops *l* and *n* on the *r* –th route) (Ceder, 2016). The travel time can be the shortest path time, but in most of the transit networks it is longer than shortest path time in order to provide better coverage for remote areas in the city. d_{rnl} is the travel demand between stops *l* and *n* on the *r*-th route; travel demand is constant in this study. Because the real-time data of traffic is not available, the demand is considered based on the population of the census blocks in origin.

Table 2: variables used in the decision-making procedure

Variable	Definition	Unit or Value	Features used	Analysis
$\boldsymbol{N_{rn}}$	Number of Stops of the transit network	1 If node ***n*** on the route ***r*** is used as stop and 0 otherwise	Stop locations, Census blocks	Locate stops using census data
$\boldsymbol{WD_{rn}}$	Walking distance from a block to the stop	meters	Census blocks, stop locations	Select blocks with select by location tool
$\boldsymbol{td_{rnl}}$	Travel distance between stops ***L*** and ***n*** on the route ***r***	meters	Segmented centerline, stops	Calculateting the distance
$\boldsymbol{spt_{rnl}}$	Shortest path between stops ***L*** and ***n*** on the route ***r***	meters	Segmented centerline, stops	Calculate distance on each segment using network dataset.
$\boldsymbol{d_{rnl}}$	Travel demand between stops ***n*** and ***L*** on route ***r***	Number of passengers	O-D matrix	Create the O-D matrix layer in ArcGIS using network analyst

4-4 TND Procedure

The TND is a multi-objective optimization procedure based on the TND model proposed in previous section. The model consists of the objective functions to be minimized subject to a set of constraints. The swarm intelligence algorithms (ant colony optimization, and honeybee optimization) are implemented for evaluation of the set of solutions. In the first step georeferenced map of census blocks with attributes such as population of the blocks is created, from excel data files of census. In the next step of the design, the location for major terminals are determined based on population centers and attractive destinations in Sanandaj. Later the major terminals in the peripheries of the city are connected to downtown terminal to generate the base network. Afterwards, several peripheral terminals are connected using beltway bus lines. The number of beltway lines is different for each TND scenario proposed. In other steps of the design, designed transit network alternatives are examined using GIS, ant colony and honeybee methods to based on the objectives proposed in the TND model. The TND scenarios are ranked based on the scores they achieve for each objective. The sum of these scores for each TND determines the ranking of each scenario based on the GIS, ant colony and honeybee evaluations. Also, existing network is compared with the TNDs proposed and ranked based on the score achieves for coverage, travel distance and number of stops.

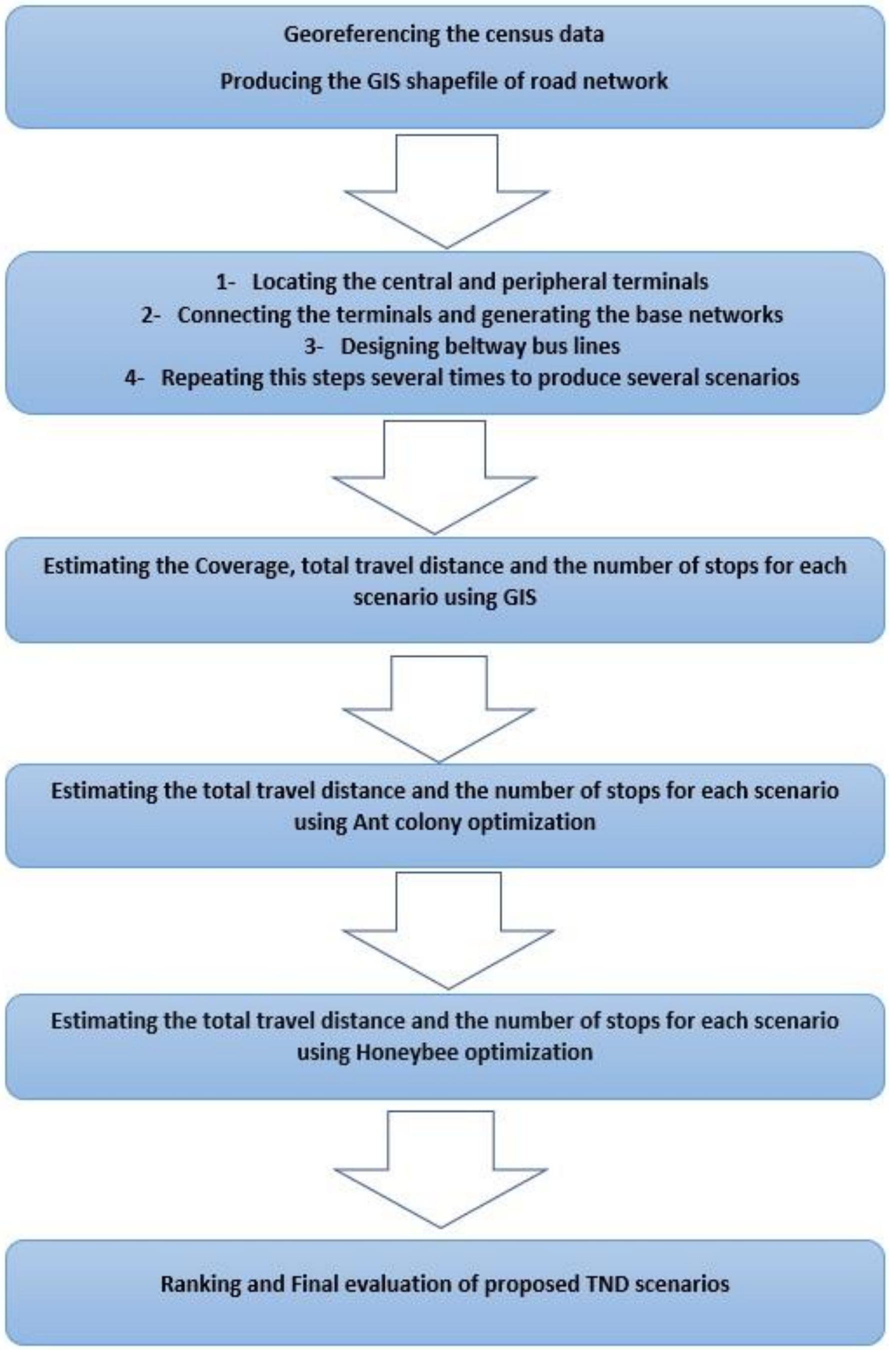


Figure 8: Bus network design procedure

4-4-1 Determining central and peripheral terminals

In the first step of the TND procedure, attractive destinations are determined based on their potential for generating trips from peripheries. For the case of Sanandaj, attractive locations for travelers is generally in downtown core and districts around that area. The location of these destinations will serve as potential central terminals. Central terminals are the hub nodes in the transit network. Moreover, peripheral terminals are selected based on the location of population centers that generate a significant number of trips toward the downtown. Districts and towns with high density of population in peripheries are potential locations of the peripheral terminals.

As mentioned, central terminals will be located around the old districts in the downtown core because they are the location of main businesses and bazaar. Also, retail stores, movies theaters, shopping centers and religious and historic sites are located near that area. Downtown core and districts nearby have become the main destination for the trips during the day which has resulted in a radial pattern of travel in the city.

Peripheral terminals can be located in peripheral towns such as Baharan, Hasan Abad, Naysar, Abidar, 5th Azar, Besat, Faiz Abad, Ostandari or Padegan, Takiya-va-Chaman, Abas Abad, Nabovat square, Haji Abad, Shebli, 25th Farvardin, or Shohada. They generate significant traffic toward the Central business district (CBD) during the day, especially in morning and evening.

4-4-2 Generating base transit networks

By connecting peripheral terminals to the central terminals, the base network design will be constructed. The base network designs in this study have a radial pattern. They directly connect the highly populated peripheral districts to the limited number of central terminals. The base network for each scenario can be different, considering the peripheral areas included in the initial design of the routes for each TND.

After the selection of peripheral terminal locations in each TND scenario, in order to design the base network each peripheral terminal is connected to a central station around CBD by a bus route. The main purpose of the base network design is to satisfy travel demand between major origins and destinations (Cipriani, Fusco, Patella, Petrelli, & Quadrifoglio, 2019; Cipriani et al., 2012).

4-4-3 Designing beltways to connect peripheral terminals

In order to finalize the TND, peripheral stations should be connected to each other. This step is performed by designing beltway routes between peripheral stations. With the help of beltways transferring from one radial route to another is possible with minimum number of transfers (preferably one transfer). Beltway routes designed in each scenario directly connect peripheral terminals and link the population centers together. The peripheral beltway lines will help to travel in the outskirts of the city without going through the traffic around CBD. Also, there is no need to transfer between radial routes when moving from one town or district to another. The traveler must take the bus on the beltway to move between the peripheral towns.

4-4-4 Evaluating Transit Network

The solutions generated using GIS will be examined focusing on exploring the sets of solutions based on the values of objective functions. The GIS-based procedure is developed to facilitate visualization and analysis of TND solutions. The aim of the evaluation is to explore and compare the results generated to find more suitable transit network designs for the City of Sanandaj. A series of hypotheses will be tested here to answer the following research questions: (i) Are there significant differences between the swarm intelligence assessment outcomes? (ii) Are there significant differences between the proposed transit network scenarios?

Chapter 5

Results and Discussion

In this chapter, the data used to design the transit network include the road network shapefile produced in GIS, georeferenced census blocks and the census attribute data, attractive destinations, location of peripheral towns. Using the available data, several TNDs are generated in order to be further investigated. Each TND is evaluated based on the objectives proposed such as minimizing walking distance, travel distance and the number of stops. Also, the TND scenarios are assessed in ArcGIS to find out how much of the city population have access to the bus service for each TND, based on different walking distances. There is a trade-off between minimizing costs and increasing the access to the transit service. Minimizing operational cost can decrease the accessibility, while, increasing the access to transit system is costly, due to the need for bigger fleet and number of routes.

Reducing walking distance requires longer routes and more transit stops around highly populated census blocks. This will increase the network length and number of stops due to the need to cover every major origins and destinations in the city. Reducing the travel distance and number of stops in a transit network generates a low-density network that reduces the coverage of the transit system. Therefore, there should be a balance between the access to the transit system and network size to satisfy the objectives proposed in this research.

5-1 Proposed transit network designs (TNDs)

The existing transit system in Sanandaj is a radial design. There is no map of the existing transit system. The current transit system is connected only in the downtown area. In the GIS procedure, several TNDs are constructed. The first network design is similar to the existing transit system in Sanandaj. It has a radial design without any beltway routes. The existing transit system is not a connected network outside of downtown and it does not have any beltways.

The proposed TNDs have been displayed in the following figures of this section. The TNDs proposed, except for the first network, include beltways to increase the coverage of system. On one hand, travelers prefer to take a bus on the beltway to go to a radial route than direct access by walking to the radial line (Saidi, Wirasinghe, & Kattan, 2016). On the other hand, increasing the number of radial routes generates higher attractiveness of CBD and reduces the importance of the beltway routes. In case of Sanandaj, most people travel to CBD and beltway bus lines act as feeder lines between the radial routes. There are several ways to access any destination in the city from a peripheral location (Saidi et al., 2016) that includes: traveling directly from the periphery to the final location without using bus system, traveling using only radial lines, traveling using beltway (ring) routes and radial routes can be used as well.

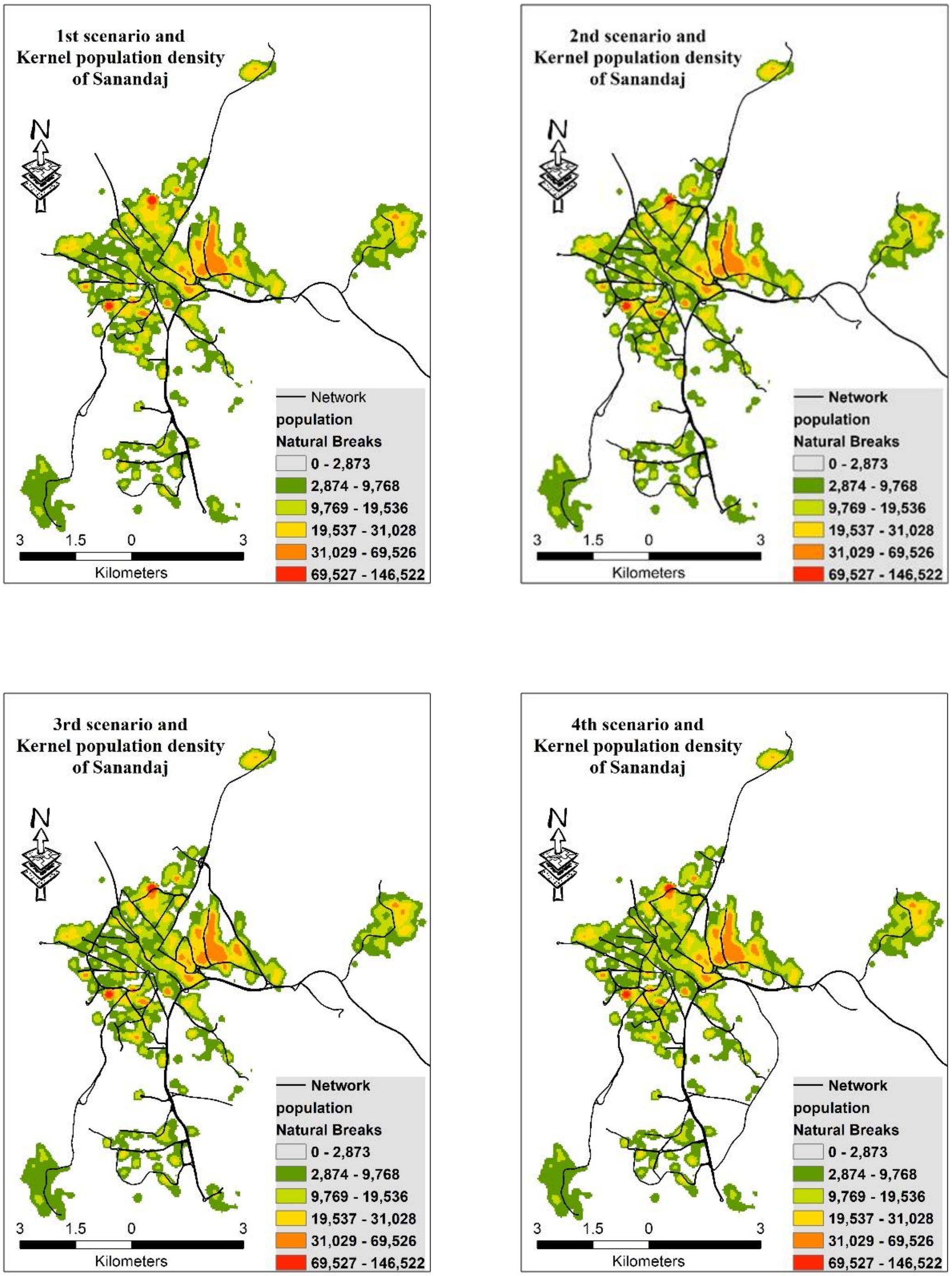


Figure 9: Maps of a set of TNDs proposed and kernel population density of Sanandaj

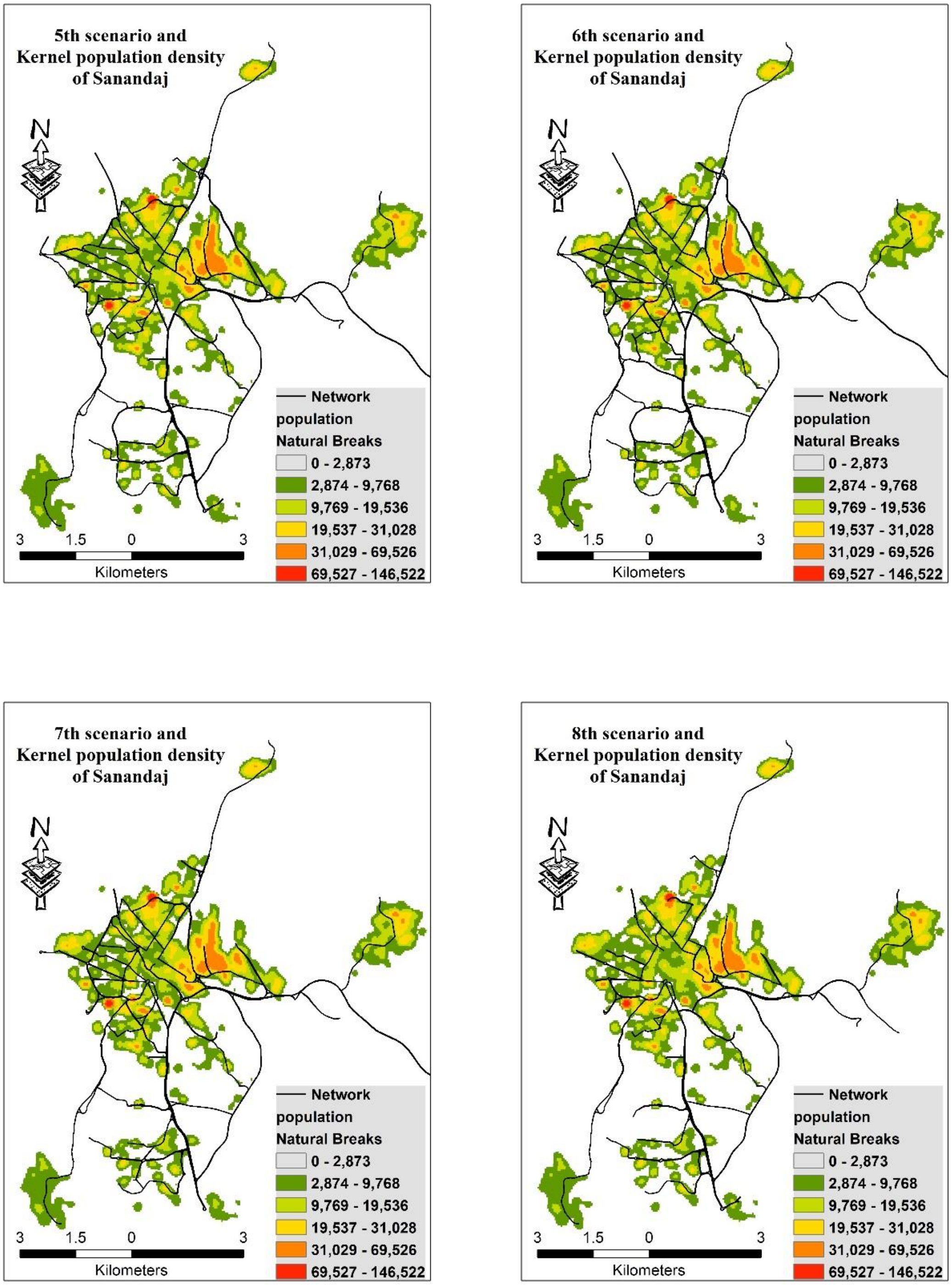
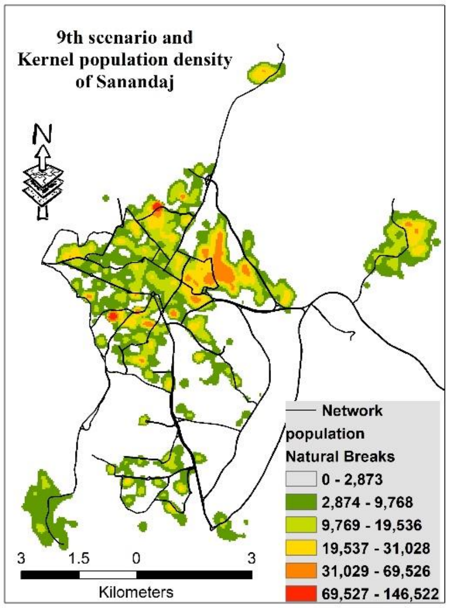
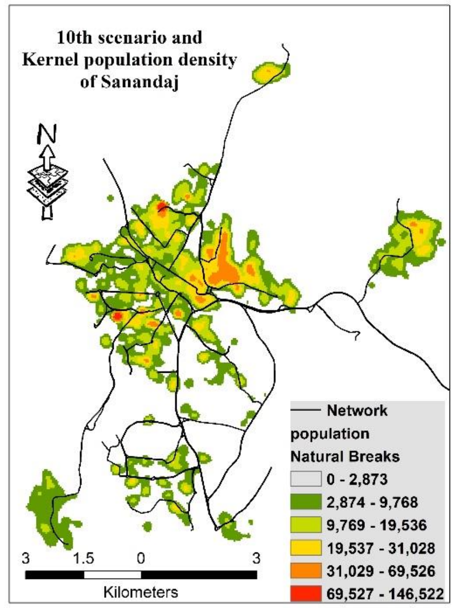


Figure 10: Maps of a set of proposed TNDs and Kernel Population Density of Sanandaj





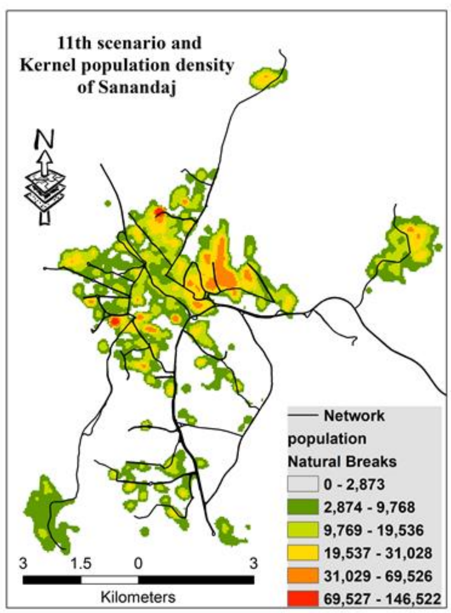


Figure 11: Maps of a set of proposed TNDs and Kernel population density of Sanandaj

The 1st scenario: The reason for the selection of radial routes without considering a beltway for th first network design is due to high attractiveness of CBD. This design is similar to the current system in Sanandaj. Although, the radial routes in the first scenario do not cover some highly populated areas of Sanandaj, they provide coverage for most of important destinations and towns. The lack of beltways affects the accessibility of network due to longer walking distances to and from routes. Therefore, in the next scenarios, ring lines around CBD or peripheries of the city will be proposed in order to provide a better access to the bus service for the populated peripheral districts and around the city core.

The 2nd scenario: The second bus network proposed provides a cartwheel design that includes beltway lines around downtown area. The ring lines can transport passengers in the peripheral districts. They also connect the radial lines in order to provide the transfer options between the lines. The beltway line around the downtown area provides a better coverages of destinations. This design has not included any external ring line in the peripheral towns which generates a lower network size (an objective of TND model), but it also provides lower service in some industrial and residential sites out of the downtown area, compared to several other designs. Also, compared to the first network design, this scenario offers comparatively better service for the residential blocks in the city.

The 3rd scenario: Third network design is also a cartwheel design that introduces beltway lines for the bus system on the east side of the city. The bus on the beltway route moves through the eastern areas and it is connected to the radial lines that transfer passengers to from downtown to the peripheral districts. People currently use this beltways to drive to their destinations using private vehicles while they avoid the traffic of the downtown core.

The 4th scenario: This bus network includes internal beltway lines near CBD that connects radial lines. Passengers can take the bus on these bus lines to move around the CBD area without going through downtown core.

The 5th scenario: It offers several external beltway lines that link the peripheries and towns in outskirts of Sanandaj. Passengers can use the beltways to travel in the peripheral districts and take a transfer bus to downtown from another district.

The 6th scenario: This TND includes higher number beltways, compared to previous TNDs. This will generate more connectivity and better transfer options between radial routes. Also, this network design provides more routes for passenger to take the bus on ring lines in order to avoid the traffic congestion in the peak hours of the day.

The 7th scenario: This network includes two parallel beltways moving through the western districts of the city. The beltway routes are designed around the CBD area. These beltways connect several radial bus lines. There are two points of transfer for each radial lines passing through the western areas of Sanandaj. The connections, which are the transfer locations, are mostly located in busy locations in Sanandaj.

The 8th scenario: The base network generated for this design is a star network. In order to increase the coverage, beltway lines are added to the design. In this type of design, no bus route passes through CBD. The radial bus lines start from the ring line outside of CBD. This design connects the radial lines and avoids the traffic of the downtown area and reduces the number of buses in the CBD to zero. It will help in reduction of traffic congestion.

The 9th bus network: It consists of several radial routes which they have been linked by beltways. In this design several bus lines have been removed, compared to the previous TNDs to reduce the density of bus lines in CBD and areas near downtown and the traffic congestion that can be caused by the buses. It also provides relatively good access to the bus system in peripheral areas.

The 10th scenario has a main radial line from downtown to the remote areas in the northern periphery of Sanandaj and it is connected to an internal beltway line. Also, parallel lines moving from east to west through busy locations of the city in the TND helps to transport more passenger from on side of the city to the other. Many TNDs in this research provide beltway lines to avoid the busy areas while 10th TND offers parallel lines in these areas.

The 11th scenario: This TND is proposed based on having a lower number of bus lines in the peripheral areas. In the 11th scenario, only an external beltway has been proposed in order to achieve a lower cost of operation. The radial bus lines start outside of the CBD area to avoid the traffic congestion. The only line included in the downtown is on a highway that passes through downtown core.

5-2 Coverage analysis of proposed TNDs

The coverage of proposed TNDs can be measured based on the walking distance to the stops. Using tools in GIS, the coverage in different neighborhoods of the city and peripheral towns have been analyzed. The coverage analysis is a two-step approach. In the first step two buffers around the scenario centerlines are generated, for 100 meters and 300 meters walking distances. In the second step, the blocks centroids within the buffers generated are selected as the population within the walking distances.

Different minimum and maximum walking distance constraints have been proposed in the literature. The examples are maximum distance between 300 and 400 meters by Alterkawi (2006) and standard distance of 400 meters by Demetsky and Lin (1982). Farwell and Marx (1996) suggest that walking distance more than 400 meter is very inconvenient for transit users. Therefore, in this study the range of possible values for the walking distance to the stops is limited to less than 300 meters, due to compact urban structure of the study area because Sanandaj is a city with high population density.

The coverage of population for proposed TND scenarios for the walking distance of 100 meters is displayed in the following figure. First scenario has been used as the base scenario for comparison with other TNDs. First TND is radial network that generates lowest coverage for the transit system compared to others. Also, the 6th scenario provides the highest coverage of population of census blocks for the short walking distance. Approximately, half of the population of Sanandaj is in short walking distance of 5th and 6th TNDs, while 6th scenario performance is slightly better than 5th scenario. The difference between the coverage of 6th and 5th scenarios with other TNDs is significant, considering the population of Sanandaj.

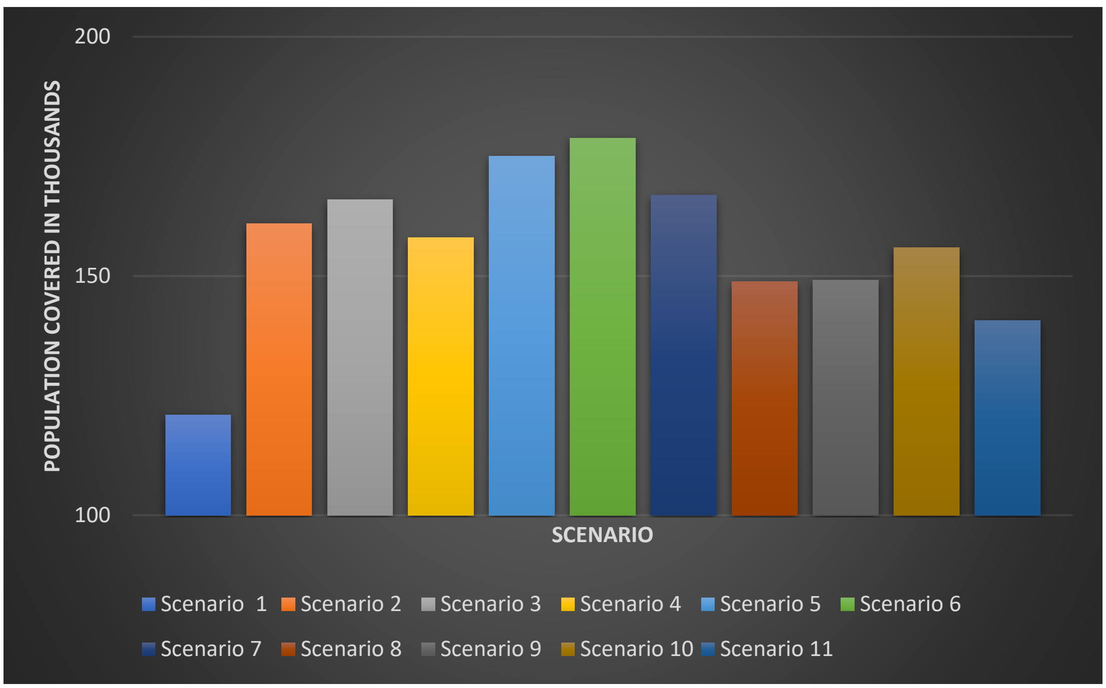


Figure 12: Coverage of TNDs for 100 meters walking distance to the network

The following figure is displaying the evaluation of TNDs for longer walking distance of 300 meters to the bus network. The results are Similar to the previous figure for the short walking distance. The performance of the 6th and 5th scenarios are better than the rest of the TNDs. The first scenario's coverage, as a radial network, is lower than other TNDs.

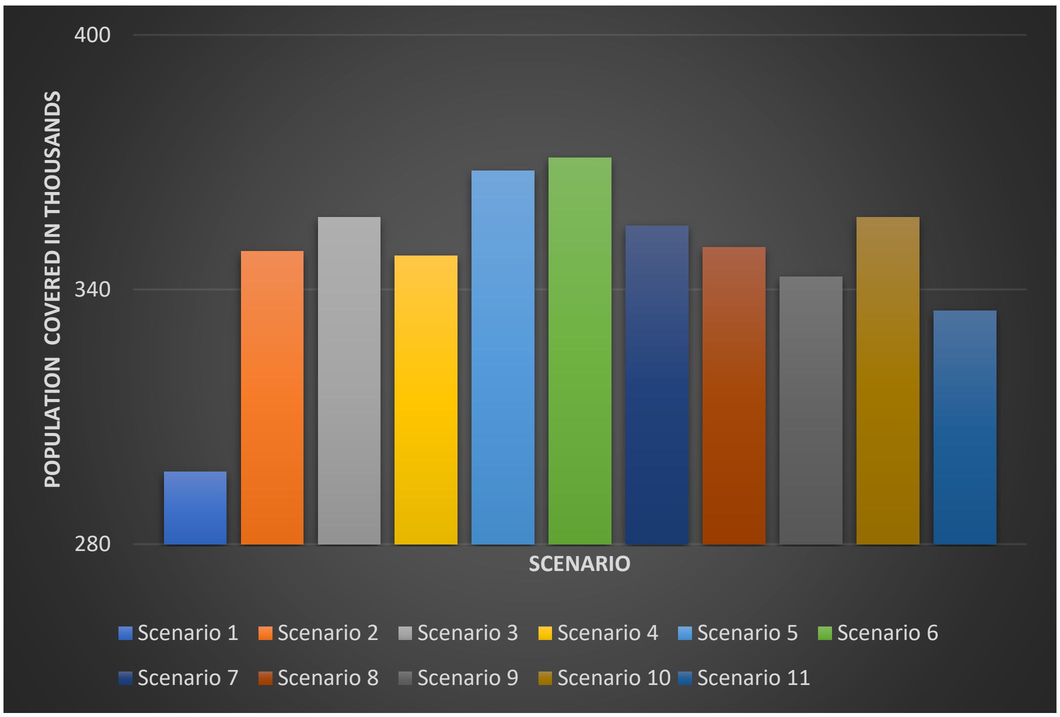


Figure 13: Coverage of TNDs for 300 meters walking distance to the network

Moreover, the next figure illustrates an estimate of the number of important locations such as the Bazaar, movie theaters, shopping malls, government buildings, universities, colleges and other attractive locations in Sanandaj that can be reached within walking distance of 300 meters of the bus lines for the proposed TNDs.

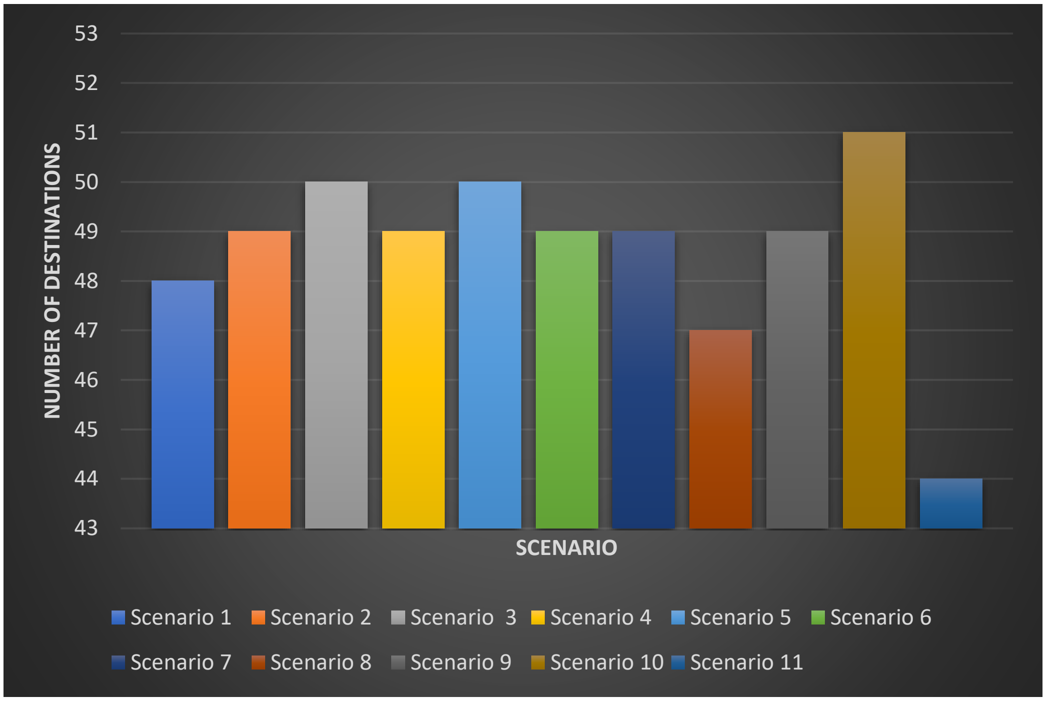


Figure 14: Proposed TNDs coverage of major destinations (300 m walking distance)

Analysis of the results displays that the 10th TND offers highest access for the population of Sanandaj for longer walking distance to network, but it performs poorly for the shorter walking distance. Also, the 6th and the 5th TNDs produce relatively similar coverage for 100-meters and 300-meters walking distances. Considering the two scenarios of walking to the stops, 5th and 6th TNDs provide better coverage for the transit system in Sanandaj, compared to other designs. The 11th scenario offers lower access to the major destinations in the city, due to dispersed routes and lack of enough bus lines passing through the downtown core.

5-3 Evaluation of TNDs using GIS

GIS has the ability of measuring the travel distance of the proposed TND scenarios. Also, number of stops can be calculated. The stops are generated in 300 meters intervals on the network using the equal spacing approach for stop placement. The results are provided in the following figures. The first chart is the comparison of travel distances with the 1st scenario, as a radial design with no beltway, having the lowest travel distance.

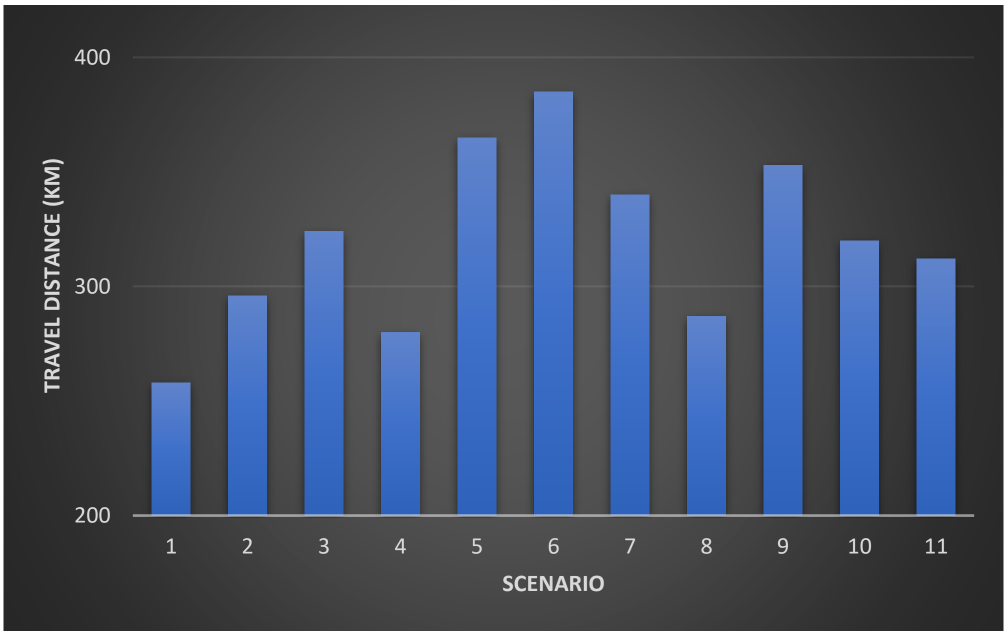


Figure 15: Total travel distance of the proposed TND scenarios estimated by GIS

Next chart displays the number of stops generated in GIS for each network alternative. The 1st TND scenario, which is considered as the basic network design with no beltways, has the lowest number of stops which is significantly lower than other designs and the existing transit system in Sanandaj.

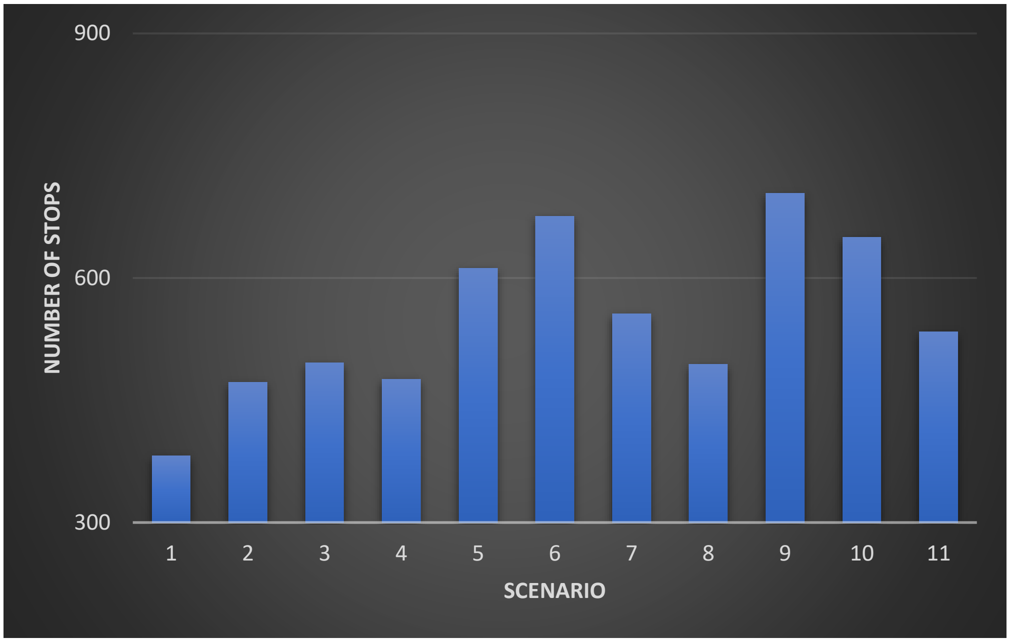


Figure 16: Number of stops generated on the TNDs scenarios

5- 3-1 TNDs score based on GIS analysis

The results of the analysis in GIS are presented in the following table. Although, the existing network offers a low travel distance, overall performance of the network compared to most of proposed alternatives is poor, considering the scores achieved based on the objectives of transit network design. Overall score of the scenarios, based on three objectives of travel distance, number of stops and coverage of the bus system is calculated. First TND has the highest score due to low travel distance and number of stops, because it is a radial design with smaller network size. Also, the 8th scenario scores high because of relatively low network size.

Table 2: Ranking the TND scenarios based on GIS

	Travel Distance (KM)	Number of Stops	Coverage (100 m)	Overall Score
Highest Score	**1, 2, 4, 8, current**	**1, 2, 3, 4, 7, 8, 11**	**1, 8, 9, 11**	**1, 8**
	3, 5, 6, 7, 9, 10, 11	**5, 6, 9, 10, current**	**2, 3, 4, 5, 6, 7, 10**	**2, 4, 11**
			current	**9**
Lowest Score				**5, 6, 10, current**

5- 4 Evaluation of TNDs using ACO

Ant Colony provides an estimate of total travel distance and number of stops generated for the proposed networks. In the following figure, the objective function values (vertical axis) for 11 scenarios are displayed. The objective function values are the total travel distances in meters. Top left diagram is related to the first scenario. Toward right, there are diagrams of second and third scenarios. The diagram for the 11th scenario, is at the bottom right corner of the figure. Each diagram displays the objective function value changes in 10 iteration of the ACO algorithm.

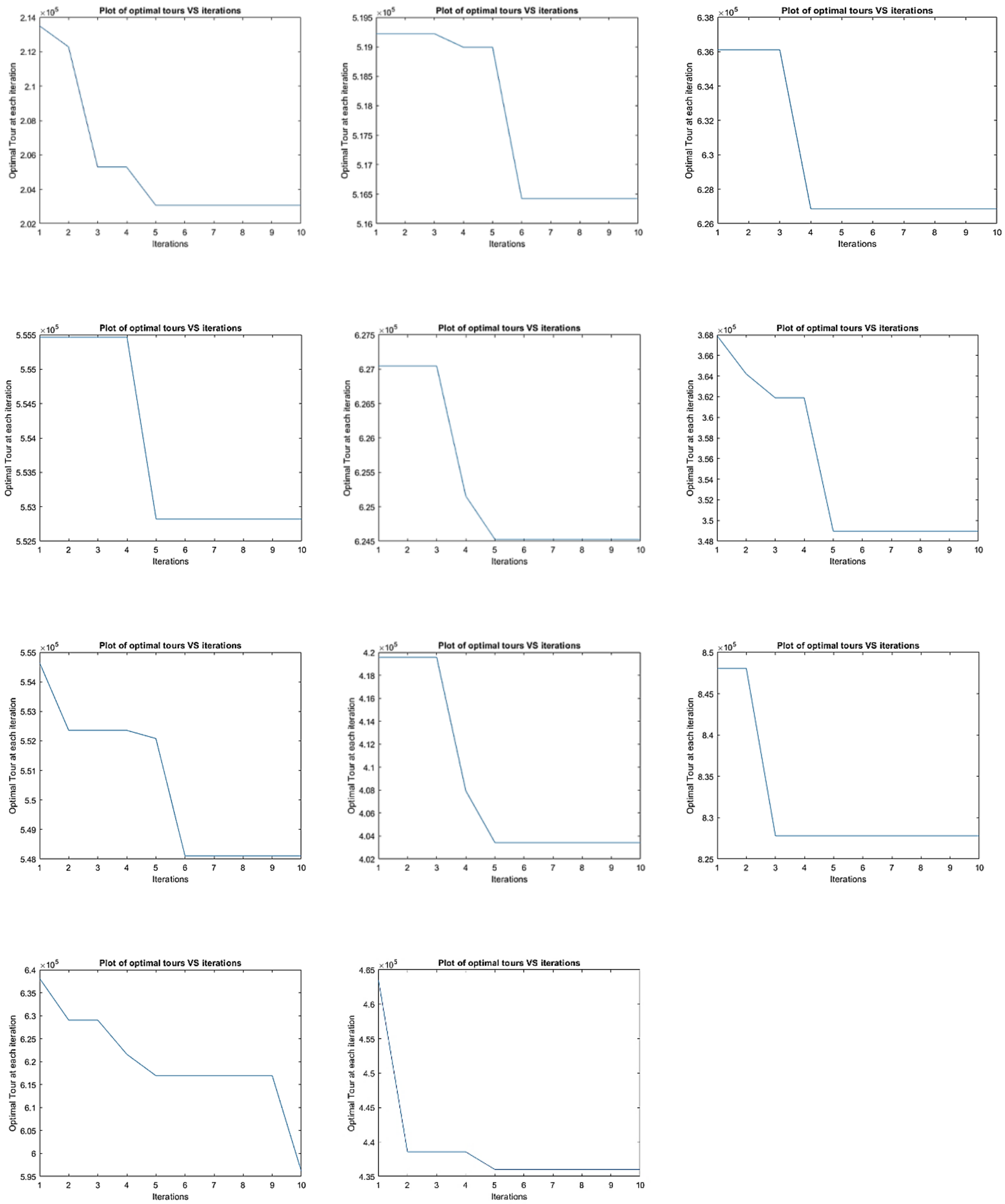


Figure 17: The total travel distance of the 11 proposed TNDs

In the next figure, the set of diagrams display the objective function values (vertical axis), which are the number of stops, for 11 TNDs. The first diagram, top left, is the objective value for the first TND for 10 iterations of the ACO algorithm. Toward the right in the figure, there are diagrams of second and third TNDs. The 11th TND's diagram is at the bottom right of the figure.

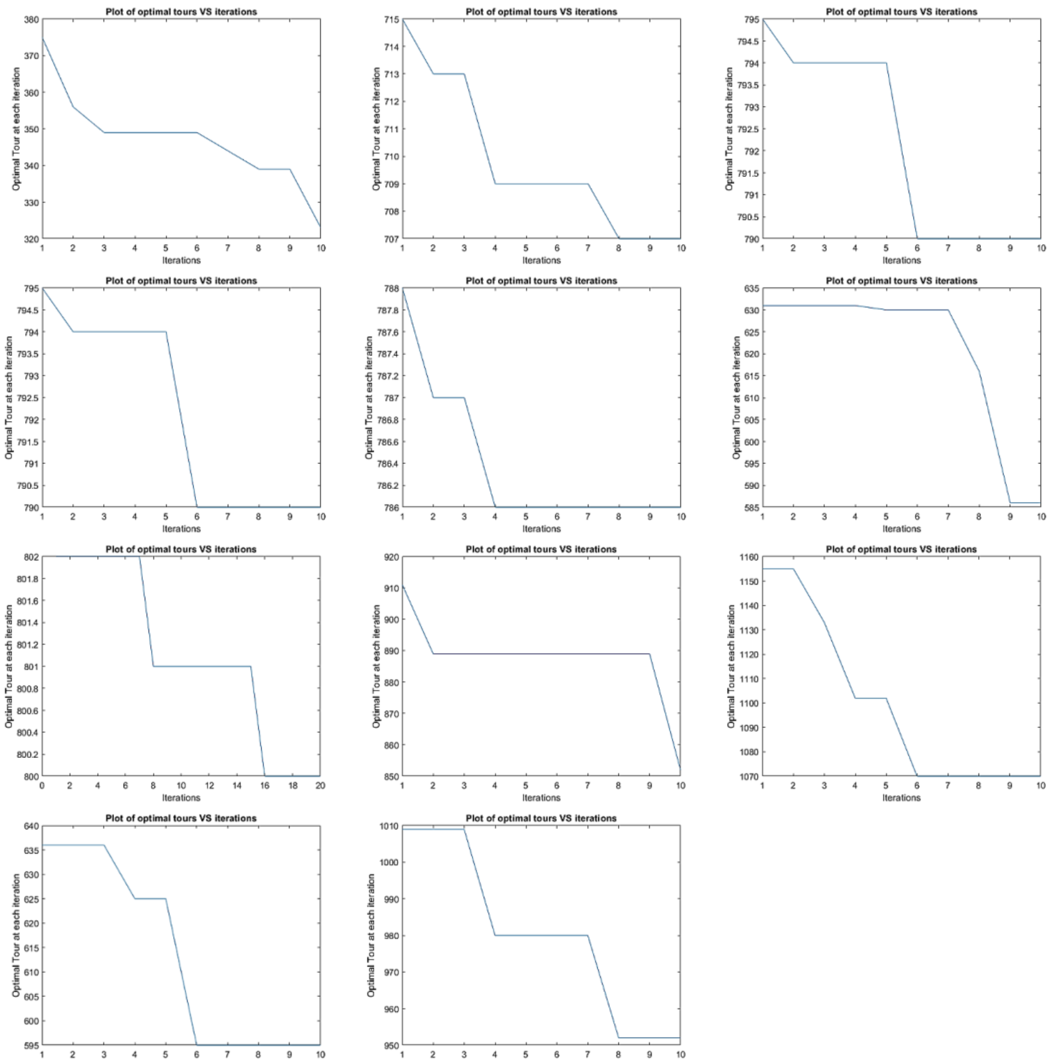


Figure 18: Number of stops generated by ACO for 11 proposed TNDs

The results of the evaluation are provided below. The 6th TND generates lower total travel distance. This network design also has a comparatively low number of stops, compared to others. While, the 6th TND offers lower total travel distance and number of stops, it has relatively similar coverage for the population within 100 and 300 meters of the bus system regrading other TNDs. Moreover, the first scenario is a small sized network with comparatively small number of stops. Exclusion of ring lines from the first TND reduces the coverage of the bus system. It has the lowest coverage of population in Sanandaj for short walking distance and the lowest cost of operation due to small network size. Also, it does not provide enough service for the population in the peripheries due to lack of beltway routes in the design.

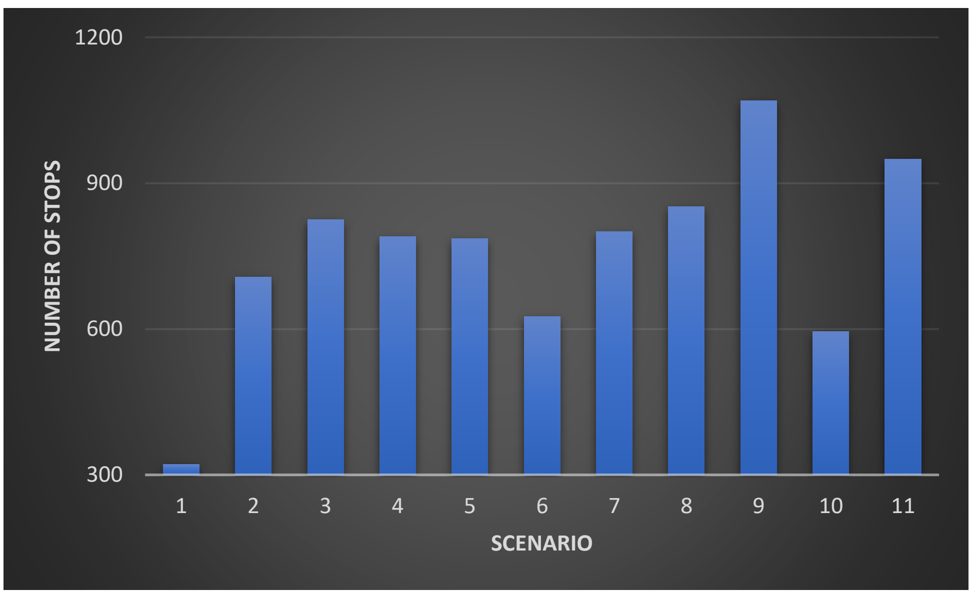


Figure 19: Number of stops generated by ACO method for TND scenarios

Based on the results of the ACO algorithm, provided in the following figure, first and 6th scenarios have the lowest and second lowest travel distances among the TNDs. While 6th scenario provides relatively good coverage for the bus system, the first scenario, as a radial design, offers lower coverage of the population.

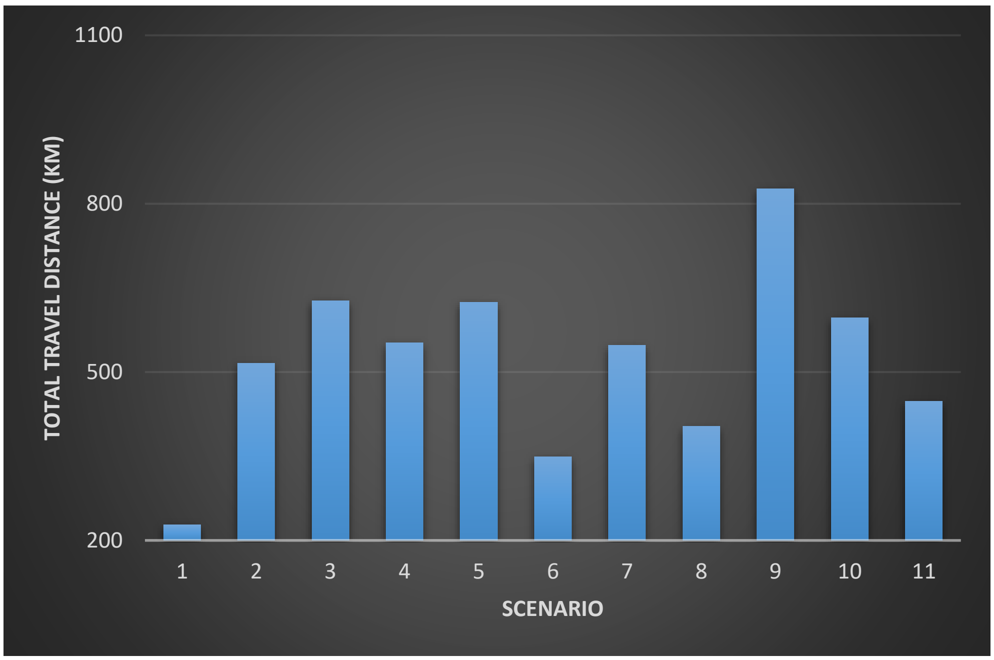


Figure 20: TND scenarios' total travel distance generated by ACO method

5-4-1 TNDs score based on ACO results

In this section, the TND scenarios are ranked based on the level of satisfaction for each objectives provided by ACO algorithm. The overall ranking of each scenario is the linear sum of the scores obtained for each objective. Based on the ranking results, first scenario has the highest score among other TNDs. Due to radial design of the first scenario, it generated a low travel distance and number of stops which will reduce the costs of operation. The 9th scenario has the lowest score due to high travel distance and number of stops and very low coverage.

Table 3: Ranking the TND scenarios based on the ACO results

	Travel Distance	Number of Stops	Overall Ranking
Highest Score	1, 6, 8, 11, current	1, 10	1
	2, 3, 4, 5, 7, 10	2, 3, 4, 5, 6, 7, 8, current	6, 8, 10, current
	9	9, 11	2, 3, 4, 5, 7, 11
			9
Lowest Score			

5-5 Evaluation of TNDs using Honeybee optimization

The honeybee method evaluates the networks using three types of honeybees. First group of bees search the network to find the paths with shortest travel distance and smallest number of stops. The second and third group of bees use the results of first group as input to find a tour of the TNDs with lower objective values. The algorithm generates only one final function value for each objective.

The Honeybee method generated the lowest number of stops for the 8th scenario followed by 10th scenario with the second lowest number. Also, the 1st and the 9th TNDs have comparatively low number of stops, while the rest of TND scenarios have more than 600 stops, based on the honeybee assessment.

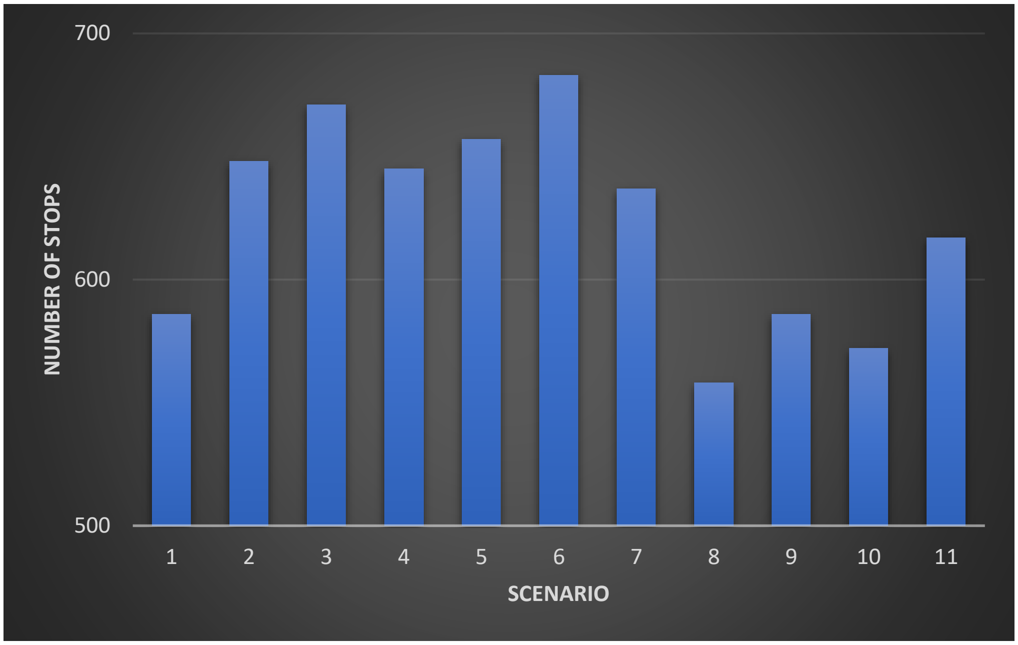


Figure 21: Number of stops generated using Honeybee method for TND scenarios

For the Honeybee assessment of travel distance of the TNDs, which is displayed in the following figure, the 8th scenario has the lowest travel distance. Also, the 9th, the 10th and first scenarios offer identical total travel distances, which is 176 km. The rest of the scenarios have higher travel distances.

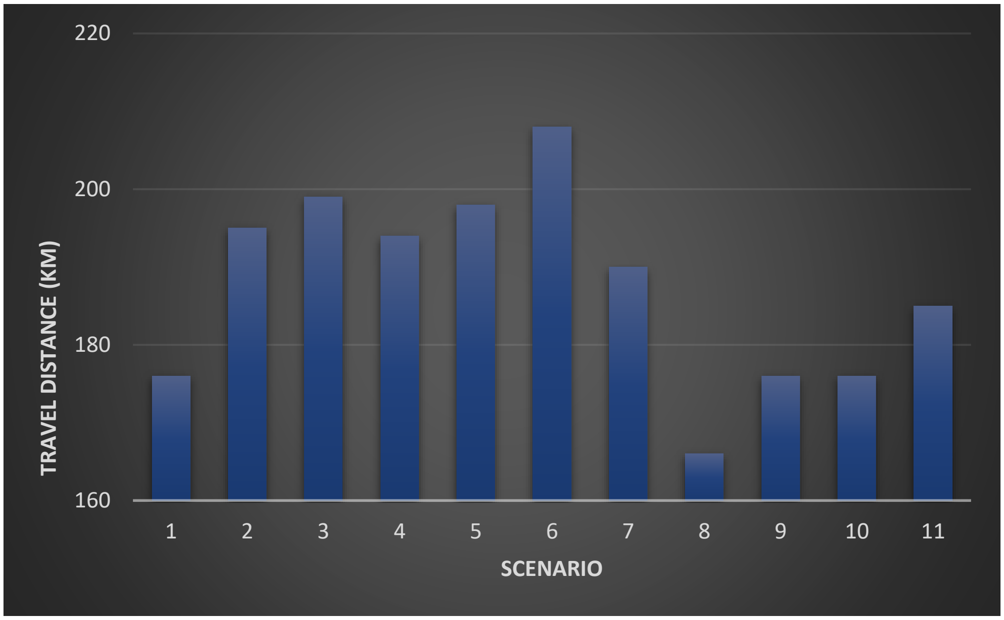


Figure 22: TND scenarios' total travel distance (km) generated by Honeybee method

Generally, TNDs with larger network size provide several beltway lines to cover the peripheral areas. While the beltways increase the operation costs, they also increase the access to the bus network. TNDs with the beltways provide service to the remote areas in the city. Most of the TNDs with larger size that include beltways in the peripheries or around ring lines around CBD have better coverage. In other words, with longer travel distance in the TNDs a larger number of census blocks within the 100 meters distance of the bus lines is covered. The GIS analysis tool (Select by Location) is used to displays how the coverage changes when the network layout or length changes.

5-5-1 TNDs score based on Honeybee results

The ranking of the TND scenarios considering the coverage and the Honeybee assessment results for number of stops and the total travel distance is provided in the following table. The overall scores of the scenarios are calculated as the sum of the scores they received for each objective function. The overall score displays the level of optimality of the TNDs proposed. Based on the scores, several scenarios such as 1st, 8th, 9th and 10th scenario are more suitable options for transit system in Sanandaj regarding our objectives. The existing bus system in Sanandaj has a low performance and it is not considered as an optimal option for the transit system, based on these scores and ranking.

Table 4: Ranking the TND scenarios using Honeybee results.

Highest Score	Number of stops	Travel Distance	Overall Score
	1, 8, 9, 10	**1, 8, 9, 10**	**1, 8, 9, 10**
	2, 3, 4, 5, 6, 7, 11	**2, 3, 4, 5, 7, 11**	**2, 3, 4, 5, 7, 11**
	current	**6, current**	**6**
			current
Lowest Score			

5-6 Discussion

Based on the results of the three algorithms 1st and 8th scenarios are more suitable design considering the objectives proposed. They reduce the network size and operation cost and the cost related to adding stops to the network will be reduced due to lower number of stops needed for theses TND scenarios. Also, the current bus network is not a suitable alternative for Sanandaj based on the results of the evaluation. This network needs to be modified in order to have more optimal design such as some of designs proposed to reduce the costs and increase the access and coverage of the system.

Moreover, based on the importance of the transit network design objectives for the administration, different weights can be given to the objective functions and the overall score and ranking of the TNDs can change. Therefore, the final ranking of the transit network designs depends on the importance of the service compared to the operation costs. The bus fare in Sanandaj is a flat rate. If they increase the fare for longer distances, higher travel distance will not be a problem because the operator can cover the costs with higher fare and the importance of travel distance and number of stops will be reduced, compared to the coverage of the bus network.

The current network has a low travel distance, 252 km, and large number of stops, compared to the proposed alternative. But the major issue is the coverage of the existing network which very low compared to the proposed scenario. This might be due to small network size and lower accessibility of the current network in the population centers which makes it inconvenient. The evidence of low accessibility and coverage of the current transit system is having only the 2 percent share of trips in Sanandaj. Every TND scenarios proposed provide better access based on coverage analysis for short (100 meters) and medium (300 meters) distances of population blocks to the proposed network alternatives. Changing the location of stops can change the coverage of the TND scenarios to some extent, which is one of the limitations of the current research. But still with adjustment of coverage based on different locations for the stops in the network alternatives proposed, these TNDs provide better access and geographic coverage than the current transit system.

Radial designs such as the first scenario are more favorable for operators because of lower operation costs, but they also reduce the level of service provided for the population in the peripheries. Therefore, a radial network is not a favorable TND for the users of the transit system. Other TNDs with more beltways are costly to operate, but they provide better access to the transit system for the population in Sanandaj, the city used as an example in this study. The choice of TND for Sanandaj depends on the budgetary restrictions of the city administration, because adding beltways to the bus system generate better access but it also increases the cost of running the bus system.

In the TNDs proposed, the problem of access to the peripheries is solved by providing beltway lines that does not exist in the bus lines operating in Sanandaj. Implementing the results and further assessment of these outcomes using participatory methods such as surveys will provide us with better results in TND since the user's point of view and what is an optimal public transportation network in their view is important.

There is a clear trade-off between the proposed objectives in the TND model. Creating a balance between the different points of view, which have been considered in the objectives proposed, is an important task in transit network design process. The operator's view is to reduce the cost of operation which can be achieved by reducing the travel distance and number of stops. Radial networks and Hub-and-spoke designs, such as the first TND scenario, generally satisfy the operator's view of reducing the costs related to the vehicles and crew due to smaller network size. The user's view focuses on better access to the bus system in the different districts of the city and reducing the walking distance to and from the network.

The results of the honeybee method and GIS are more reliable, compared to the ant colony assessment outcome. The spatial and analytical abilities of GIS will reduce the level of uncertainty in the produced results and makes it more reliable than ant colony optimization. Also, honeybee uses several group of bees to search the solution and find the most optimal path based on the objectives of the transit network design. Each group of bee receives feedback from the previous group and uses the partial solution selected by the former group and finds a better path on the network. Therefore, it's results can also be more reliable than the ant colony that uses only one set of ants to search the space.

Chapter 6

Conclusion

6-1 Contributions

The results of this study contribute to GIScience and urban transportation by providing an innovative approach for GIS-based transit network design. The GIS procedure consists of several levels to design and evaluate the TNDs. Spatial aspect of transit network design is emphasized. Also, combination of GIS and metaheuristics in the procedure helps us to design multi-level design process that can construct and evaluate the networks alternative at the same time. In previous studies based on heuristic and metaheuristic methods this approach is not common. In the previous studies, only the heuristic or metaheuristic method is responsible for every step of the design, and some measures are not considered with other objective in the transit network design procedure. Having the visual and spatial analysis capabilities of GIS helps us to construct the network alternatives considering the built environment and of the city. Also, access and geographic coverage of the TNDs can be measured using GIS applications, while metaheuristics do not have spatial, visual and analytical abilities of GIS. They might not be able to assess the geographic coverage and accessibility of the proposed TNDs, which is important in any TND procedure. Moreover, the results of GIS analysis can be ranked and compared with metaheuristics results.

In this study we attempted to address several key issues for tackling the TND problem. First, spatial multi-objective optimization problems (such as the TND problem) are still very challenging to solve and there is a limited number of studies demonstrating how effective the combination of swarm metaheuristics and GIS can solve the spatial optimization problems. In this research, an attempt is made to integrate swarm intelligence and GIS and use their visual and analytical capabilities for solving the TND problem. Second, the previous studies on TND tend to focus on implementing a single metaheuristic method (such as the ant optimization algorithm) for solving the optimization problem. The proposed approach contributes to TND and GIS by implementing two distributed and decentralized multi-agent metaheuristics for evaluating alternative transit network configurations.

This research displays the multi-objective nature of the transit network design procedure. Since each objective is related to one critical aspect of the network design which must be considered in the modeling procedure, a single objective does not satisfy the user and the operator aspects of the transit network design, simultaneously and comparing the results together. This approach contributes to decision making by producing improved TNDs and enhances the capability of planners to make decisions in the process of public transport planning. The stakeholders' point of view has been considered to some extent by using a collection of objectives based on their perspective in construction and evaluation of the network alternatives. Here, our focus is on agent as the decision maker and one of the limitations is the lack of human decision makers or experts that their perspective.

Also, the ranking and scoring system offered in this research can display the efficiency of the proposed transit network alternatives. It can help us in the transit network design procedure to find more optimal solutions. Comparison of the ranking results of each method with others can also display the reliability and efficiency of GIS, ant colony and honeybee algorithms in transit network design research.

6-2 Limitations and recommendations

One of the limitation of this study is that the stops locations are random and the walking distance to the bus network, which has been considered here as the basis for coverage analysis, might not be exactly same as the distance to the stops. In order to increase the access and coverage of each scenario we can adjust the location of the stops in order to near the blocks with higher density of population.

Also, measuring the linear distance from the TNDs to the census blocks centroids can be replaced with network distance when a detailed network of alleys and residential roads in GIS is ready to measure the network distance from a block to the stop on the bus network. In order to do this, the available datasets can be cleaned and updated by the city administration and connect every link and add missing alleys or residential roads to be linked with the main street network. Due to large number of nodes and links this is a long process that needs to be done by a group of GIS users.

Another issue is the related to the data needed for the stop placement analysis. The attribute data in Sanandaj does not have the detailed information about the number of work force and students for every census blocks, in some blocks the data is missing. If the administration provides the data in future, further analysis of the TNDs accessibility for different age groups and work force and students who commute on daily basis can be performed.

In future planning of the city, more accurate and up to date census and population data is needed to analyze the access of each block to the bus network. Using GIS applications can help in providing detailed spatial information about the blocks, because the census data were originally attribute data without any spatial coordinates. In the proposed GIS procedure, census blocks have been assigned to the locations based on their IDs in the attribute table.

One of the policies that the city administration can consider for future, in order to reduce traffic congestion in Sanandaj, is allocating lanes in the main streets to the transit system. This will help in reduction of the number of cars travelling to the downtown core from peripheries. It can also promote using transit system due to lack of enough space on the roads for private cars in the CBD area.

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Appendix1

Authors	Objectives	Decision variables	Network	Demand	Methodology
Cipriani et al. (2012)	Minimize transit users' cost, operator's cost and external costs	Transit routes	Irregular	Many to many, Elastic	Heuristic Metaheuristic (GA)
Borndörfer et al. (2007)	Optimize flow of passengers and frequency of bus lines	Transit routes, Passenger flow	Grid	Many to many, Fixed	Exact method
Álvarez et al. (2010)	Minimize waiting time and travel time of passengers	Transit routes Stops	Irregular	Many to many, Space-time dependent	Heuristic
Wang, Yan, Zhou, and Zhang (2016)	Minimize total service time of dispatched feeder buses	Fleet size, Transit routes, Operation time	Not given	Many to one, Fixed	Metaheuristic (GA)
Sun et al. (2013)	Minimize traveler cost, operator cost and environmental cost	Transit routes, Pollution, Vehicle types Stops	Irregular	Many to many, Fixed	Metaheuristic (DE)
Fan and Mumford (2010)	Minimize total travel distance and total number of transfers of all passengers	Demand Average travel time	Irregular	Many to many Fixed	Metaheuristic (HC & SA)
Shrivastava and O'Mahony (2006)	Minimize user's in-vehicle and transfer time cost, and vehicles operation cost	Frequency Transit routes	Irregular	Many to many, Space-time dependent	Metaheuristic (GA)
Ma et al. (2017)	Minimize passenger's cost, Operational cost, and Societal cost	Stops Departure times	Irregular	Many to many, Space-time dependent	Metaheuristic (GA)
Mauttone and Urquhart (2009b)	Minimize user's in-vehicle, waiting, transfer time cost, and fleet size	Frequency, Transit routes	Irregular	Many to many, Fixed	Heuristic
Zarrinmehr, Saffarzadeh, Seyedabrishami, and Nie (2016)	Maximizing the transit ridership and minimizing operational costs	Transit routes	Grid	Many to many, Elastic	Heuristic
Mauttone and Urquhart (2009a)	Minimizing operator cost (total number of routes and duration) and users' cost (travel time)	Transit routes	Grid	Many to many, Fixed	Heuristic
Alt and Weidmann (2011)	Public transit generalized cost (passenger and service provider cost)	Transit routes	Irregular	Many to many, Fixed	Metaheuristic (GA, ACO)
Poorzahedy and Safari (2011)	Minimize the combined cost of user (travel time) and investment cost (fleet size)	Fleet size	Irregular	Many to many, Fixed	Meta-heuristic (AS)
Miandoabchi, Farahani, and Szeto (2012)	Maximize the demand share of bus mode and users' benefit	Number of lanes, Passenger flow	Irregular	Many to many Fixed	Metaheuristic
Černá, Černý, and Přibyl (2011)	Minimizing length of the route with minimum number of stops	Transit routes Stops	Irregular	Many to many Fixed	Exact method Heuristic

Liu, et al. (2018)	Minimize operator's cost and Maximize the level of demand satisfied	Vehicle occupancy, Number of Passengers, Route length, Stops	Irregular	Many to one Space-time dependent	Bayesian Network Analysis
Alonso, Moura, dell'Olio, and Ibeas (2011)	Minimize users, operator and social costs	Fleet size Transit route length	Irregular	Many to many Space-time dependent	Meta-heuristic (Tabu)
Kuo (2014)	Minimize number of transfers and travel time, Maximize coverage	Transit routes Number of transfers	Irregular	Many to many Fixed	Meta-heuristic (SA)
Shimamoto, Murayama, Fujiwara, and Zhang (2010)	Minimize Operator and passengers' cost	Transit routes Frequency	Irregular	Many to many Fixed	Meta-heuristic (GA)
Lownes and Machemehl (2010)	Minimize total cost (user, operator, un-served demand)	Transit routes Number of passengers	Irregular	many to many, Fixed	Exact method Meta-heuristic (Tabu)
Chew, Lee, and Seow (2013)	Minimize total route length (operator) and travel time (user) and un-served demand	Transit routes Demand	Irregular	Many to many, Fixed	Meta-heuristic (GA)
Miandoabchi, Farahani, Dullaert, and Szeto (2012)	Maximize total user benefit, bus demand and coverage, minimize generalized travel cost	Passenger flow, Transit routes, Demand	Irregular	Many to many Fixed	Meta-heuristic (GA)
Cadarso and Marín (2017)	Minimize the location cost of stations, sum of routing costs per passenger group	Transit route, Stops, Passenger flow	Irregular	Many to many Fixed	Exact method
Y. Liu et al. (2017)	Maximize total number of bus riders	Waiting time, Travel time and distance, Fare	Irregular	Many to many, Elastic	Exact method
Schöbel (2012)	Minimize number of transfers, riding and travel time	Transit Routes, Number of transfers	Irregular	Many to many, Space-time dependent	Exact/Heuristic
Z. Li, Song, He, and Bi (2018)	Minimize un-served demand	Stops, Vehicle type	Irregular	Many to one, Space-time dependent	Exact Method
Si, Zhang, Zhong, and Yang (2011)	Minimize air pollution, energy consumption and traffic congestion	Fare, Toll	Grid	Many to one, Elastic	Exact method
X. Li, Liu, Liu, and Gao (2015)	Minimize total travel time, user and operation cost, maximize coverage, direct flow & daily load	Transit routes, Number of passengers , Number of transfers	Irregular	Many to many Elastic	SAW and TOPSIS
Levin, Jafari, Shah, and Boyles (2017)	Minimize fuel, tolls, and transit fees, travel time	Transit route, Travel mode	Grid	Many to many Elastic	Exact method
F. Zhao and Zeng (2006)	Minimize total user travel cost	Transit routes, Headways Demand	Irregular	Many to many Fixed	Meta-heuristic (GA, SA)
Si et al. (2011)	Minimize passenger cost and operator cost	Headways	Irregular	Many to many Space-time dependent	Meta-heuristic (GA)
Laporte, Mesa, Ortega, and Perea (2011)	Minimize construction cost, cost to population coverage ratio	Transit routes, population	Irregular	Many to many Fixed	Heuristic
Qin, He, and Ni (2014)	Minimize total travel cost	Transit routes, Traffic flow	Irregular	Many to many Space-time dependent	Exact method
Zhu et al. (2017)	Optimize travel time and traffic	Demand Average travel time	Irregular	Many to many Fixed	Exact Method
Heydar, Yu, Liu, and Petering (2016)	Minimize the total evacuation time	Demand	Irregular	Many to many Fixed	Heuristic, Meta-heuristic (SA)

Matisziw, Murray, and Kim (2006)	Maximize demand coverage, Minimize route length	Demand Stops	Irregular	Many to many Fixed	Heuristic
H. Zhao and Jiang (2015)	passengers' waiting time, transfer time, total travel time	Transit routes Frequency	Mandl's Swiss network	Many to many Fixed	Heuristic
Gallo et al. (2011)	Operator costs, Transit user costs, car user costs, external costs	Transit routes frequency fares	Irregular	Many to many Elastic	Meta-heuristic (GA), Heuristic
Curtin and Biba (2011)	Maximize transit service	Transit routes	Grid	Many to many Fixed	Exact method
Bagloee, Sarvi, and Ceder (2017)	total travel time	Transit Routes	Irregular	Many to many Elastic	Heuristic
Yu, Yang, Jin, Wu, and Yao (2012)	maximize direct and transfer demand density	Stops, Number of transfers	Grid	Many to many Fixed	Meta-heuristic (ACO), Heuristic

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