공학박사 학위논문

Multi-objective Optimization for Bus Network Design Problem Using Pareto Optimal

파레토최적해를 이용한 버스네트워크 설계 다목적 최적화

2020 년 8 월

서울대학교 대학원

건설환경공학부

박 수 진

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이 논문을 공학박사 학위논문으로 제출함

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박수진의 박사 학위논문을 인준함

2020 년 8월

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Abstract

Public transportation is a service that provides access to various opportunities and can reduce the mobility gap through efficient network design. However, services are concentrated in a specific area considering economic efficiency, resulting in spatial imbalances in services and inefficiency to users.

In this study, bus network design algorithms were presented, including operators, users, and public aspects. An efficiency of operators and users and the competitiveness of public transportation between modes and areas were considered. Toy network was organized according to the urban network topology and demand pattern, and the analysis was performed by applying the algorithm of this study. The applicability of the algorithm was confirmed through the actual network.

An improved network could be derived from both operators and the public compared to previous research focused on operational efficiency. Suggested a method to select and apply Pareto optimal according to the planner's judgment. The bus network design algorithm in this study can be used as a means of decision criteria and it can be applied to cities that require a balanced network supply with limited resources.

Keyword : TNDFSP, Equity, Unmet Demand, Multi-Objective, Pareto Optimal

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Contents

Table List

Figure List

Chapter 1. Introduction

1.1 Background

Public transportation is an important element of sustainable urban development as a service that provides access to a variety of opportunities (occupations, services, etc.) or mobility to regions (Camporeale et al., 2017; El-Geneidy et al., 2016). Public transportation is a means that everyone can use, and by improving access, alleviation of urban congestion enables rapid movement between machine shops. Efficient public transport network design can reduce the mobility gap between choice riders and captive riders (Welch, 2013). Therefore, efficient public transport network design is very important in the social, economic and structural aspects of the city (Fan and Machemehl., 2008).

However, the number of automobiles and the cost of road congestion have been continuously increasing as the means of sharing in public transportation has been continuously decreasing in the last five years. According to Beimborn et al. (2003), passenger cars are used due to the lack of public transportation services between the end points, many stopovers, and other personal characteristics (load, age, disability). Jiang (2018) analyzed that when the public transportation service is unfair, the use of passenger cars increases, and as a result, the congestion of the city increases.

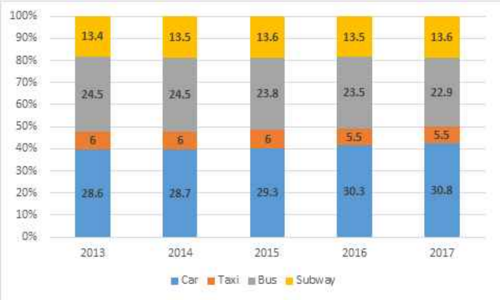


Figure 1.1 Modal Split (Capital Area)

Figure 1.2 Number of Car and Traffic Cost

Existing public transport network design studies considered many factors such as cost, profit, demand, environmental pollution, traffic congestion, transit, and equity. At this time, the objectives between the stakeholders (operators, users, the public, the environment, etc.) are different, so it is regarded as a multi-purpose problem in nature, and needs to be balanced for different purposes (Camporeale et al., 2019). However, in the existing studies of optimization of public transportation networks, considering the economic efficiency, spatial imbalance occurs where services are concentrated in a specific area. Besides, inefficient services may occur from the user's side due to line circuity or frequent transfers. Efficient route network design maximizes the operator's profit(profit) and provides services that can be moved through a small number of transfers (Yan et al., 2013; Nikolić and Teodorović, 2013). A transfer can be reduced by direct service as an indicator of user inconvenience. However, if the service is concentrated in a specific area such as a demand-dense area, some users may suffer disadvantages because it is not evenly distributed to all areas. (Szeto and Jiang., 2014; Meng and Yang., 2002). Therefore, the route network design must consider not only efficiency but also equity (Chen and Yang., 2004; Fan and Machemehl., 2011, Bok and Kwon., 2016).

The purpose of this study is the transit network design considered operators, users, and the public as the spatial expansion of cities and the various city's topology. The objective function of each part is as follows. Operators are set to maximize profits, users to maximize convenience, and the public to maximize equity. The profit was calculated by taking into account the operating cost of the total operating income. The user's discomfort measured the unmet demand through a certain number of transfers because the user's discomfort is increased when frequent transfers occur. To reduce regional differences, equity was measured as the competitiveness of public transportation. This study is defined as the difference in the travel time difference between public transportation and passenger cars for each model to reduce the gap between regions (Zhao and Feng., 2006; Á. Ibeas et al., 2010; Ferguson et al., 2012). Previous studies on multi-purpose used a weighted summation that combines multiple objectives into a single objective. However, these methods are difficult to determine weights and cannot provide various solutions to designers. Therefore, in this study, optimization was performed using Non-dominate Sorting Genetic Algorithm-II (NSGA-Ⅱ), a multi-purpose optimization algorithm capable of identifying relationships between objective function.

1.2 Research Scope

This study is shown in the following figure 1.3, and consists of a total of six chapters. First, Section 2 defines the scope of public transport planning research conducted in this study. Then, in addition to the commonly used cost function among the objective functions of optimization, the previous studies on unsatisfactory demand and equity are reviewed and defined for each index in this study.

In Chapter 3, the limitations of the existing research methods for the multi-objective optimization method are reviewed. The algorithm and application method of this study is described based on this. Also, local search methods and normalization were performed to search for efficient solutions and solve the scale problem between objective functions. Also included are encoding methods with constraints used in the networks design problem.

Chapter 4 summarizes the objective function and variables used through a review of previous research. It also described assumptions that used reality because it could not reproduce all situations.

In chapter 5, the toy network was constructed according to the representative network topology of the city and the demand ratio in the city center, and the algorithm of the study was applied. First, in the Pareto solution, the bus network's characteristics representing the optimum value for each objective function and the change in the objective function according to the urban demand ratio were analyzed. Second, the change according to the increase or decrease of each objective function was analyzed through the marginal effect analysis. Lastly, the improvement and limitations of this study were described by comparing the method of maximizing profit used in previous research generally.

Finally, Chapter 6 presents the bus network design direction in the city based on the experiments conducted in Chapter 5. Also, not only the contributions and applications of this study, but also limitations and future research methods are presented.

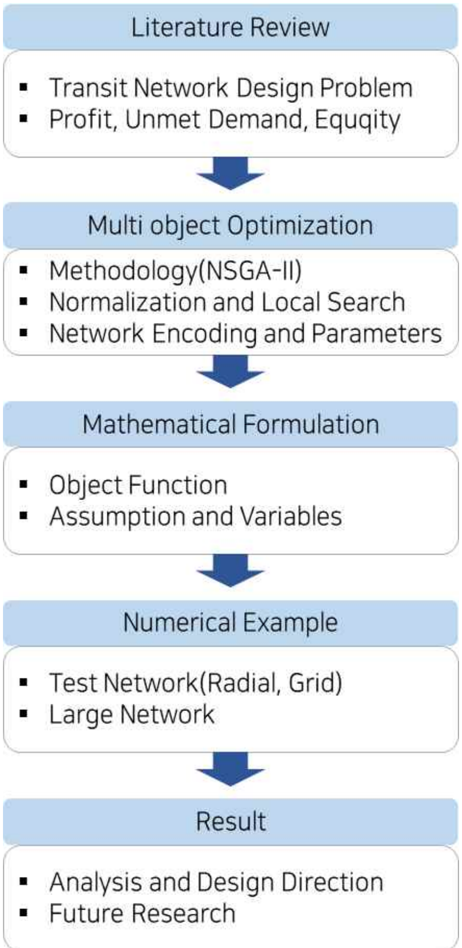


Figure 1.3 Research Flow

Chapter 2. Literature Review

2.1 Transit Network Design

The public transportation plan is composed of 5 steps of route design, frequency setting, operation plan setting, vehicle layout plan, and crew arrangement plan as shown in Table 2.1 below. This is the most important factor because the overall cost of the public transportation system is greatly changed by the first stage, route design (Owais et al., 2015).

Table 2.1 Transit Planning Process

Independent Inputs	Planning Activity	Output
Demand data Supply data Route performance indicator	Network design	Route changes New routes Operating strategies
Subsidy available Buses available Service available Current patronage	Frequencies setting	Service Frequencies
Demand by time of day Times for first and last trips Running times	Timetable development	Trip departure times Trip arrival times
Deadhead times Recovery times Schedule constraints Cost structure	Bus scheduling	Bus schedules
Driver work rules Run cost structure	Driver scheduling	Drivers scheduling

Source: Ceder and Wilson. (1986)

Public transport network design problems include various terms such as Network Design Problem (NDP), Transit Network Design Problem (TNDP), Transit Route Network Design Problem (TRNDP), Bus Transit Route Network Design Problem (BTRNDP), and Urban Transit Network Design Problem (UTNDP).

Guihaire and Hao (2008) basically defined three problems of public transport route network design: design (TNDP), frequency setting (TNNSP), and time tabling (SUSE). Also, it is defined as design and frequencies setting (TNDFSP = TNDP + TNFSP), scheduling (TNSP = TNFSP + TSTP) and TNDSP (TNDP + TNFSP + TSTP) according to the combination of problems as shown in Figure 2.1. This study is a TNDFSP study that determines the public transportation route and frequencies.

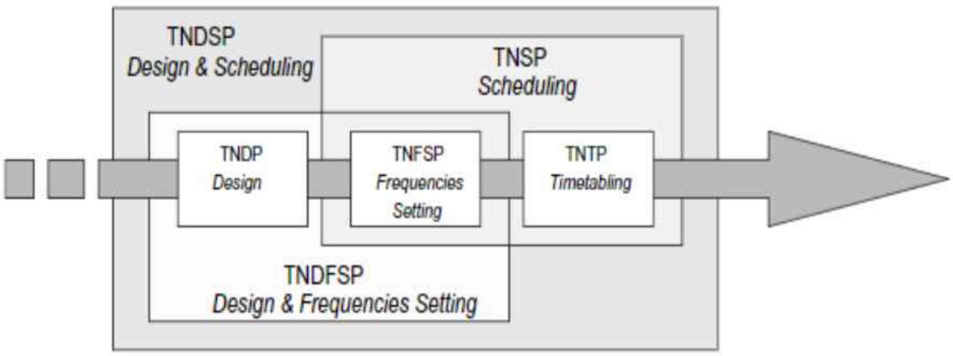


Figure 2.1 Transit Network Design problem Structure

Source: Guihaire and Hao., 2008

The urban transport network design is essentially a matter that various stakeholders. Representative stakeholders include operators, users, the public (government), and the environment and systems.

The operator's objective is mainly to minimize the operating cost or maximize the profit due to the number of vehicles, the total length, and frequency, which affect the operating cost.

The user's object is to minimize the travel time by organizing the in-vehicle time, waiting time, access time, and transfer penalty. Also, in terms of convenience, the goal is to maximize the direct demand that can reach the destination without transfer, can reach under a certain number of transfers, or minimize the number of transfers.

The public side maximizes equity to minimize deviations between areas and modes, as in Section 2.3 below. Also, to minimize vehicle emissions such as CO2, maximizing the total cost of the system, and total social surplus..

The constraints used in network design problems can be summarized as follows. Frequency constraints to prevent over/under frequency setting and the number of stops are mainly applied to prevent excessive circuity. Besides, constraints on the number of lines or budgets are also applied.

This study is the Transit Network Design and Frequency Setting Problem (TNDFSP), and the decision variable is the combination of the route network and the frequency. The previous study used fixed demand due to the complexity of the problem, but variable demand should be considered because demand and the transit network have a variable relationship(Pternea, et al., 2015). Therefore, the applied variable demand, according to the public transportation network in this study. Table 2.2 summarizes the objective function, constraint, and algorithm used in previous TNDFSP.

Table 2.2 Literature Review of TNDFSP

Author	Object	Constraint	Algori-thm
Lampkin and Saalmans. (1967)	Max. Direct Passenger Min. Total Travel Time	Fleet Size	H
Kocur and Hendrickson (1982)	Max. Operator Profit Max. Social welfare	Deficit	M
Spasovic et al. (1993/1994)	Max. Operator Profit Max. Social welfare	Capacity	M
Hasselstrom (1979/1981)	Min. Number of Transfers Max. Number of Passengers	Budget	M
Ceder and Wilson. (1986)	Min. Excess Travel Time Min. Transfer and Waiting Time Min. Vehicle Costs	Minimum frequency, Fleet size, Route length	H
Van nes et al. (1988)	Max. Fulfil the demand Max. Number of direct trips	Fleet size	M
Shih and Mahmassani. (1994/1998)	Min. Travel Time Max. Satisfied Demand Min. Fleet Size	-	O
Bussiek. (1998)	Max. Number of direct passengers Min. Operating Cost	Level of service, Number of resources	M

Continue Table 2.3

Author	Object	Constraint	Algori-thm
Imam (1998)	Max. Operator Profit	Capacity	O
Chien and Spacovic. (2001)	Max. Operator Profit Max. Social welfare	Capacity	H
Van Nes. (2002)	Max. Social welfare	Frequency	M
Blum and Mathew (2011)	Min. Passenger Cost (Including Unmet Demand) Min. Operating Cost	Frequency, Fleet Size, Transfer	E
Li et al. (2012)	Max. Operator Profit	Capacity, Headway, Length, Spacing	H
Canca et al. (2016)	Max. Operator Profit	Budget	M
Canca et al. (2019)	Max. Operator Profit	Budget, Number of Station, Frequency	H
Dou et al. (2019)	Min. Non-served Passenger Min. Operating Cost	Number of Station, Operating Time	M
Ranjbari et al. (2020)	Min. Total Travel Time Min. Deadheading Time	Demand Coverage, Total Satisfied Demand, Fleet Size, Frequency, Number of Route	O
Duran-Micco et al. (2020)	Min. Total Travel Time Min. Emission	Budget	H

Source: Guihaire et al. (2008), Kepaptsoglou and Karlaftis(2009), Additional Search

H: Heuristic, E: Evolutionary, M: Mathmatical, O: Other

2.2 Unmet Demand

The decision variables used in the previous studies have been used in various ways for each study. The objective functions used are summarized as operator cost, profit, demand, Emission, number of transfers or transfer demand, equity. Public transportation is an essential element of the city, and economic efficiency needs to be considered. Therefore, it is considered to minimize the operating cost or to maximize the profit. Costs can be reduced if the only efficiency is considered, but services may be provided in demand-concentrated areas, resulting in some trip has a frequent transfer. Frequent transfers cause inconvenience to the user, and thus the efficiency of the user can be secured by reducing the transfer(Szeto and Jiyang., 2014; Yan et al., 2013; Khanzad et al., 2016). In the previous study, the user's convenience was defined using Unmet Demand or Unsatisfied Demand.

Pternea et al. (2015) have the purpose of minimizing the total cost for the operator costs, user costs, and external costs, including unsatisfactory. Baaj and Mahamassani (1995) reflect that users avoid transfer because travel time increases due to transfer, and the demand that cannot reach the destination without or single transfer is defined as unsatisfactory demand. Mauttone and Urquhart (2009) equally allowed only one transfer.

Nikolić and Teodorović (2013) defined the demand for two or more than transfer as unsatisfactory because the total number of transfers can be reduced by optimizing the transit network. The goal was to maximize satisfied demand, minimize total travel time, and minimize unsatisfied demand.

Zhao and Zeng (2006) have the purpose of minimizing transit demand and maximizing service coverage. 58% of respondents considered only transfers within two times, reflecting the results of a survey showing their willingness to make one transfer for a trip(Stern, 1996).

Zhao and Jiang (2015) have the purpose of minimizing total travel time and user dissatisfaction. In general, it is not appropriate for two or more transfers to occur when a trip, so the demand for transfers two or more times was defined as the dissatisfaction of the user.

Also, the previous studies used user inconvenience for direct trips(Van Nes et al., 1988; Baaj and Mahmassani., 1995; Zhao and Ubaka., 2004; Zhao., 2006; Szeto and Wu., 2011; Nayeem et al., 2014), or the number of transfers or demand exceeds a certain number of transfers(Cipriani et al., 2012; Nikolić and Teodorović., 2014; Buba and Lee., 2018). A previous study has defined the demand for more than one or two transfers as a user inconvenience. The Smart Card data on weekdays(2017, 5.17), the total number of the direct trip was 16,273,347 (75%), one transfer was 4,568,921 (21%), two transfers were 737,647 (3%), and three or more transfers were 116,758(1%). It was analyzed that 96% of the total trip was completed by one transfer.

Table 2.3 Transit Network Design with User Inconvenience

Author	Object	Constraint	Def. of Unmet or Unsatisfied Demand	Decision Variable	Algorithm
Baaj and Mahmassani. (1995)	Max. Direct Demand Min. Waiting Time Min. Transfer Time	Headway, Fleet Size	-	Route, Frequency	O
Van Nes et al. (1988)	Max. Direct Demand	Budget, Frequency, Fleet Size	-	Route, Frequency	M
Zhao and Ubaka. (2004) Zhao. (2006)	Min. Number of Transfer Min. Total User Cost Min. Service Coverage	Length, Frequency, Directness, Fleet Size	More than 2 transfer	Route, Frequency	SA
Zhao and Zeng. (2006)	Min. Transfer Max. Service Coverage	Route Directness, Length	More than 2 transfer	Route	SA
Mauttone and Urquhart(2009)	Min. Operator Cost Min. User Cost	Frequency , # of Transfer	More than 1 transfer	Route, Frequency	GRASP
Szeto and Wu. (2011)	Min. Total Travel Time Min. Transfer Demand	Fleet Size, Frequency, # of stops, Target Station	-	Route, Frequency	GA
Cipriani et al. (2012)	Min. Operator Cost Min. User Cost Min. Unmet Demand	Frequency, Length	-	Route	GA

Author	Object	Constraint	Def. of Unmet or Unsatisfied Demand	Decision Variable	Algorithm
Yan et al. (2013)	Min. Total Operator Cost	Frequency, Length, Fleet Size	More than 1 transfer	Route, Frequency	SA
Nikolić and Teodorović. (2013)	Max. Satisfied Demand Min. Total Travel Time Min. Total Number of Transfer	# of Transfer	More than 2 transfer	Route, Frequency	BCO
Szeto and Jiang. (2014)	Min. Transfer Demand	Fleet size, Frequency, # of stops, Target Station	-	Route, Frequency	ABC
Nayeem et al. (2014)	Min. Total Travel Time Min. Transfer Demand	-	More than 1 transfer	Route	GA
Nikolić and Teodorović. (2014)	Max. Rejected Demand Min. Total Travel Time Min. Fleet Size	# of Transfer	More than 2 transfer	Route, Frequency	BCO
Pternea et al. (2015)	Min. Operator Cost Min. User Cost Min. External Cost	Budget, Frequency, Length, # of station	More than Max. transfer	Route, Frequency, Vehicle type	GA

Zhao and Jiang. (2015)	Min. User Cost Min. User dissatisfactory	Frequency, Directness, Fleet Size, # of Route,	More than 2 transfer	Route	MA
Buba and Lee. (2018)	Max. Unmet Demand Min. Total Travel Time	Frequency, Fleet Size	More than 1 transfer	Route, Frequency	DE

GA: Genetic Algorithm
SA: Simulated Annealing
ABC: Artificial Bee Colony
BCO: Bee Colony Optimization
DE: Differential Evolution
M: Mathematical approach
MA: Memetic Algorithm
O: Other

2.3 Equity

In the case of routes considering only efficiency, not only frequent transfers but services concentrated in specific areas may cause other areas do not receive appropriate services. It means that some users may be disadvantaged because the network improvement is not evenly distributed(Meng and Yang., 2002; Chen and Yang., 2004). Public transportation should be provided to all as public service, and it is important to provide adequate accessibility through spatial distribution. Therefore, spatial distribution(equity) of public transportation services is an important factor(El-Geneidy et al., 2016; Bok and Kwon., 2016).

Public transport Equity has been considered since the 1970s, and as the importance of service distribution increases, planners and policymakers have reflected equity in transit design. Bertolaccini (2015) classified public transport equity into three categories: horizontal equity, vertical equity, and equity between means. Also called horizontal fairness or egalitarianism, it is also called spatial equity by providing the same service regardless of individual or group needs. Vertical equity is to provide services according to the level of need, taking into account the inequality of individuals or groups. Equity between mode means that the public and private sectors guarantee the same mobility level, unlike vertical/horizontal equity.

Fan and Machemehl (2011) used spatial equity as a constraint. To prevent users get lower services than before when transit designing, the ratio of the travel time in the improved network compared to the current network cannot exceed a certain level.

$$Spatial\,Equity = \frac{t^{RTN_{ij}}}{t^{CTN_{ij}}}$$

where, t_{ij}^{RTN} : Minimum total travel time from i to j in the redesigned transit network

t_{ij}^{CTN} : Minimum total travel time from i to j in the redesigned transit network

Ferguson et al. (2012) have the purpose to minimizing the gap in each mode's accessibility differences to evaluate equity. Accessibility is composed of the route and travel time between origin and destination for each means.

$$A_{ij}^{w} = A_{ij}^{w,c} - A_{ij}^{w,b}$$

$$A_{ij}^{w,c} = \frac{R^{c}}{N_i} D_{ij} (S_j^{w})^{\alpha} e^{-\beta t_{ij}^{c}},\ A_{ij}^{w,b} = \frac{R^{b}}{N_i} F_{ij} (S_j^{w})^{\alpha} e^{-\beta t_{ij}^{b}}$$

where, A_{ij}^{w} : Accessibility

$A_{ij}^{w,c\,\mathrm{or}\,b}$: Car or bus accessibility

$R^{c\,\mathrm{or}\,b}$: Number of car or bus route between a pair of sub-areas

N_i : Number of intersection in the origin sub-area

S : Number of employment opportunities in destination sub-area

D_{ij} : Number of potential departure times

F_{ij} : Total frequency of bus routes between sub-area

$t^{c\,\mathrm{or}\,b}$: Total travel time by car or bus between sub-area

α, β : Constants

Kim et al. (2019) used the ratio of transit travel time to car travel time as an indicator of equity. As a constraint for selecting areas with less equity than the entire network, a transit design was performed to minimize the total cost.

$$DOCO_j = \frac{\sum_j (\min t_{ij}^t - \min t_{ij}^a)}{\sum_j \min t_{ij}^a}, \quad TDOCO = \frac{\sum_{ij} (\min t_{ij}^t - \min t_{ij}^a)}{\sum_{ij} \min t_{ij}^a}$$

where,$t_{ij}^{t\,\mathrm{or}\,a}$: Travel time by transit or car from i to j

Camporeale et al. (2017) and Camporeale et al. (2019) applied demand weights to Delbosc and Currie (2011)'s service supply indicators to provide public transportation services to many users and used them as equity. A transit network design was conducted to minimize the total system cost using the equity index calculated using the Gini coefficient as a constraint. Delbosc and Currie (2010) fixed the service range of buses, trams, and railroads to 400m, 400m, and 800m. Evaluated the service level within each analysis unit, as shown in Figure 2.2. After calculating the service level, the equity measured by evaluating the degree of service provision compared to the cumulative population, as shown in Figure 2.3 below.

$$W.SI = (\sum_{N} \frac{Area_{Bn}}{Area_{CCD}} * SL_{bn}) * (100 - \frac{(\sum_{I} w_i x_i) * 100}{pop_D} + 1)$$

where, N: Number of work access buffer to stops in each CCD

B_n : Buffer for each stops, station in each CCD

SL: Service level(#bus, tram, train vehicle arrivals per week)

w_i: Weight assigned to each variable

x_i: Value of variable (adults without cars, persons aged over 65 years, persons with a disability pension, low-income households, students, etc.)

pop_D: Total population in the distric D

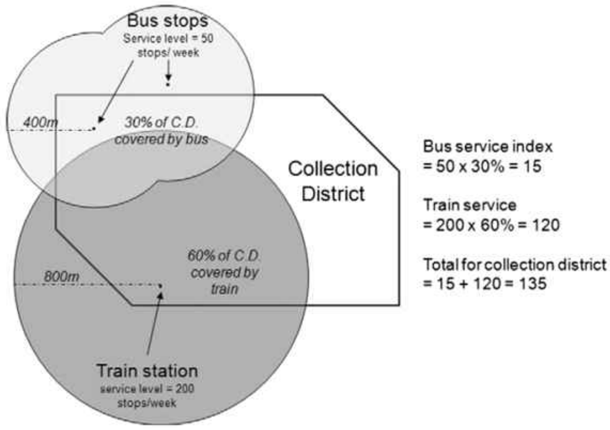


Figure 2.2 Supply Index

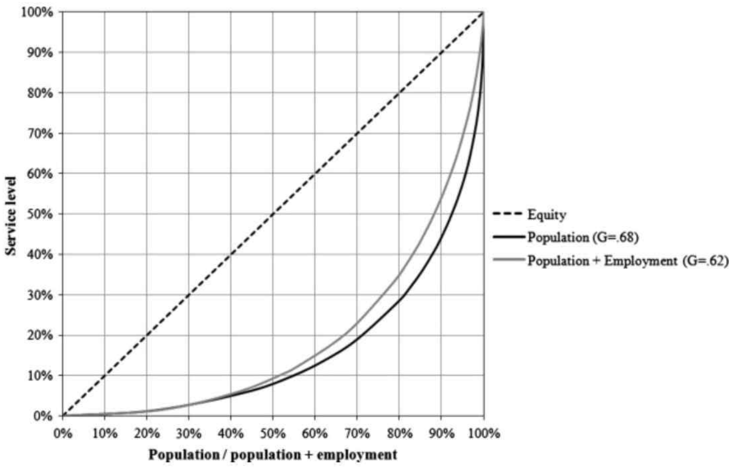


Figure 2.3 Equity Assessment

El-Geneidy et al.(2016) equity was defined through accessibility indicators based on specific needs such as job, school, and shopping. Regarding the specific demand, the number of jobs, schools, shopping malls, etc. that exist in other regions are regarded as opportunities and are applied when it is possible to arrive within a specific time from the departure area to the arrival area only.

$$A_{ij} = \sum_j o_j * f(C_{ij})$$

$$f(C_{ij}) = \begin{cases} 1 \text{ if } C_{ij} \le t_{ij} \\ 0 \text{ if } C_{ij} > t_{ij} \end{cases}$$

$where, o_j$: Number of jobs(opportunities) in zone j

$f(C_{ij})$: Weighting function

Akbarzadeh (2017) evaluated equity by counting the transit accessibility at each stop in units of traffic analysis zone (TAZ). Each stop's accessibility is calculated by operating time, line length, capacity, speed, and frequency combination of operated lines.

$$P_{l,n} = C_l * f_l * h_l * V_l * D_l$$

where, $P_{l,n}$: Connectivity power of station n brought about by a line l

C_l: Vehicle capacity of line l

f_l: Frequency of line l

h_l: Operation hours(1 day)

V_l: Speed

D_l: Number of stations

Jiang(2018) defined equity as the minimum traffic cost difference between before and after transit network improvement to users. The difference in total traffic cost and equity before and after network improvement is used as objective function.

The evaluation of equity using the Gini coefficient and the evaluation of equity using the difference in travel time before and after network improvement has limitations. It is impossible to grasp the level of service between each origin/destination and mode. Public transportation is an important means to have a competitive edge in a car-centered society. A car should be used as a standard to meet the basic level and convenience of traffic(Jhao., 2006; Ibeas et al., 2010; Ferguson et al., 2012; Jha et al., 2019), The level of service between origin/destination can be evaluated using the difference between the shortest travel time for cars and public transport(Zhao and Zeng, 2006). However, if only the total travel time in the network is minimized, the average traffic level can be improved, as shown in Figure 2.4(a). However, the deviation may increase in the future. Therefore, if both spatial and mode accessibility are considered simultaneously, the accessibility deviation can be effectively reduced, as shown in Figure2.4(b) (Martens et al., 2012).

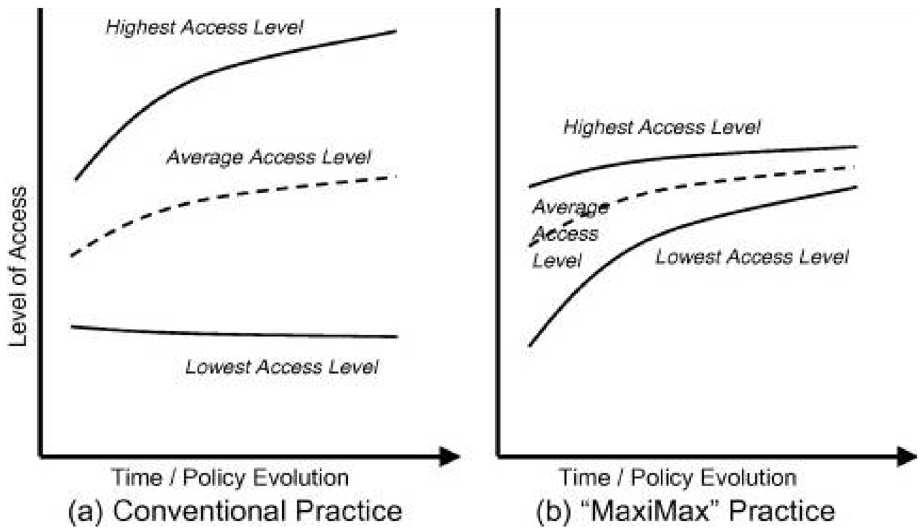


Figure 2.4 Comparing Access Level

Various studies have been conducted to apply equity to the transit network design from a spatial and mode perspective. In this study, intend to design by considering the equilibrium between spatial and mode simultaneously.

Table 2.4 Transit Network Design with Equity

Author	Object	Constraint	Def. Equity	Decision Variable	Algorithm
Fan and Machemehl. (2011)	Min. Operator Cost Min. User Cost Min. Unsatisfied Cost	Length, # of Route, Frequency, Spatial Equity	Travel Time Improvement Ratio	Route, Frequency	GA
Ferguson et al. (2012)	Min. Accessibility Gap	Budget	Differences between Car and Transit Accessibility	Route, Frequency	GA
Kim et al. (2019)	Min. Operator Cost Min. User Cost	Length, Frequency, Equity, Redundancy, Circuity	Degree of Competitiveness	Route, Frequency	GA
Camporeale et al. (2017)	Min. Social Cost	# of Route, Fleet Size, Equity, Demand Coverage	Service Index	Route	GA
Camporeale et al. (2019)	Min. Social Cost	# of Route, Fleet Size, Equity	Weighted Service Index	Route, Frequency	GA
Jiang. (2018)	Max. Minimum improvement in the Travel cost Max. Equity	Fleet size	Difference in travel time before and after improvement	Frequency	ABC

2.4 Algorithm

2.4.1 Multi-objective Optimization

During the design phase of public transportation in Step 5, the network design and frequency setting problems are NP-hard problems with a large search space, and optimization performed using a meta-heuristic solution. Meta-heuristic is most widely used for real-world problems with multiple purposes. They are divided into single solution-based methods such as Tabu search and Simulated Annealing, and population-based methods such as Genetic algorithm and Ant Bee Colony optimization.

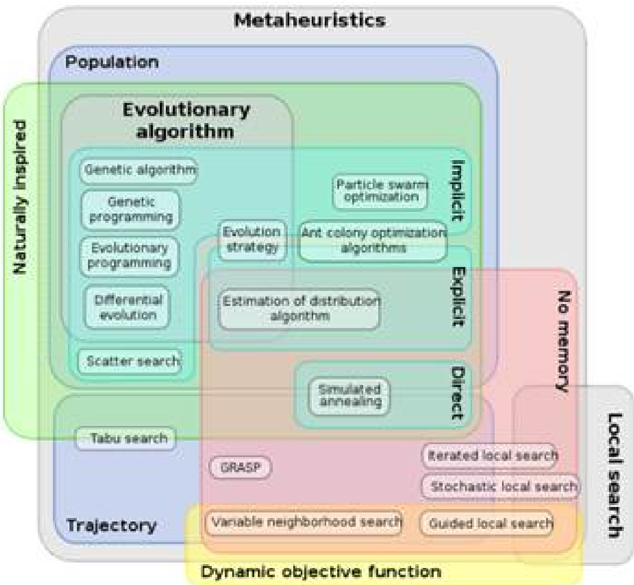


Figure 2.5 Metaheuristic Algorithm

Source: Beheshti, Z., Shamsuddin, S. M. H. (2013).

In complex problems such as TNDFSP, the single solution-based method is more likely to fall into the local optima, and the population-based method is known as a method closer to the real optima (Mauttone, and Urquhart., 2009; Arbex and Cunha, 2015; Buba and Lee) ., 2018; Nayeem et al., 2018; Mahdavi et al., 2019).
In the multi-objective study, there is two methods. One is a single objective function using weights, and the other is obtaining a Pareto Optimal Set in which solutions do not have an superiority over each other. The weight depends on the planners' judgment, and it is not easy to determine. Also, it is impossible to provide a variety of solutions to transport planners' because the relationship between each objective function cannot figure out(Zhao and Zeng, 2007; Fan and Machemehl, 2006a; Fan and Machemehl, 2006b; Fan and Machemehl., 2008, Owais et al., 2015). On the other hand, a method that can optimize multi-objective simultaneously without giving an superiority between objective functions get a Pareto Optimal Set with the same value. Pareto Optimal Solution is a solution that exists in the same Pareto Frontier. It is a non-dominated solution because it cannot improve the value of other targets without worsening the value of one or more of its object.

Table 2.5 Multi Object Optimization

Author	Object	Decision Variable	Algorithm	Single / Multi obj.
Won et al. (2006)	Min. Construction Cost Min, Peak-hour Traffic	Route	NSGA-II	M
Mauttone and Urquhart. (2009)	Min. User Cost Max. Operator Profit	Route and Frequency	GRASP	M
Sharma et al. (2009)	Min. Avg. Travel Time Min. Std. Travel Time	Route	NSGA-II	M
Fan et al. (2009)	Min. User Cost Min. Operator Cost	Route	SEAMO	M
Mumford. (2013)	Min. User Cost Min. Operator Cost	Route	SEAMO2	M
Chew et al. (2013)	Min. User Cost Min. Operator Cost	Route	GA	M
Cooper et al. (2014)	Min. Avg. Travel Time Min. Operator Cost	Route	Parallel GA	M
Arbex and Chunha. (2015)	Min. User Cost Min. Operator Cost	Route and Frequency	AOGA	M

Author	Object	Decision Variable	Algorithm	Single / Multi obj.
Duran et al.(2019)	Min. Total Travel Time Min. Emission	Route and Frequency	GA	M
Jha et al. (2019)	Min. User Cost Min. Operator Cost	Route and Frequency	GA	M
Mahdavi et al. (2019)	Min. User Cost Min. Operator Cost	Route and Frequency	GA	S
Owais et al. (2015)	Min. User Cost Min. Operator Cost	Route and Frequency	GA	S
Agrawal and Mathew. (2004)	Min. User Cost Min. Operator Cost	Route and Frequency	Parallel GA	S
Fan and Machemehl. (2006b)	Min. User Cost Min. Operator Cost Min. Demand Cost (No service Provided)	Route and Frequency	GA+SA	S
Hosapujari and Verma. (2013)	Min. User Cost Min. Operator Cost	Route and Frequency	GA	S
Roca-Riu et al. (2012)	Min. User Cost Min. Operator Cost	Route and Transfer Stop	TS	S

Author	Object	Decision Variable	Algorithm	Single / Multi obj.
Gallo et al. (2011)	Min. User Cost Min. Operator Cost Min. Car User Cost Min. External Cost	Frequency	Other	S
Yu et al. (2011)	Min. User Cost Min. Operator Cost	Frequency	TS	S
Kuan et al. (2006)	Min. User Cost Min. Operator Cost	Route and Frequency	ACO	S
Zhang et al. (2020)	Min. Direct Travel Cost Min. Transfer Travel Cost Min. Demand Cost (No service Provided)	Route and Frequency	ACA, GA	S

2.4.2 Local Search

Multi-objective optimization studies have solved the problem through meta-heuristic algorithms using genetic algorithms based on natural selection and evolution. A genetic algorithm is a method to find the optimal solution by evaluating genes generated through selection, crossing, and mutation by randomly generating a population in the initial. The TNDP study is a problem finding a combination of route and dispatch interval; it is possible to search for a solution using the Genetic Algorithm efficiently. Previous studies, however, have solved this problem by applying a variety of Local Search because they are not suitable for tuning into a solution close to optimal.

Zhao and Ubaka (2004) and Zhao and Zeng (2006) used neighborhood search using key nodes. Find the Key node(n_1,n_2,n_3) in the generated paths, as shown in Figure 3.7, and search for the adjacent node. Then, the shortest path is generated using the combination of the key node and the adjacent node.

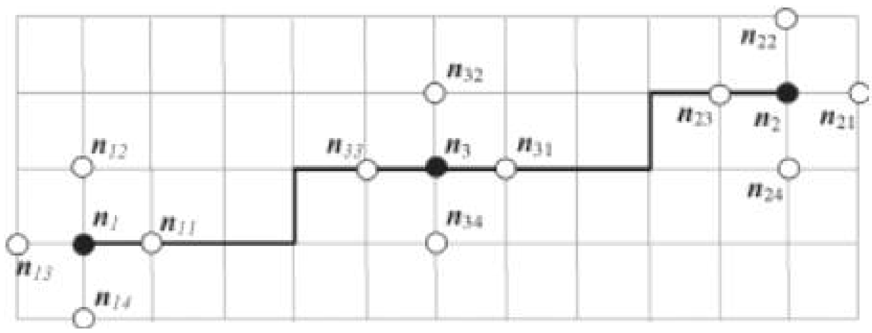


Figure 2.6 Three Key node Representation of Transit Route

Source: Zhao and Ubaka(2004)

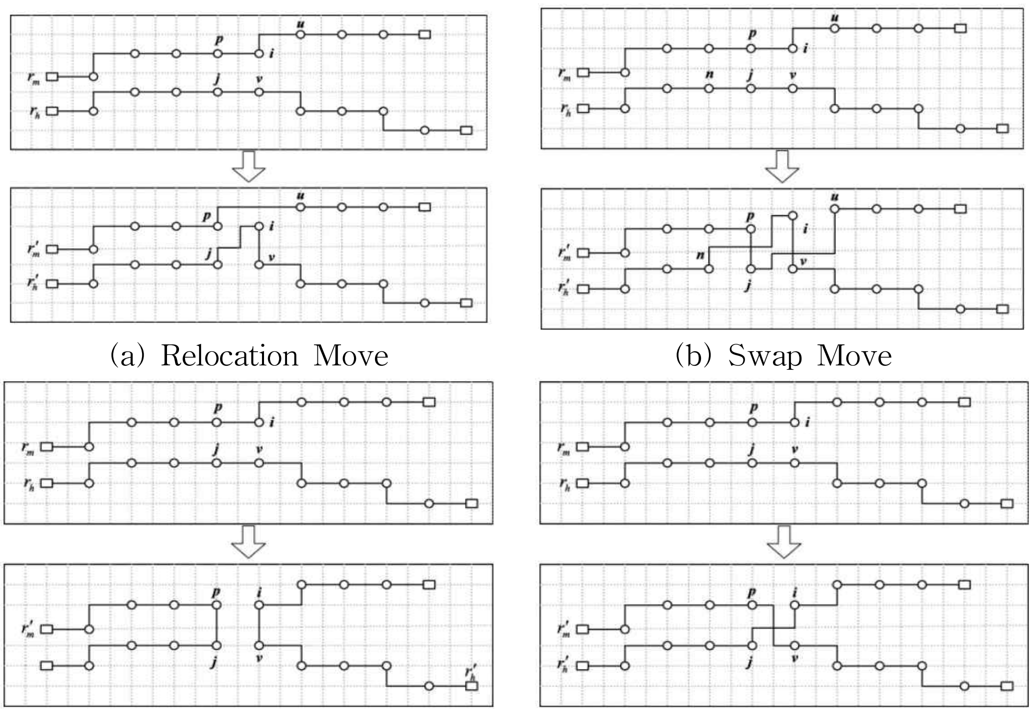
Fan et al. (2009) added a new node at the end of the generated route or deleted it at the starting point. Fan and Mumford (2010) improved the study of Fan et al. (2009) by exchanging the order of the first node and the last node if it is impossible to add nodes to the generated route.

Szeto and Wu (2011) defined the sum of the distances between two stops as the Hamming distance on one route. The method of controlling the diversity of genes was applied to improve the performance of the algorithm.

Zhao et al. (2015) used four local search methods: Relocation Move, Swap Move, and Opt-move (2 types). First, Relocation Move deletes any stops among the two routes, as shown in Figure 2.7(a), and connects the stops from other routes. Swap Move is similar to Relocation Move, but as shown in Figure 2.7(b), a random stop is selected on each route and exchanged with other routes to connect to the original route. In the previous two methods, one stop was exchanged between two routes, but the 2-opt Move method is divided into type A and type B by exchanging two stops. Remove two stops (random links) on each route, type A connects the beginning or end of the removed link on each route, as shown in Figure 2.7(c), and type B shows Figure 2.7(d). Similarly, the beginning and end of the removed link of each route are crossed and connected.

Dib et al. (2017) applied the method of changing to the shortest path, considering the weight of alternative paths to improve the initial solution.

In the previous study, for efficiency improvement, the solution, demand evaluation for all combinations of adjacent stops and, various operators were used. These methods can increase the calculation time, depending on the number of cases. Therefore, in this study, local search was performed using a mutation of some stops of offspring.



(a) Relocation Move (b) Swap Move

(c) 2-opt-type A (d) 2-opt-type B

Figure 2.7 Illustration of Local Search

Source: Zhao et al.(2015)

2.5 Summary and Research Direction

In this chapter, the index used in the existing transit network design studies and objective functions of operators, users, and the public sector is reviewed. The algorithm applied to multi-objective optimization and the Local Search Method for improving algorithm efficiency were reviewed.

Most of the studies used the operating revenue to consider route operating costs and income from the operator's perspective. However, due to limitations arising from the transit network design by applying only operational efficiency, it is intended to simultaneously consider unsatisfactory demand or equity in terms of users and the public.

As a result of reviewing previous studies, the user's objective function was generally set using the travel time. However, because travel time increases due to transfer, there is a tendency to avoid a transfer(Pternea et al., 2015; Buba and Lee., 2018). Therefore, the unmet demand, which can consider the convenience of the side and the user's travel time, was used for the objective function. Unmet demand has been evaluated according to various criteria by researchers, but in this study, reasonable transfer criteria were established based on actual trip data. In this study, based on the analysis of smart card data, the number of transfer determined to be one, and it is intended to calculate the unmet demand for more than one transfer request among the total transit demand.

In most cases, equity assessed the average level of traffic in terms of mode or space. To get competitiveness of transit in a car-centered society, and prevent future deviations in service level, evaluate the differences in service levels between mode and area is a need. Deviations in competitiveness of transit were defined as equity.

In the case of multi-object, as in this study, a method for deriving a single optimal solution is applied by applying weights between objectives. However, determining the weight is very difficult due to the complexity of the problem because it is determined by the planners' experience or point of view. Therefore, this study to apply the NSGA-II algorithm that satisfies several objectives simultaneously without superiority between objective functions. Also, a local search method was used to mutations some stops in the offspring to search for efficiency.

The optimal solutions that satisfy the operator, user, and public's objective functions at the same time using the algorithm introduced earlier are network composed of bus routes. The shortest path between stops is created based on the initial car travel time. When the transit network is created, it is applied and then modal split and recalculating the travel time, and evaluate the solution based on this. The travel time that is the basis for route creation does not change, and the initial travel time is used identically.

Chapter 3. Methodology

3.1 NSGA-II

NSGA-Ⅱ is an algorithm proposed by Deb(2000) and is a widely used method for multi-object optimization with efficient and high performance. NSGA-Ⅱ used the non-dominant ranking and the overcrowding distance to determine the fitness. Unlike the existing ranking method, the non-dominant method is ranked according to the dominance of the solution shown in Figure 3.1, even if it is in the same front. The overcrowding distance determines fitness with the same rank by calculating the density with adjacent solutions, and get a diversity of solutions through this process.

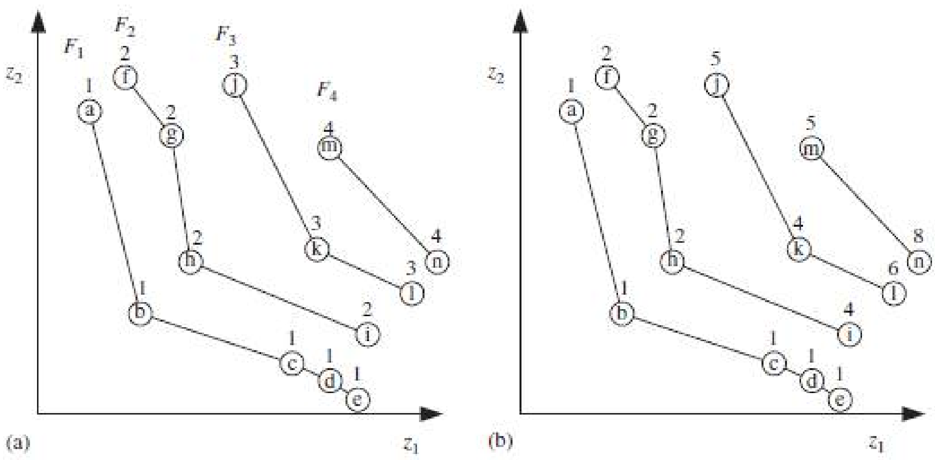


Figure 3.1 Ranking Method(Left: Existing, Right: NSGA-II)

Figure 3.2 shows the process of NSGA-II. First, a parent generation P_t of size N is created, and a child generation Q_t having the same size is generated through cross-over and mutation. By combining with P_t and Q_t make R_t of size 2N, the ranking is given. Solutions that receive the same ranking are re-ranked using the crowding distance method. The parent P_{t+1} of the (t+1) generation selects N solutions having the highest rank in R_t. At this time, if the size exceeds N when a specific rank is included, the crowding distance is calculated to exclude the low-ranking solutions, and finally, N are selected. This process is then repeated until the conditions are met.

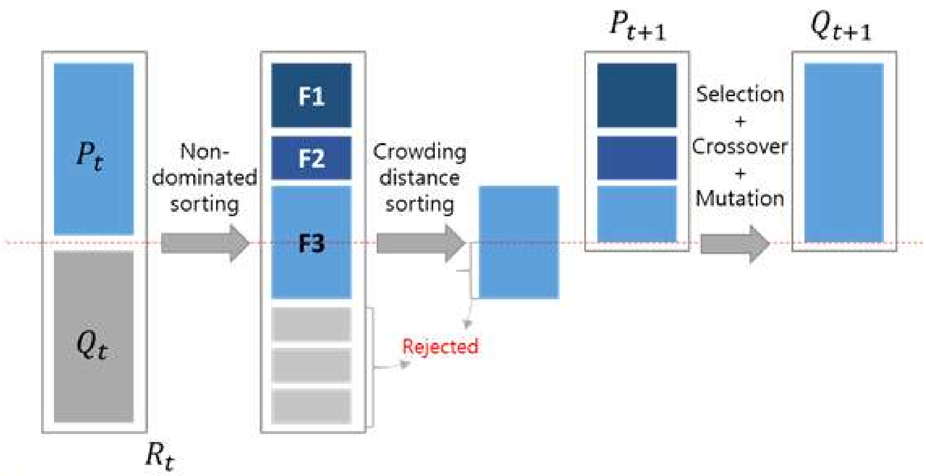


Figure 3.2 Procedure of NSGA-II

However, in the ranking process, the crowding distance is performed using the closest solution shown in Figure3.3. At this time, if the scale of the objective function is different, the influence of the objective function with a large scale increases because the Euclidean distance is used. Solving the scale problem between objective functions that do not have superiority can be solved using normalization between each objective function. Patel et al. (2011) and Liu and Chen (2019) improved the solution's diversity and efficiency through normalization of the adjacent solution. In this study, normalization was performed using the following formulation using the previous study method.(Deb et al., 2002; Yijie, and Gongzhang., 2008).

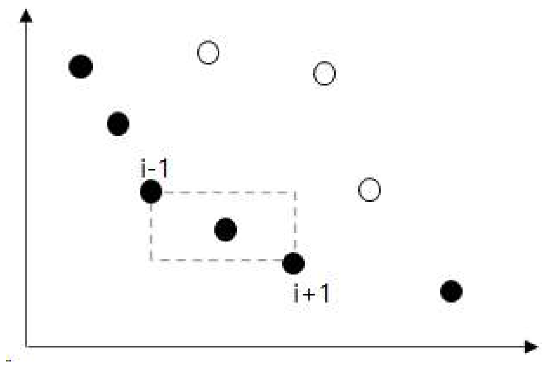


Figure 3.3 Crowding Distance

$f_m(x) = \frac{f_m(x) - f_{\min}}{f_{\max} - f_{\min}}$, where $f_m(x)$ is the normalize m^{th} value

3.2 Algorithm

3.2.1 Procedure and Network Encoding

This study performs data input, traffic assignment, network design and modal split, and network evaluation, as shown in Figure 3.4 to derive a solution set that satisfies the objectives of operators, users, and the public.

First, to input the toy network and traffic volume to make a travel time to be used for the modal split, the traffic assignment is performed. When creating a bus network, the shortest path based route is formed using the car travel time. After the bus network is created, a modal split performed by the logit model, and the car and the bus are assigned to the toy network. Evaluate the generated bus network according to the three objective functions, and repeat the process of creating and evaluating the bus network until the termination condition is satisfied.

Creating a procedure of the bus network is organized, as shown in Figure 3.5. First, a total of two or more lines consist of the bus network is determined. When the number of lines determined, to set the number of stops and frequencies of each line. The stops randomly select at least three stops candidates in the toy network and configure the routes in the order of the selected stops. If the extension of the generated route exceeds the maximum length, the stop is selected again. Suppose the generated route does not, the frequency is randomly assigned from 1 veh/hour to 6 veh/hour. When creating a bus network, the constraints that are applied include the number of stops, the total number of lines, and the line length.

In this study, each line must be input separately because solution candidates are consist of bus lines, as shown in Figure 3.6. It was consist of a nested list. As shown in Figure 3.7, the Nested List type is a large list of the bus network, and the line in the bus network is composed of individual lists and arranged. The lines in the list, the stops put in order, and the frequency setting after the last stop is entered. For example, in line 1 of Figure 3.6, the stops put 1-3-4-5 in order, as shown in the first list in Figure 3.7. If the frequency per hour is 4, 4 is entered after the last stop 5.

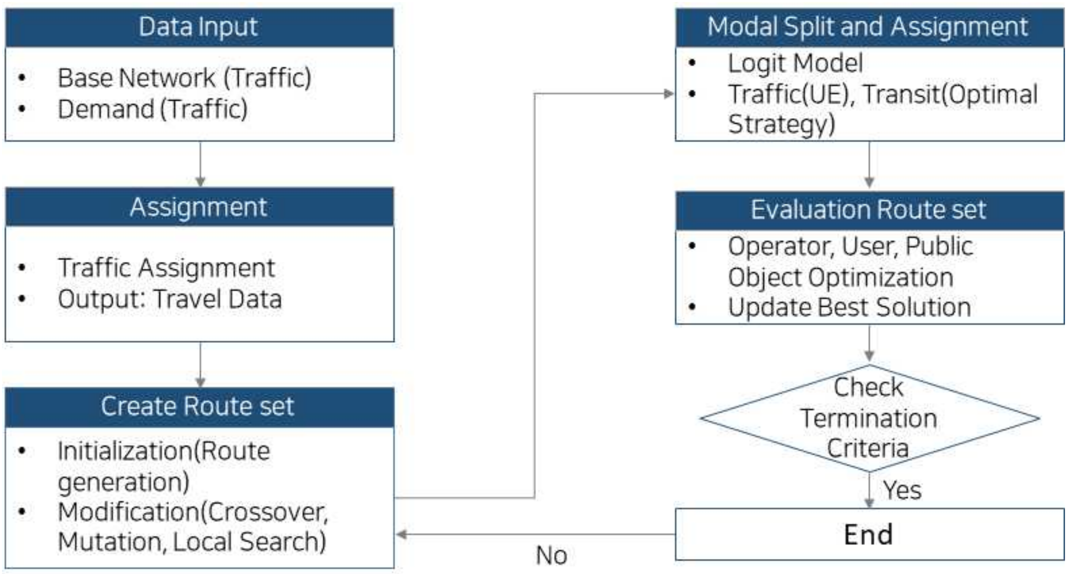


Figure 3.4 Procedure of Algorithm

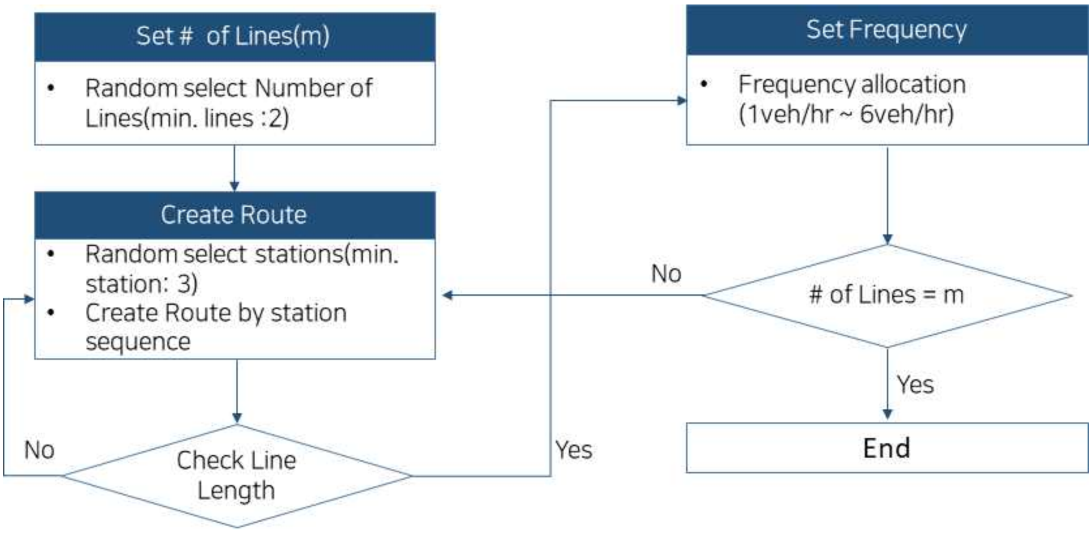


Figure 3.5 Create Bus Network

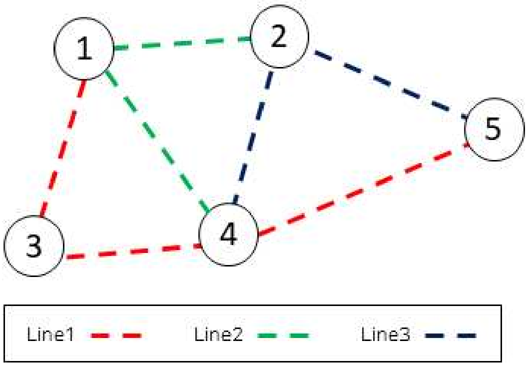


Figure 3.6 Example of Solution Candidate

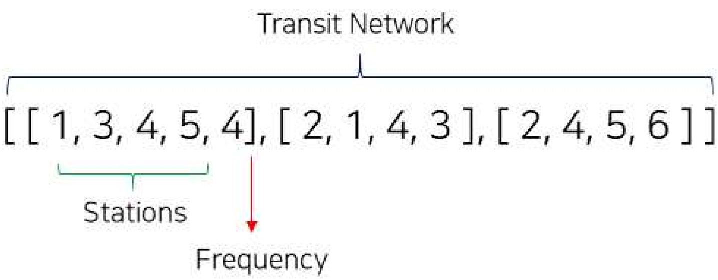


Figure 3.7 Example of Network Encoding

3.2.2 Cross-over and Mutation

In this study, the cross-over and mutation method of Jha et al (2019) was applied. Line Cross-over Operator applies one point cross-over to cross part of two lines in network based on random points as shown in Figure 3.8. If the number of lines after crossing does not satisfy the constraint, it is removed from Offspring. Station Cross-over Operator performs cross-over based on the same stop for any two lines, as shown in Figure 3.9. If there is no same stop, cross-over is performed based on a stop selected randomly. That is the same as Line Cross-over. If the lines do not satisfy the constraint after cross-over, it is removed from the Offspring. Line Mutation is changed by randomly selecting a line in the bus route network, as shown in Figure 3.10 using Random Resetting. In the previous study, the probability of cross-over is 0.8 to 0.9, and the probability of the mutation is 0.05 to 0.1 known to be appropriate. In this study, the probability of cross-over is 0.8, and the probability of mutation is 0.1 were used.

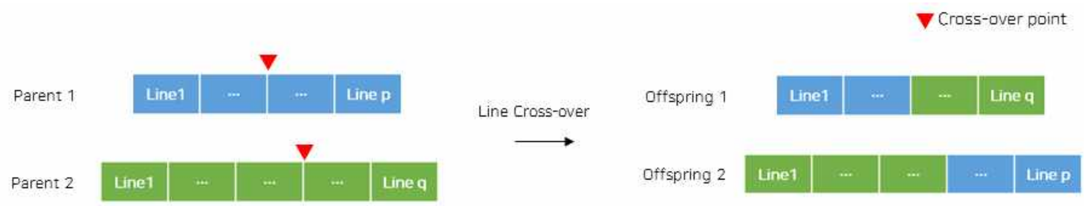


Figure 3.8 Illustration of Line Cross-over

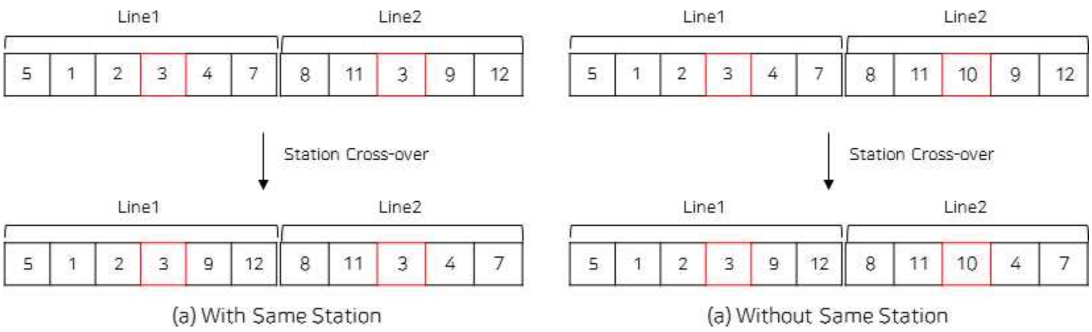


Figure 3.9 Illustration of Station Cross-over

Figure 3.10 Illustration of Line Mutation

3.2.3 Local search

Genetic Algorithm can efficiently find solutions when the range of solutions is complicated and extensive, but it is not suitable for searching for solutions that are close to optimal. Therefore, in this study, the method used in the studies of Zhao and Zeng. (2004) and Zhao and Ubaka. (2006) was used to efficiently search for solutions that are close to optimal through solution adjustment by local search. This study's local search is a cross-over the stops adjacent to each stop based on the stops existing line, as shown in Figure 3.11. In the previous study, line with the highest demand is selected based on all combinations of adjacent stops, but this only considers the profit. Therefore, mutation performed with a probability of 0.2 in this study because all combinations of stops cannot be searched. This is not performed when the newly created line does not satisfy the line length or the number of stop constraints.

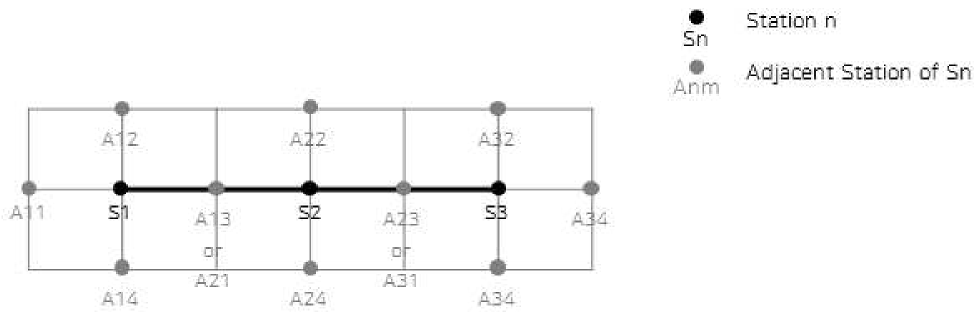


Figure 3.11 Illustration of Local Search

Chapter 4. Model Formulation

4.1 Summary

This study is a study of transit network design considering the three aspects: operator, user, and the public, to relive the urban congestion and improve service distribution according to changes in urban structure and traffic patterns. This is a TNDFSP problem that determines the bus network and frequency of lines in the network that satisfy the objective function as decision variables.

The objective function of this study is to maximize profit, minimize unmet demand, and maximize equity between areas and modes. The purpose of the operator is to maximize the total profit, excluding operating expenses from operating income in the transit network design study, generally. Here, the operating cost is determined by the total length and the number of lines. The unmet demand is to minimize unmet demand by treating one or more transfers as satisfactory for up to one transfer or less. In the case of equity between regions and Sudan, the goal is to minimize the difference in the shortest travel time between public transportation and cars at each origin and destination.

Transit demand is variable because it depends on transit networks and frequency(Pternea et al., 2015). Therefore, modal split and network evaluation are performed considering the travel time by transit network that satisfies the objective function.

4.2 Assumption and Variables

This study is a problem of optimizing transit network and frequency that can maximize profit, minimize unmet demand, and maximize equity between area and mode. Since TNDFSP is a feasible region is a non-convex as an NP-hard problem, it is tough to find an optimal solution. Because there are limitations in considering all situations, research is conducted based on appropriate assumptions. Also, the description of the variables used in this study is as follows.

<u>General Assumption</u>

- Demand is symmetric
- modes have two, buses and cars only
- Any Node can be a stop
- Buses are affected by road conditions

<u>User side Assumption</u>

- The total volume is preserved, but the distribution rate of each modes varies depending on the road and public transportation assignment results.
- The travel time of transit consists of access time, in-vehicle time, waiting time, and transfer penalty.
- The passenger arriving at the stop assumes a random and uniform distribution, so the waiting time of the passenger is 1/2 of the headway.

Objective Function Variables

f^k : Frequency of Line k

h : Headway(min)

l^k : Length of line k

l_{max} : Maximum Length of Line k

f_{min} : Minimum Frequency

f_{max} : Maximum Frequency

d_{ij}^t: Transit Demand from i to j

tf_{ij}^0: Direct Transit Demand from i to j

tf_{ij}^1: Transit Demand with transfer once from i to j

$\min t_{ij}^{a \text{ or } t}$: Minimum travel time from i to j Using Car or Transit

$t_{ij}^{a \text{ or } t}$: Travel time from i to j Using Car or Transit

n_i : Number of Origin Zone

n_j : Number of Destination Zone

o : Operation Cost (Won/km)

β : Transit Fare(Won)

$P(m)$:Probability of selection mode m

U_k :Utility of mode k

n :Number of modes

$U_{ij,m}$:Utility of mode m from origin to destination

$TT_{ij,m}$: Total travel time of mode m from origin to destination

$TC_{ij,m}$: Total travel cost of mode m from origin to destination

D_m : Dummy variable

C_m : Coefficient of utility function

α_1, α_2 : Parameters

Logit Model and Assignment Variables

$\overline{q_{od}}$: Car volume from origin to destination

$\widehat{q_{od}}$: Transit volume from origin to destination

q_{od}: Total volume from origin to destination

$\overline{t_{od}}$: Minimum path time of car between origin and destination

$\widehat{t_{od}}$: Minimum path time of transit between origin and destination

$\overline{c_{od}}$: Minimum path cost of car between origin and destination

$\widehat{c_{od}}$: Minimum path cost of transit between origin and destination

α_1: Travel time parameter for utility function

α_2: Travel cost parameter for utility function

U_m :Utility of mode m

TT_{ij} :Total travel time from origin to destination

TC_{ij} :Total travel cost from origin to destination

$\hat{D}$: Transit dummy variable

l_a: Length of link a

$\overline{v_a}$: Free flow speed on link a

α, β: Parameter for BPR function

x_a :Volume on link a

c_a :Capacity on link a

$v_{ij,r}$:Volume from origin to destination using path r

$\delta^a_{ij,r}$: If path r include link a 1, otherwise 0

A : Link set

I: Node set

A_i^+: Outbound link set at node i

A_i^- : Inbound link set at node i

g_i : Transit volume from node i

x_a^t : Transit volume on link a

t_a^t : Transit time on link a

f_a : Frequency on link a

w_i : Waiting time on node i

4.3 Model Formulation

4.3.1 Objective Function

The purpose of this study is to make a bus network and set the frequency of each line to maximize profit, minimize unmet demand, and maximize equity, which can balance with stakeholders (operator, user, and public).

Objective 1

$$Max.\ \beta\sum_{ij} d_{ij}^{t} - o\sum_{k} *(\frac{60}{h})*l_k \tag{1}$$

Objective 2

$$Min \sum_{ij} d_{ij}^{t} - tf_{ij}^{0} - tf_{ij}^{1} \tag{2}$$

Objective 3

$$Min \sqrt{\frac{\sum_{ij}(E_{ij} - \overline{E})^2}{n_i * n_j}} \tag{3}$$

subject to

$$f_{\min} \leq f^k \leq f_{\max}$$

$$l^k \leq l_{\max}$$

$$h = \frac{60}{f}$$

$$E_{ij} = \frac{\mathrm{min}t_{ij}^{t} - \mathrm{min}t_{ij}^{a}}{\mathrm{min}t_{ij}^{a}} \quad (\text{if } \mathrm{min}t_{ij}^{t} - \mathrm{min}t_{ij}^{a} < 0,\ E_{ij} = 1)$$

The profit is the total operating profit minus the total operating cost. The operating cost consists of the total length and the fleet size, and the operating cost per km was based on the standard transportation cost of Seoul as of 2016. At this time, length constraint applied so that excessive circuity did not occur, and the minimum and maximum frequency per hour were set to 1 to 6 units. When calculating profit, the bus fare based on the metropolitan area was applied to the public transportation fare. Transfer means the inconvenience of service for transit users, to efficient network design can make a trip with less transfer and increase modal split of transit(Zhao and Zeng, 2006; Yan; et al., 2013; Nikolić and Teodorović, 2013; Szeto and Jiang, 2014). Using smart card data in south Korea to define the unmet demand, and two or more transfers was defined as the unmet demand. As shown in Equation (2), the unmet demand was calculated as the total transit demand, excluding transit demand without or with one transfer.

Public transportation is to provide mobility to everyone, and the distribution of services is important. However, considering efficiency (cost and transfer), services are concentrated in a specific area, and the service gap between areas increases.

Previous studies have used differences in travel time between modes, the level of service, and the improvement of travel time for evaluating equity (Barbati. 2012; Camporeale et al., 2017).

However, in a car-centered society, comparing only the level of service in transit can not improve the mode competitiveness, so it is possible to assess regional accessibility using the difference in travel time between modes (Ferguson et al., 2012; Zhao and Zeng., 2006). Therefore, this study aims to minimize the differences in regional competitiveness of public transportation, which can be expressed as Equation (3).

4.3.2 Logit Model

The logit model with the travel behavior of users was used in this study. The following equation calculates the probability of selecting the mode k. The utility function of each mode used in the logit model is calculated by the travel time and travel cost. The parameters are based on data from the metropolitan area based on 2016.

$$P(k) = \frac{\exp(U_k)}{\sum_{k=1}^{n} \exp(U_k)}$$

where, $P(k)$:Probability of selection mode k

U_k :Utility of mode k

n :Number of modes

$$U_{ij,m} = \alpha_1 * TT_{ij,m} + \alpha_2 * TC_{ij,m} + D_m + C_m$$

where, $U_{ij,m}$:Utility of mode m from origin to destination

$TT_{ij,m}$: Total travel time of mode m from origin to destination

$TC_{ij,m}$: Total travel cost of mode m from origin to destination

D_m : Dummy variable

C_m : Coefficient of utility function

α_1, α_2 : Parameters

The utility function is consist of travel time, travel cost, and dummy variables with modes characteristics. The parameter shows a negative value because the utility function decreases with increasing travel time and travel costs. The total travel time is based on the shortest path, the travel cost of transit consists of the fare according to the travel distance, and travel cost of the car is calculated as the fuel cost. The traffic volume by the logit model is as follows.

$$\overline{q_{od}} = \frac{q_{od}}{(1+\exp(\alpha_1(\overline{t_{od}} - \widehat{t_{od}})) + \alpha_2(\overline{c_{od}} - \widehat{c_{od}})) + \widehat{D}}$$

$$\widehat{q_{od}} = q_{od} - \overline{q_{od}}$$

where, $\overline{q_{od}}$: Car volume from origin to destination

$\widehat{q_{od}}$: Transit volume from origin to destination

q_{od}: Total volume from origin to destination

$\overline{t_{od}}$: Minimum path time of car between origin and destination

$\widehat{t_{od}}$: Minimum path time of transit between origin and destination

$\overline{c_{od}}$: Minimum path cost of car between origin and destination

$\widehat{c_{od}}$: Minimum path cost of transit between origin and destination

α_1: Travel time parameter for utility function

α_2: Travel cost parameter for utility function

$\hat{D}$: Transit dummy variable

4.3.3 Traffic Assignment

User equilibrium is based on Wardrop's first principle, which is user change the route for reduced travel cost. There is no more changes because user's choice will not get the benefit when equilibrium state. The travel time for all routes actually used are equal, and less than those which would be experienced by a single vehicle on any unused route. Equilibrium problem is to find the link volume that satisfies the user equilibrium conditions when OD are assigned properly. It is mathematically expressed as follow.

$$Min\, z(x) = \sum_a \int_0^{x_a} c_{a(w)} dw$$

$$s.t\ \ x_a = \sum_i \sum_j \sum_r v_{ijr} * \delta^a_{ijr}$$
$$\sum_r v_{ij,r}$$
$$v_{ij,r} \geq 0$$

where, $c_{a(w)}$:Cost of link a with link volume w

x_a :Volume on link a

c_a :Capacity on link a

$v_{ij,r}$:Volume from origin to destination using path r

$\delta^{a}_{ij,r}$: If path r include link a 1, otherwise 0

The travel time for each link is calculated by BPR function as follow.

$$t_a(x_a) = \frac{l_a}{\overline{v_a}}[1+\alpha(\frac{x_a}{c_a})^{\beta}]$$

where, l_a: Length of link a

$\overline{v_a}$: Free flow speed on link a

α,β: Parameter for BPR function

x_a : Volume on link a

c_a : Capacity on link a

The objective function and constraint of vehicle assignment based on user equilibrium is as follows.

$$Min\, z(x_a) = \sum_a \int_0^{x_a} t_a(w)dw$$

$$\text{subject to. } x_a = \sum_i \sum_j \sum_r v_{ijr} * \delta^{a}_{ijr}$$

$$\sum_r v_{ij,\,r} = \overline{q_{od}}$$

$$v_{ij,\,r} \geq 0$$

where, $v_{ij,\,r}$:Volume from origin to destination using path r

$\delta^{a}_{ij,r}$: If path r include link a 1, otherwise 0

$\overline{q_{od}}$: Car volume from origin to destination

4.3.4 Transit Assignment

The optimal strategy(Spiess and Florian ,1989) is used for transit assignment in this study. The optimal strategy is set of rules for users to reach the destination and minimizes the expected total travel time including waiting time. The type and number of strategies depends on the information that users can use during the trip. If there is no additional information during the trip, strategy defines a path simply. Figure 4.1 show a example of optimal strategy from A to B.

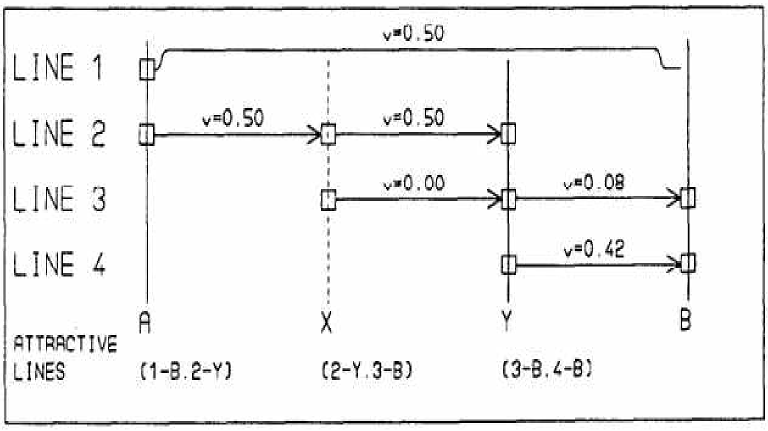


Figure 4.1 Optimal strategy(From A to B).

source: Spiess and Florian ,1989

- If no more additional information during the trip, take line 2 to node Y and transfer to line 3.
- If user know the next line to be served while waiting on the node, if line 1 was taken exit at B; if line 2 was taken, transfer at Y node and take line 3 or 4 then exit B.

- If more information available to users, such as waiting time, arrival time or seen out of the vehicle window, the complex the strategies may become; Wait for line 1 for 5 minutes, take line 2 otherwise; if user find line 3(express bus) at node X then transfer line 3; otherwise continue to node Y and transfer there to line 3 or 4.

The strategy considered only second example of the previous case. They assume that the user can get information which line will be served next only while waiting at the node during the trip. This strategy is feasible if the route of the strategy does not contain cycles and minimizes total travel time. Transit trips consists of that may include some or all of the following:

0. Set NODE to origin node.
1. Board vehicle that arrives first among the vehicles of the set of attractive lines at NODE.
2. Alight at the predetermined node.
3. If not yet at destination, set NODE to current node and return to step 1. Otherwise the trip is completed.

Transit trip consist of access and egress to the stop, boarding and alighting time, waiting time. The object function and constraints in the optimal strategy are as follow.

$$Min \sum_{a} x_a^t t_a^t + \sum_{i} w_i$$

$$\text{subject to. } \sum_{a \in A_i^+} x_a^t - \sum_{a \in A_i^-} x_a^t = g_i$$
$$x_a^t \le f_a w_i$$
$$x_a^t \ge 0$$

where, A : Link set

I: Node set

A_i^+ : Outbound link set at node i

A_i^- : Inbound link set at node i

g_i : Transit volume from node i

x_a^t : Transit volume on link a

t_a^t : Transit time on link a

f_a : Frequency on link a

w_i : Waiting time on node I

Transit assignment by optimal strategy assume that it is reasonable to board the first arriving vehicle on the route in strategy sets. It is need to consider the number of vehicles required for route after final assignment, because of this strategy does not care about the capacity.

Chapter 5. Numerical Example

5.1 Toy Network

5.1.1 Network Explanation

Because the transit network design depends on the network topology and traffic pattern(Chien et al. 2001), do experiment by using a grid network and a radial circular network representing the city, and these have different characteristics. As shown in Figure 5.1, the Central Business District(CBD) assumed the center of the city. The city is separated into CBD and Non-CBD. Demand pattern classified 7 types, and the ratio of demand per unit area in the CBD compared to Non-CBD is -90%, -60%, -30%, 0%(uniform distribution), 30%, 60%, 90%. For the convenience of analysis, the area of the zone in each network is configured identically.

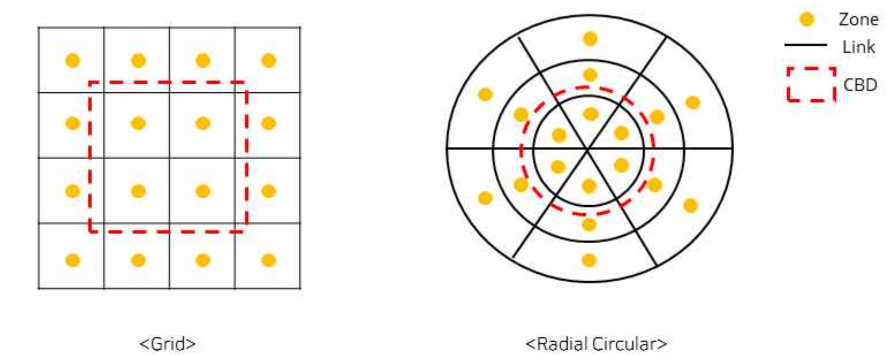


Figure 5.1 Classification topology

Generally, the grid network has high accessibility between internal areas and high competitiveness among alternative routes. The grid network in this study consists of 16 Zones, 65 Nodes, and 160 Links, with a total traffic volume is 80,000 trips/day. The radial circular network have highest accessibility to the CBD and relatively low connectivity between other areas Non-CBD. It consists of 18 Zones, 55 Nodes, and 144 Links, with a total traffic volume of 90,000 trips/day. Table 5.1 summarizes the composition of networks by topology and the actual cities with each network type.

Table 5.1 Summary of Network

Network	Detail of Network			
	Number of Zones	Number of Links	Trip (trip/day)	Actual City
Grid	16	65	80,000	Newyork, Barcelona Gangnam
Radial Circular	18	55	90,000	Beijing, Paris, Moscow

Tables 5.2 and 5.3 show that the CBD demand is 90% lower than the Non CBD in the grid network and the radial circular network. As an example of a grid network, it can be seen that the total traffic volume of each zone in CBD is 645 trip, and the total traffic volume of each zone in Non-CBD is 6452 trip. The traffic volume was constructed according to the ratio of CBD demand compared to Non-CBD. The remaining OD Matrix is included in the appendix.

Table 5.2 O/D Matrix(Grid, CBD Demand: -90%)

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.0	570.9	570.9	570.9	570.9	43.0	43.0	570.9	570.9	43.0	43.0	570.9	570.9	570.9	570.9	570.9
2	570.9	0.0	570.9	570.9	570.9	43.0	43.0	570.9	570.9	43.0	43.0	570.9	570.9	570.9	570.9	570.9
3	570.9	570.9	0.0	570.9	570.9	43.0	43.0	570.9	570.9	43.0	43.0	570.9	570.9	570.9	570.9	570.9
4	570.9	570.9	570.9	0.0	570.9	43.0	43.0	570.9	570.9	43.0	43.0	570.9	570.9	570.9	570.9	570.9
5	570.9	570.9	570.9	570.9	0.0	43.0	43.0	570.9	570.9	43.0	43.0	570.9	570.9	570.9	570.9	570.9
6	43.0	43.0	43.0	43.0	43.0	0.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0
7	43.0	43.0	43.0	43.0	43.0	43.0	0.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0
8	570.9	570.9	570.9	570.9	570.9	43.0	43.0	0.0	570.9	43.0	43.0	570.9	570.9	570.9	570.9	570.9
9	570.9	570.9	570.9	570.9	570.9	43.0	43.0	570.9	0.0	43.0	43.0	570.9	570.9	570.9	570.9	570.9
10	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	0.0	43.0	43.0	43.0	43.0	43.0	43.0
11	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	0.0	43.0	43.0	43.0	43.0	43.0
12	570.9	570.9	570.9	570.9	570.9	43.0	43.0	570.9	570.9	43.0	43.0	0.0	570.9	570.9	570.9	570.9
13	570.9	570.9	570.9	570.9	570.9	43.0	43.0	570.9	570.9	43.0	43.0	570.9	0.0	570.9	570.9	570.9
14	570.9	570.9	570.9	570.9	570.9	43.0	43.0	570.9	570.9	43.0	43.0	570.9	570.9	0.0	570.9	570.9
15	570.9	570.9	570.9	570.9	570.9	43.0	43.0	570.9	570.9	43.0	43.0	570.9	570.9	570.9	0.0	570.9
16	570.9	570.9	570.9	570.9	570.9	43.0	43.0	570.9	570.9	43.0	43.0	570.9	570.9	570.9	570.9	0.0

Table 5.3 O/D Matrix(Radial Circular, CBD Demand: -90%)

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0
2	42.0	0.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0
3	42.0	42.0	0.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0
4	42.0	42.0	42.0	0.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0
5	42.0	42.0	42.0	42.0	0.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0
6	42.0	42.0	42.0	42.0	42.0	0.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0
7	42.0	42.0	42.0	42.0	42.0	42.0	0.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4
8	42.0	42.0	42.0	42.0	42.0	42.0	626.4	0.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4
9	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	0.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4
10	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	0.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4
11	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	626.4	0.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4
12	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	626.4	626.4	0.0	626.4	626.4	626.4	626.4	626.4	626.4
13	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	626.4	626.4	626.4	0.0	626.4	626.4	626.4	626.4	626.4
14	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	0.0	626.4	626.4	626.4	626.4
15	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	0.0	626.4	626.4	626.4
16	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	0.0	626.4	626.4
17	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	0.0	626.4
18	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	0.0

In this study, Using EMME4/API for the toy network analysis according to the CBD demand ratio. The basic settings (including constraints) and parameters of the algorithm are as follows.

<u>Basic Analysis Settings</u>

- Maximum car speed is 60km/h
- Travel time to all modes affected by road condition
- Maximum bus length is 30km(round trip)
- Maximum number of lines is 20
- Minimum number of stops 3 in each line and Maximum number of lines is 12

<u>Parameter Settings</u>

- Population = 50, Generation = 50
- Cross-over = 0.8, Mutation = 0.1

5.1.2 Result Analysis

In this section, the optimal network characteristics to each index and changes of index by its increase or decrease analyzed. The results are listed in a table in the appendix.

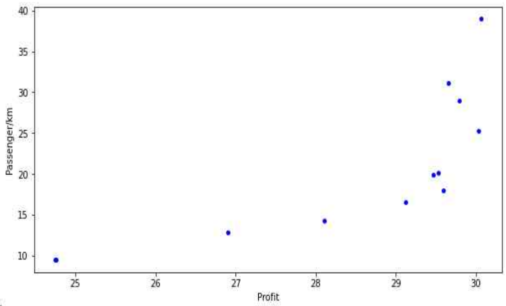
Optimal network by Index

First, analyzed the optimal transit network according to each objective function(profit, unmet demand, and equity). The detailed results of the optimal transit network for each index are listed in the appendix. As shown in Figure 5.2 and 5.3, the high-profit network has a high number of passengers per km. The operating cost increases with the line length. It is analyzed that the number of users is relatively high compared to the operating cost the line, and thus the profit increases.
As for the transit network with low unmet demand, the deviation of the number of lines per link is high, as shown in Figure 5.4 and Figure 5.5 below. Analyzed that a route network in which lines are gathered in a specific area can reduce unmet demand because it can be transferred at a specific area to diverse lines. However, in some cases, there is a transit network with a low deviation in the number of lines per link, even though the unmet demand is low, analyzed to provide only minimal services in some areas. That is, the lower the unmet demand has a higher deviation of the number of lines per link when the number of lines is similar.

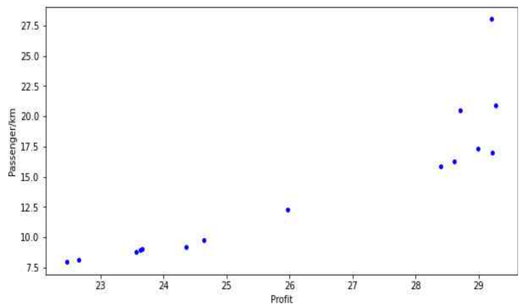
Figure 5.6 and 5.7 found that the transit network with various lines and high service frequency has the best equity. The level of service in transit should be similar to cars for the same origin and destination. It is analyzed that the transit network can get transit competitiveness in the entire network by providing services at high frequency.

The optimal transit network in each sector of operator, user, and public has the following characteristics. This showed consistent characteristics regardless of the network topology and the demand ratio in the CBD.

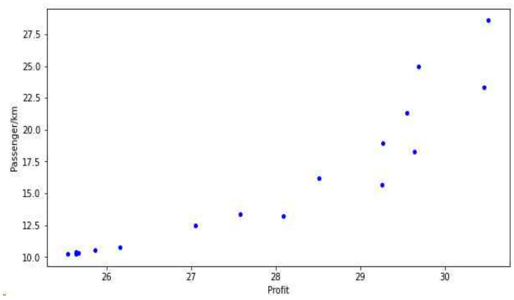
- Operator: Transit network with a higher number of users compared to line length
- User: A transit network with a high number of lines per link in a way that transfers to diverse lines in a specific area
- Public: Transit network that can move between multiple regions with various lines and high service frequency



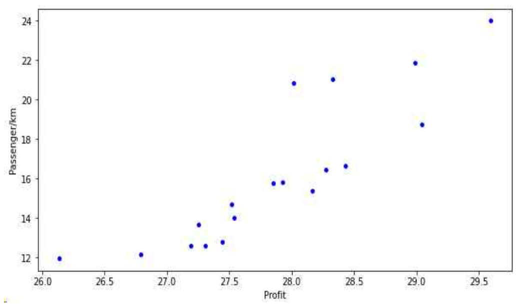
(a) Demand ratio of CBD : -90%



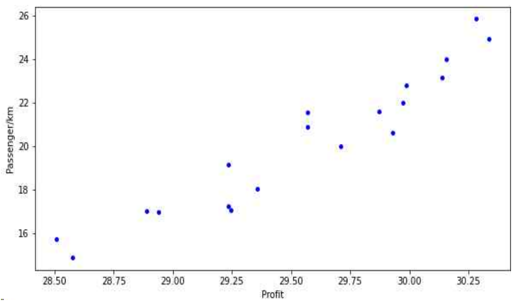
(b) Demand ratio of CBD : -60%



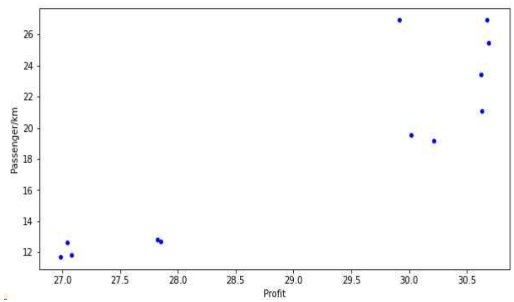
(c) Demand ratio of CBD : -30%



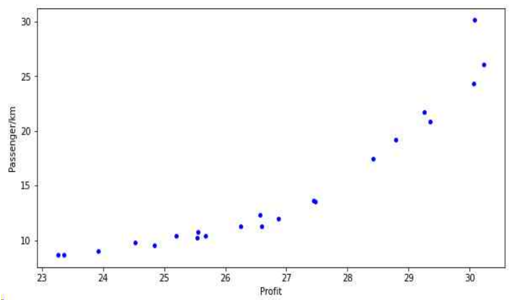
(d) Demand ratio of CBD : 0%



(e) Demand ratio of CBD : 30%

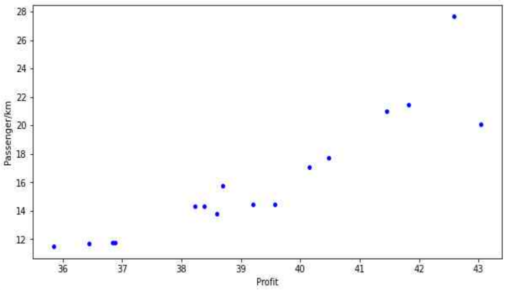


(f) Demand ratio of CBD : 60%

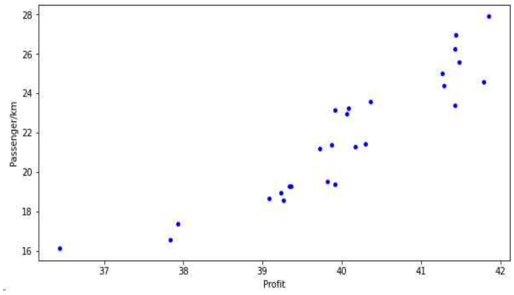


(g) Demand ratio of CBD : 90%

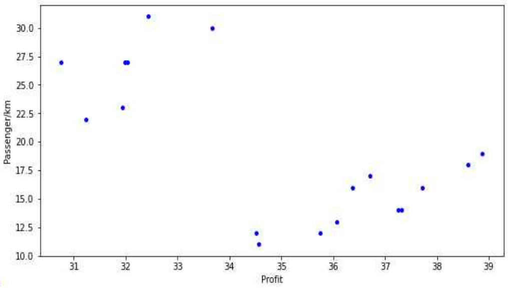
Figure 5.2 Passengers per Line Length by profit
(Grid Network)



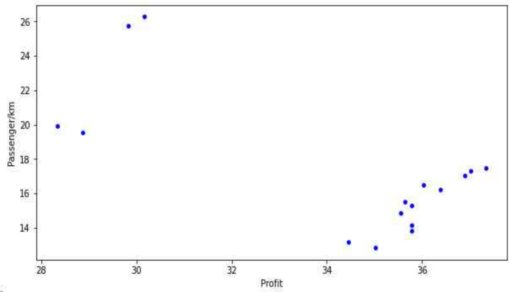
(a) Demand ratio of CBD : -90%



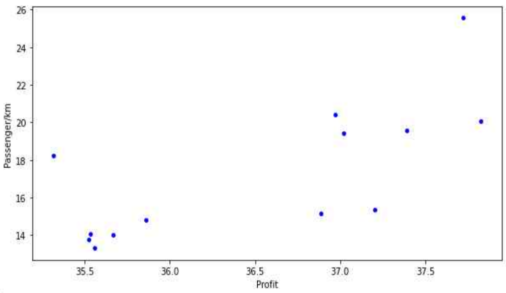
(b) Demand ratio of CBD : -60%



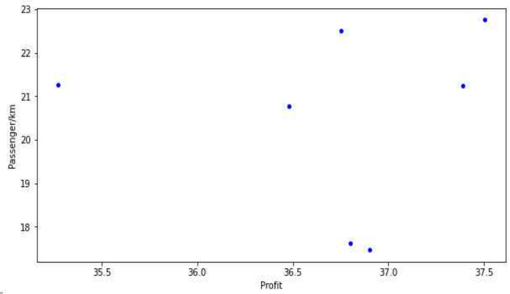
(c) Demand ratio of CBD : -30%



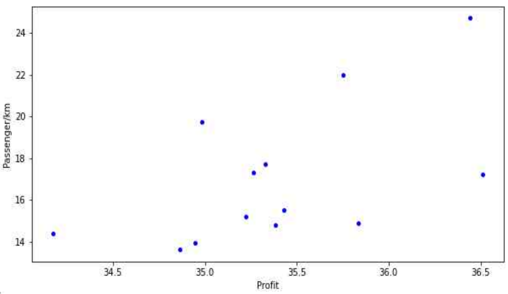
(d) Demand ratio of CBD : 0%



(e) Demand ratio of CBD : 30%

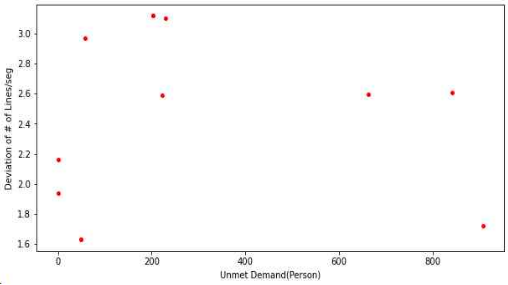


(f) Demand ratio of CBD : 60%

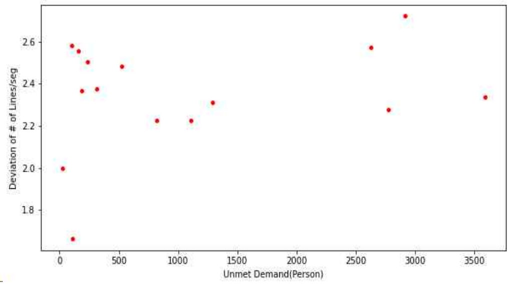


(g) Demand ratio of CBD : 90%

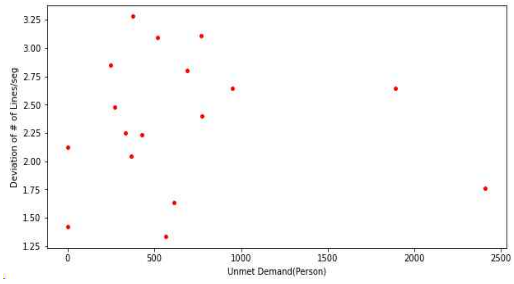
Figure 5.3 Passengers per Line Length by profit
(Radial Circular Network)



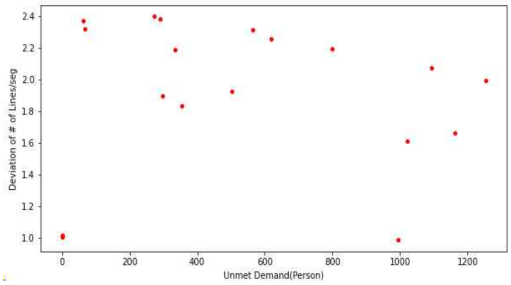
(a) Demand ratio of CBD : -90%



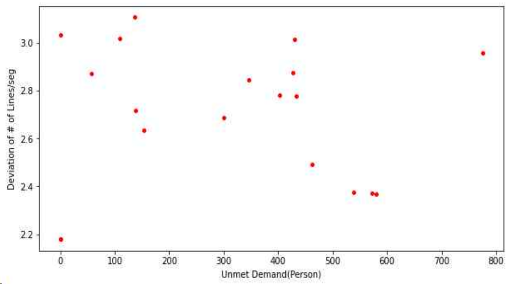
(b) Demand ratio of CBD : -60%



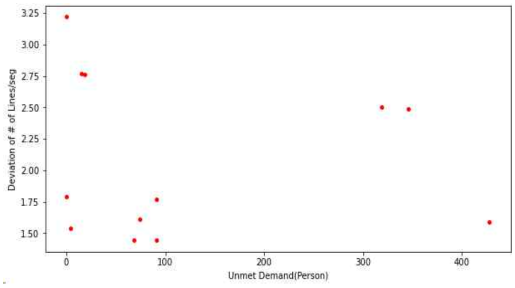
(c) Demand ratio of CBD : -30%



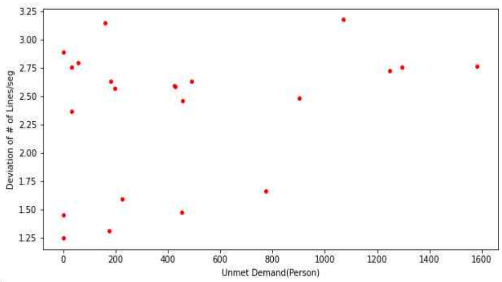
(d) Demand ratio of CBD : 0%



(e) Demand ratio of CBD : 30%

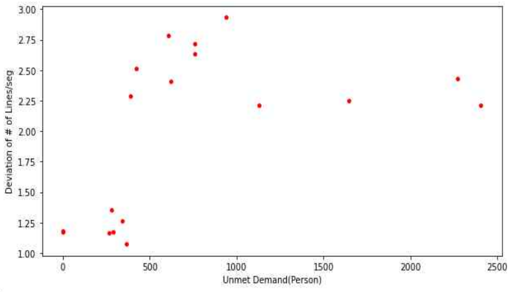


(f) Demand ratio of CBD : 60%

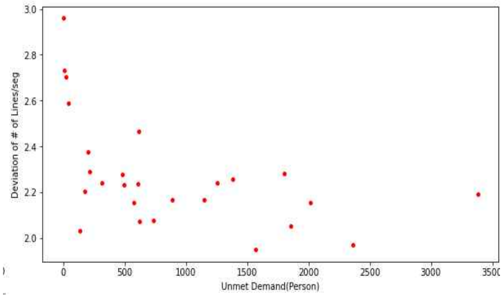


(g) Demand ratio of CBD : 90%

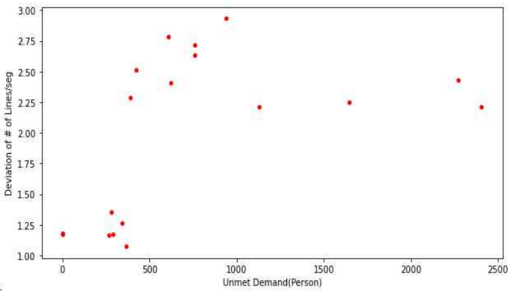
Figure 5.4 Deviation of Number of Lines per Link by Unmet Demand (Grid Network)



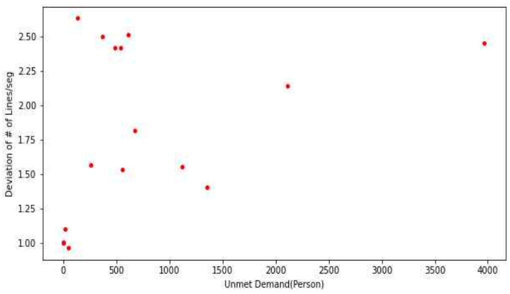
(a) Demand ratio of CBD : -90%



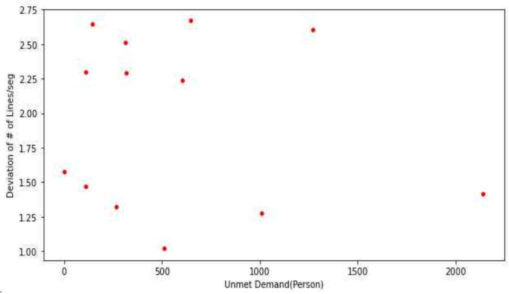
(b) Demand ratio of CBD : -60%



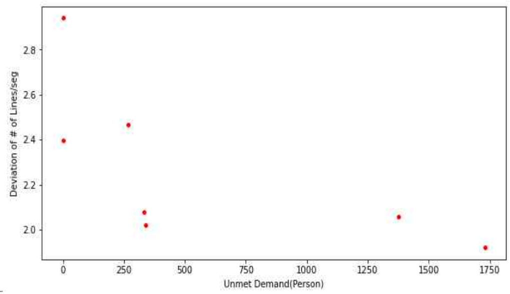
(c) Demand ratio of CBD : -30%



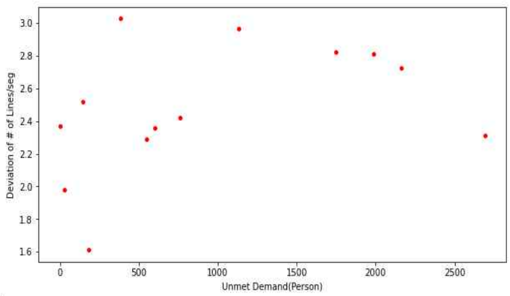
(d) Demand ratio of CBD : 0%



(e) Demand ratio of CBD : 30%

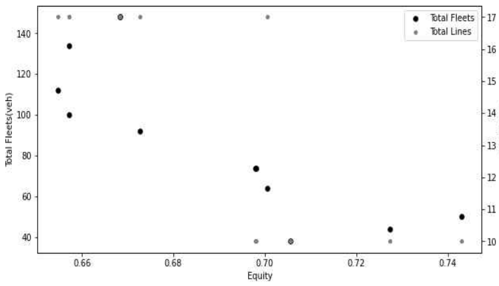


(f) Demand ratio of CBD : 60%

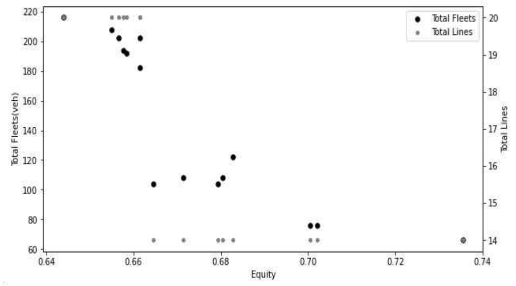


(g) Demand ratio of CBD : 90%

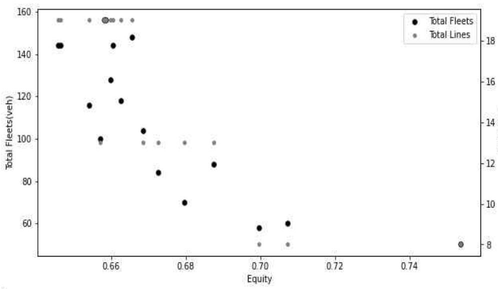
Figure 5.5 Passengers per Line Length by profit
(Radial Circular Network)



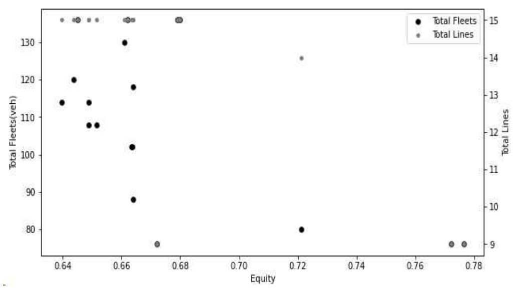
(a) Demand ratio of CBD : -90%



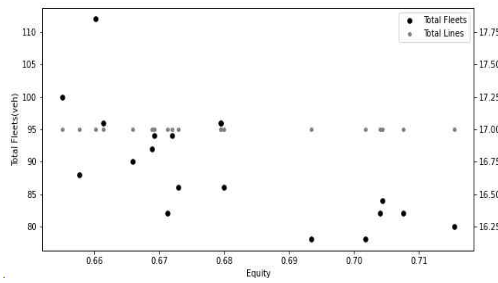
(b) Demand ratio of CBD : -60%



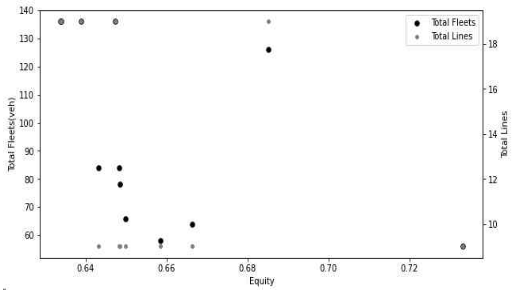
(c) Demand ratio of CBD : -30%



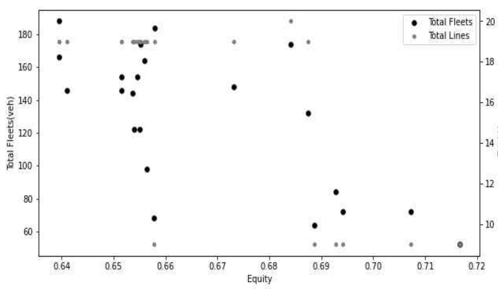
(d) Demand ratio of CBD : 0%



(e) Demand ratio of CBD : 30%

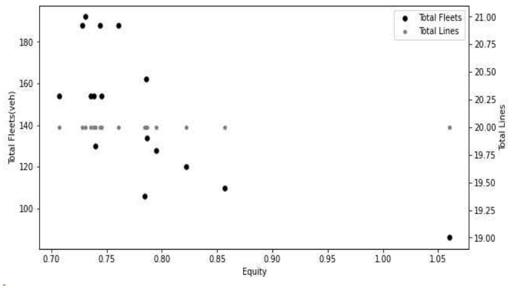


(f) Demand ratio of CBD : 60%

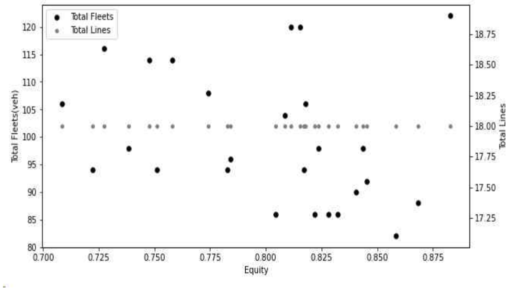


(g) Demand ratio of CBD : 90%

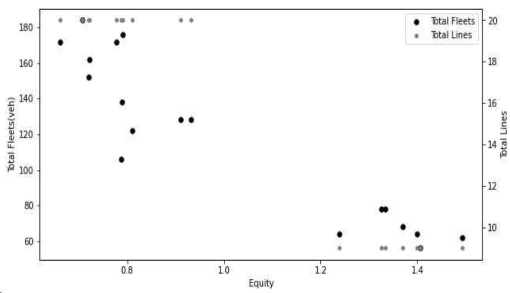
Figure 5.6 Number of Lines and Total Fleets by Equity (Grid Network)



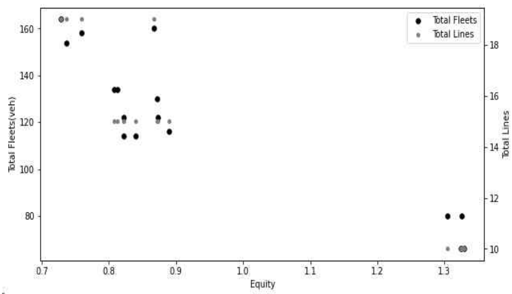
(a) Demand ratio of CBD : -90%



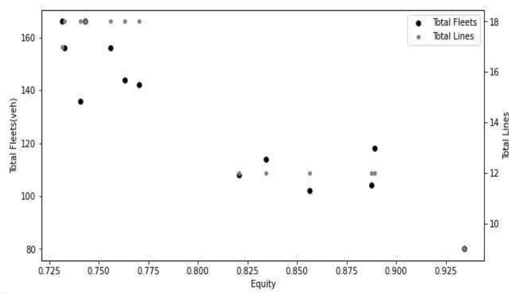
(b) Demand ratio of CBD : -60%



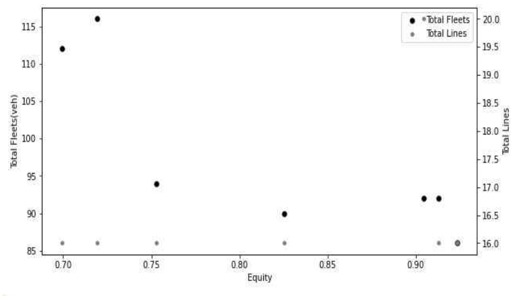
(c) Demand ratio of CBD : -30%



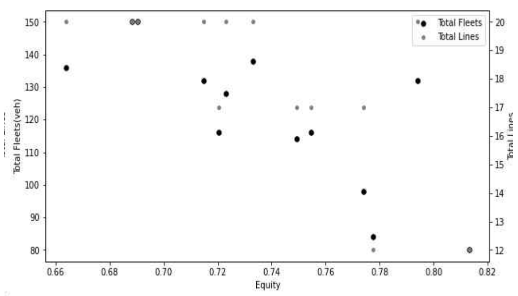
(d) Demand ratio of CBD : 0%



(e) Demand ratio of CBD : 30%



(f) Demand ratio of CBD : 60%



(g) Demand ratio of CBD : 90%

Figure 5.7 Number of Lines and Total Fleets by Equity
(Radial Circular Network)

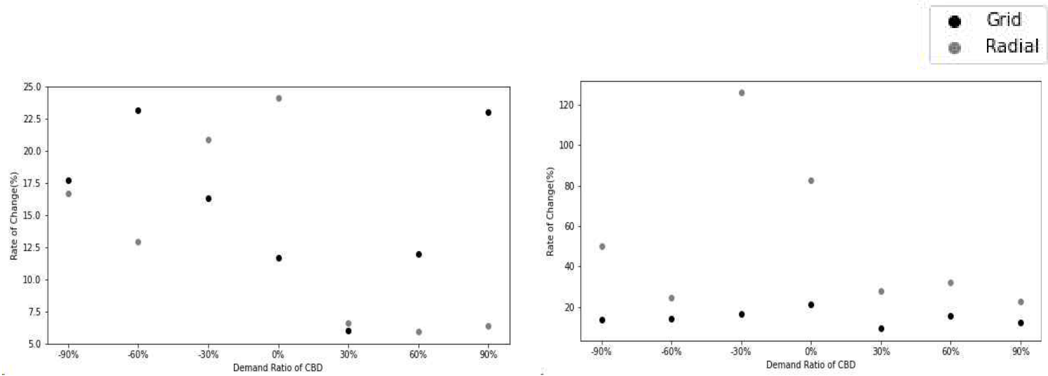
Changes by Index

In the previous two sections, changes in the optimal transit network or indexes for each objective function were analyzed. In this section, changes in indexes are analyzed according to the network topology or the demand in the CBD. The change rate of the index calculated the rate of change compared to the optimal value in the Pareto solution is used. The results are shown in Figure 5.8.

Figure 5.8(a) shows the change rate in profit, and in the case of a grid network, the change in profit occurs as the demand ratio concentrated in the CBD increases.

This is analyzed to be due to the large variation in the CBD services, as the demand in the CBD increases in the crowded area. Unlike the grid type, the radial circular network does not show a significant change in profit even if the CBD demand increases. In the case of the radial circular type, a traffic pass the CBD occurs because traffic is concentrated CBD. Therefore, demand in the CBD is low, analyzed that the difference in profits due to the service in the CBD is significant. In the case of the radial circular network, a line passing through the CBD occur because traffic is concentrated in CBD. Therefore, unlike the grid network, when the demand in CBD is low, it is analyzed that the difference in profits due to the service in the city center is significant.

Figure 5.8(b) shows that the equity change rate is varied in the radial circular network. The difference between the shortest distance and others is significant in a radial circular network; the change of equity depends on the line's circuity. On the other hand, the change rate of equity depends on CBD demand is not very different because the line's circuity is not high in the grid network, unlike the radial circular network. Profit and equity show a tendency to change depends on the characteristics of the network topology. The unmet demand has zero value because the network size is small, so rate change analysis is excluded.



(a) Profit Change by Ratio of CBD (b) Equity Change by Ratio of CBD

Figure 5.8 Index change rate by CBD demand ratio

5.1.3 Marginal Effect

In this section, when each indexes increases by 1 unit, the degree of change between profit, unmet demand and equity is analyzed. To perform normalization for the comparative analysis of the marginal effect because units of each index are different from each other. the percentile was divided into very small. The unit of each index consists of 100,000 won(profit), 100 passenger(unmet demand), and 0.01(equity). Figure 5.14, 5.15 and 5.16 is an example of the result of the change between index that can be analyzed for marginal effect. The results depend on CBD demand for network topology are listed in the appendix.

Figure 5.10 shows that as the unmet demand increase due to the profit increase. It depends on the total line length. Profit increases as line length are shorter compared with the number of passengers, however, the unmet demand decreases as the length of the route increases. It is possible to move with fewer transfers when

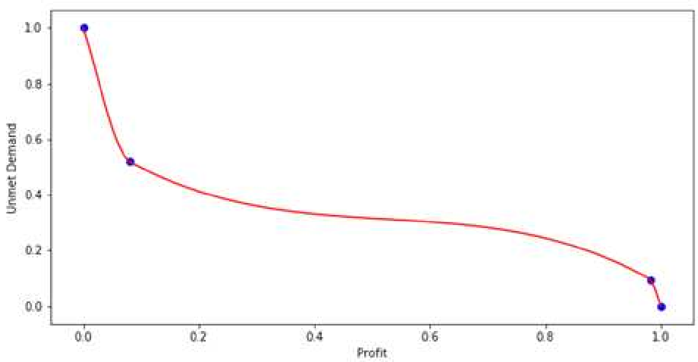


Figure 5.9 Illustration of Marginal Effect

connecting multiple regions to one route. Profit increases as the line length are connecting short compared with the number of passengers. However, the unmet demand decreases as the line length increases, as it is possible to trip with fewer transfers when a line connects several areas. Figure 5.11 shows that equity is deteriorated as profit increases due to a change between profit and equity, depending on frequency. Line length and frequency affect profits. If the CBD demand is the same, the profit decreases when the service frequency increases. However, the equity improves because of the waiting time and the travel time decrease for the same origin and destination.

Figure 5.12 shows a change between unmet demand and equity, and as the unmet demand increases, equity improves. Line length and deviation in the number of lines per link affected unmet demand. If the lines are concentrated in a specific area, the transfer decreases and improves the unmet demand. This is because equity is deteriorated due to service imbalance. In some cases, the change equity and variation in the number of lines per link conflict, analyzed by the effect of the total number of lines. Index are increased or decreased depending on the bus network's service level and have a marginal effect. The marginal effects between the indexes are summarized as follows. Decreasing line length and frequency can increase profits, but unmet demand increases due to frequent transfers, and equity is deteriorated due to increased waiting time and travel time. It can reduce the unmet demand if long-distance lines through various areas or transfers between diverse lines are possible

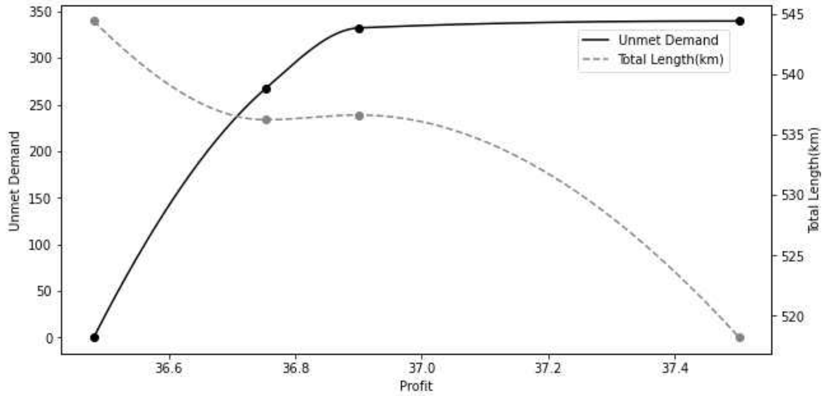


Figure 5.10 Changes between Profit and Unmet Demand

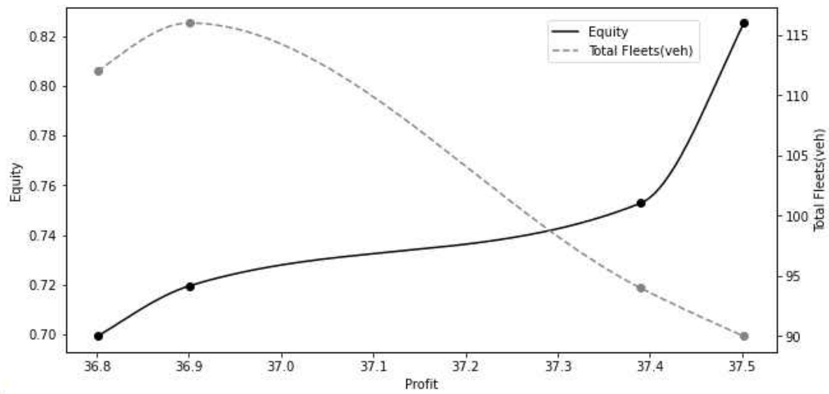


Figure 5.11 Changes between Profit and Equity

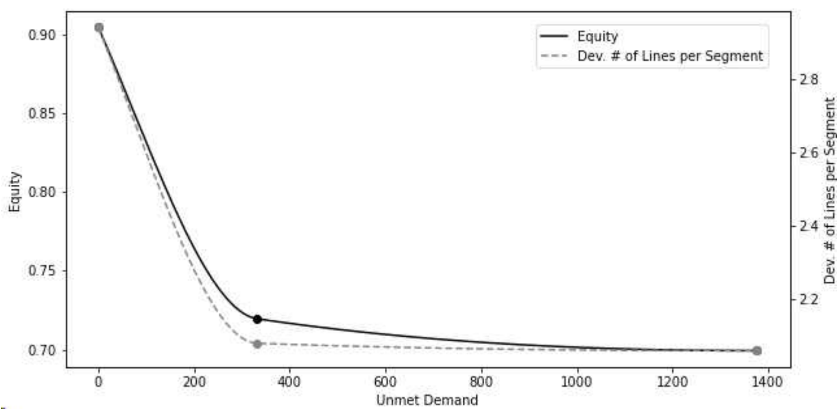


Figure 5.12 Changes between Unmet Demand and Equity

as bus network are concentrated in specific areas. Equity is deteriorated due to service imbalance at the overall network level as equity is concentrated. Equity is improved by increasing the frequency of services or evenly distributing services across the entire network; however, profit decreases due to the increase in operating costs and unmet demand increases due to frequent transfers.

The marginal effect between indexes is the same, but differences are depending on the network's characteristics. Normalization for comparison because the range of indexes in each network is different, and summarized in Table 5.4, 5.5. The marginal effect on profit and equity was found to be higher in the radial circular network. The radial circular network has the characteristic that the traffic volume is concentrated in CBD; on the other hand, the grid network has the traffic volume dispersion. Therefore, the service is increased in the high congestion area, increased passengers compared to the service, and improved travel time through congestion alleviation is analyzed to be higher than that of the grid network. The marginal effect on unmet demand was found to be higher in the grid network. There is little change in equity or profit because it has high competitiveness between routes and few circuity constraints. The detoured route can reach several stops. So, the reduction in unmet demand due to the decrease in profits or the deterioration of equity is higher than the radial circular network. It is analyzed that the indexes with high marginal effects are different due to each network's characteristics. The radial circular network has a high marginal effect of profit and equity due to the characteristics of traffic being concentrated in the CBD. The grid network has a high marginal effect of unmet demand due to the competitiveness of routes.

Table 5.4 Marginal Effect between Indexes(Grid Network)

Demand Ratio of CBD	Index					
	P-U	P-E	U-P	U-E	E-P	E-U
-90%	0.066	0.226	0.042	0.124	0.133	0.067
-60%	0.019	0.055	0.112	0.079	0.201	0.366
-30%	0.106	0.067	0.586	0.115	0.143	0.840
0%	0.594	0.203	0.216	0.070	0.319	0.087
30%	0.395	0.128	0.341	0.091	0.855	0.135
60%	0.042	0.068	0.214	0.072	0.231	0.051
90%	0.165	0.030	0.191	0.078	0.220	0.152

P: Profit, U: Unmet Demand, E: Equity

A-B: Marginal Effect of A on B

Table 5.5 Marginal Effect between Indexes(Radial Circular Network)

Demand Ratio of CBD	Index					
	P-U	P-E	U-P	U-E	E-P	E-U
-90%	0.488	0.252	0.818	0.228	0.328	0.054
-60%	0.056	0.290	0.119	0.161	0.380	0.127
-30%	0.045	0.427	0.117	0.059	0.481	0.088
0%	0.077	0.557	0.129	0.165	0.122	0.109
30%	0.036	0.942	0.072	0.087	0.051	0.062
60%	0.280	0.155	0.922	0.165	0.293	0.076
90%	0.025	0.855	0.030	0.145	0.311	0.213

P: Profit, U: Unmet Demand, E: Equity

A-B: Marginal Effect of A on B

5.1.4 Comparison with Previous Research

In this study, proposed an algorithm to the bus network design that can satisfy each stakeholder by establishing the objective expressions for the operator, user, and public. Compared to the case where only profit was used as the objective function and the case where both profit, unmet demand, and equity were used as the objective function. The bus network results for profit only and optimal values in each index within Pareto optimal are applied. The result summarizes in Table 5.6.

It was found that the profit was higher than the bus network, considering both profit, unmet demand, and equity when profit is only purposes. The number of lines is relatively small, however, if considered profit only, a route is generated that can make a large amount of money compared to the operating cost. As the bus network is concentrated in a specific area, the modal split of transit is lowered. In addition, the car's operation cost is increased because the car's traffic volume is relatively increased when the modal split of transit is lowered.

Besides, when the methodology of this study applied, when compared with the results of the route network with the highest profit, the difference in revenue was not significant, while the demand for dissatisfaction and equity were significant. Compared to the route network with the highest profit applied to the algorithm of this study, the difference in profit was not significant. At the same time, unmet demand and equity were significant. Even if the profit decreases somewhat, considering the user and the public sector together seems to be more effective in alleviating congestion and reducing overall costs.

Table 5.6 Analysis Result by objective

Division	Profit (M-won)	Unmet Demand (Person)	Equity	Modal Split(%)		Operate Cost(M-won)		Travel Time Cost(M-won)		# of Lines/seg	Passenger /km	Total Length (km)	# of Lines
				Car	Transit	Car	Transit	Car	Transit				
Profit Only	30.86	592	0.708	67.0	33.0	76.05	3.42	420.24	492.78	0.74	28.54	236	7
Pareto Solution*	26.99	346	0.634	65.7	34.3	74.40	8.70	410.15	492.88	1.98	11.67	632	19
	30.68	428	0.666	66.8	33.2	75.83	3.86	418.87	493.70	0.91	25.45	292	9
	27.04	-	0.685	66.4	33.6	75.29	7.86	415.65	492.34	1.95	12.64	624	19

* is Results of Optimal Bus Network by Profit, Unmet Demand and Equity

5.2 Large Network

5.2.1 Network Explanation

The previous section analyzed the optimal route network according to the network topology and the demand in CBD. In this section, performed a comparative analysis with the result of the toy network and large network. The large network used for the analysis is Goyang-si, Gyeonggi-do, and KTDB data as of 2018 was used. The total traffic volume was 299,099 trip/hour, of which 131,361 trip/hour (43.9%) for cars and 167,648 trip/hour (56.1%) for transit. In the experiment of this study, only buses were included in public transportation, and a total of 67 bus lines exist.

Figure 5.13 CBD in Real Network

In order to define the CBD of the large network, the area within the top 25% of the traffic volume in the region was selected as the city center based on the regional traffic volume of Jongro, Yeongdeungpo/Yeouido, and Gangnam, the three CBD of Seoul.
Table 5.7 is the result of analyzing the area and traffic volume of the CBD and Non CBD. It found that the CBD's traffic volume per unit area was 62.6% higher than the other.

Table 5.7 Volume per Area in Real Network

Division	Volume(trip/hr)	Area(km^2)	Volume per Area (trip/km^2)
Total	299,009	267.3	1,118.6
CBD	104651	66.5	1,573.7
Others	194358	200.8	967.9

The large network has a complex structure; the CBD area has a grid shape and radial circular network that is Non CBD. To find the characteristics of the large network by comparing the analysis with the toy network analysis. The large network used the EMME/4 API in the same way as the toy network. Existing bus networks exist in large network, so it is applied for the initial solution. Also, as the network size increased, the constraints were adjusted to fit the reality, and the number of iterations was doubled compared to the toy Network.

Constraint Setting

- Maximum line length is 40km
- Maximum number of lines in the bus network is 67
- The minimum number of stops is three, and the Maximum number of stops is 20 in a line.

Parameter Setting

- Population = 50, Generation = 100
- Cross-over = 0.8, Mutation = 0.1

5.2.2 Result Analysis

In this section, analyzed the optimal bus network for each index and the changes for each index. Also, a comparative analysis was performed with the existing bus network and the Pareto solution using this study method. Pareto solutions for the existing and improved bus networks are listed in the appendix.

The bus network with the best profit in the large network with high demand per total length of the line, as shown in Figure 5.14. Even though the number of lines and frequencies is low, it is analyzed that bus networks are concentrated in high demand areas, resulting in high profits. As shown in Figure 5.15, the optimal bus network for unmet demand is with high deviations of the number of lines per link. The best equity is analyzed as the bus network with high frequency and various service lines, as shown in Figure 5.16. As described above, it was found that the optimal bus network for each index shows the same results as the toy Network.

The rate change of each index was compared with the toy Network to analyze the large network's characteristics. Table 5.8 compares the cases similar to actual networks. Unmet demand was excluded from the analysis because it could not be compared, and the rate change of the profit and equity showed a pattern similar to the radial circular network. However, the ratio of the number of lines per link in the CBD is similar to that of the grid network, analyzed because the large network has grid and radial circular pattern both.

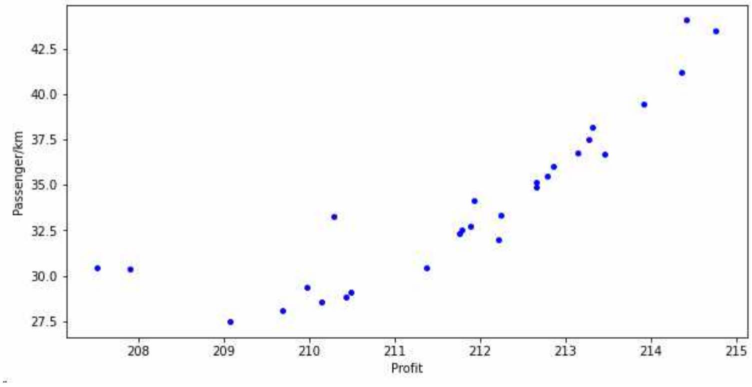


Figure 5.14 Passengers per Line Length by profit

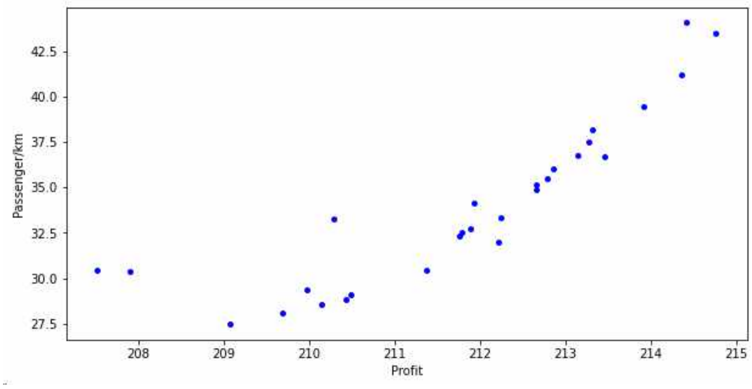


Figure 5.15 Passengers per Line Length by profit

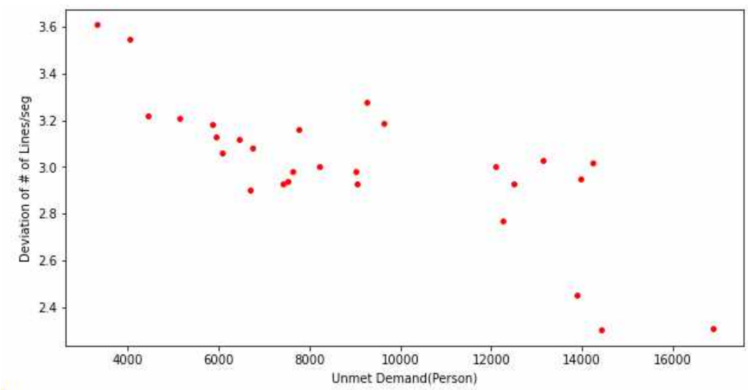


Figure 5.16 Deviation of Number of Lines per Link by Unmet Demand

Table 5.8 Comparison of Index Changes

Network Type	Rate of Change(%)		Average Value in Solutions	
	Profit	Equity	# Line/seg (CBD, %)	# Line/seg (Other, %)
Grid	12.0	15.7	83.0	17.0
Radial Circular	5.9	32.1	31.6	68.4
Large	3.4	33.5	70.8	29.2

Unlike the toy Network, the actual network has an existing bus network, so compared to the existing bus network to understand for the improvement. The bus network with the algorithm of this study applied is compared with the existing one; it is summarized in Table 5.9. Figure 5.17 shows the result of comparing the optimal bus network for each index calculated based on the existing bus network and the methodology of this study.

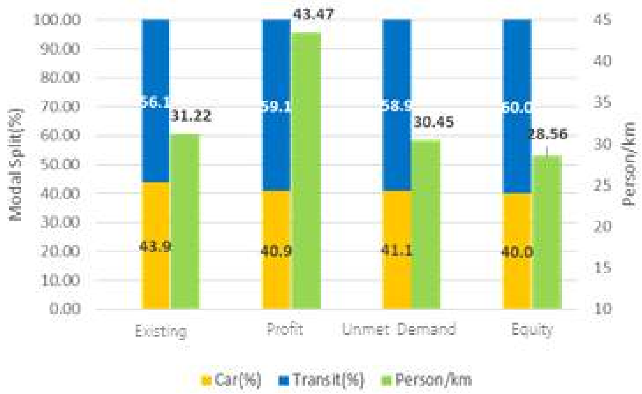
The large network has a pattern in which CBD demand is more than 60% compared to Non-CBD, and more than half of the demand moves to the CBD. The existing bus network provides short-range route-oriented services, so frequent transfers occur when a trip from a Non-CBD to CBD. Also, the congestion increased due to the frequency that did not take into account congestion, resulting in high travel time costs for each mode and a modal split of transit is low.

This study analyzed that profit, unmet demand, and equity can be improved compared to the existing network. Moreover, it is possible to reduce the operating cost and travel time of all modes by improving the modal split of transit.

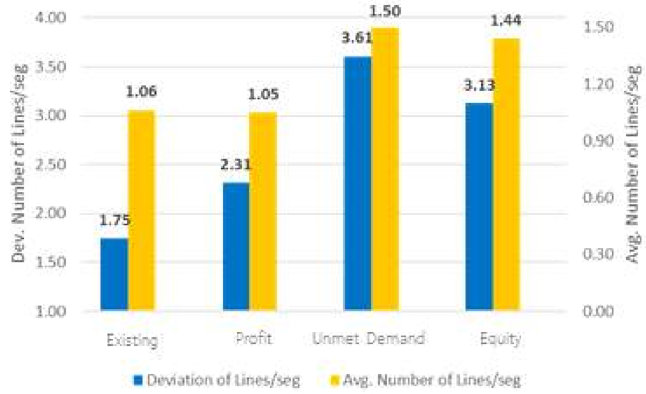
Table 5.9 Comparison with existing Bus Network

Division	Profit (M-won)	Unmet Demand (Person)	Equity	Modal Split(%)		Operate Cost(M-won)		Travel Time Cost(M-won)		Total Fleet	Total Length (km)	# of Lines
				Car	Transit	Car	Transit	Car	Transit			
Existing	198.07	48,474	1.721	43.9	56.1	117.55	19.87	372.85	2071.41	310	1164	67
Pareto Solution*	214.76	16,885	1.345	40.9	59.1	105.18	15.05	336.18	945.36	1214	171	51
	214.42	14,437	1.374	41.0	59.0	105.56	14.81	337.21	959.53	1220	168	51
	214.36	13,892	1.316	40.8	59.2	104.86	15.92	335.04	939.02	1241	176	51
	213.92	12,493	1.321	40.7	59.3	104.60	16.64	334.37	953.24	1490	196	65
	213.46	14,226	1.216	40.5	59.5	104.28	17.94	333.41	928.89	1547	202	65
	213.31	12,097	1.349	40.7	59.3	104.65	17.19	334.78	961.93	1444	204	65
	213.27	8,222	1.441	40.6	59.4	105.05	17.52	335.19	992.32	1540	200	65
	213.14	13,137	1.266	40.6	59.4	104.49	17.89	334.04	928.82	1566	200	65
	212.85	12,249	1.284	40.6	59.5	104.02	18.25	332.68	913.06	1516	214	65
	212.79	9,631	1.254	40.5	59.5	104.19	18.55	333.17	921.50	1597	204	65
	212.66	9,264	1.262	40.5	59.5	104.16	18.72	333.07	921.82	1591	207	65
	212.66	9,043	1.284	40.4	59.6	103.77	18.91	331.76	924.52	1515	213	65
	212.24	13,970	1.234	40.3	59.7	103.29	19.81	330.29	895.64	1615	214	65
	212.21	9,031	1.187	40.1	59.9	102.89	20.75	328.94	866.34	1589	227	65
	211.92	6,733	1.392	40.5	59.5	105.09	19.26	336.36	909.98	1551	216	65
	211.88	7,515	1.254	40.3	59.7	103.36	20.16	330.59	889.87	1578	219	65
	211.78	7,617	1.248	40.3	59.7	103.33	20.32	330.47	888.87	1601	218	65
	211.75	7,421	1.259	40.3	59.7	103.20	20.42	329.99	887.47	1586	221	65
	211.37	6,697	1.169	40.0	60.0	102.72	21.78	328.39	866.28	1597	237	65
	210.49	7,766	1.159	40.0	60.0	102.58	22.85	328.04	855.47	1644	239	65
	210.43	6,441	1.127	39.9	60.1	102.49	23.04	327.74	852.45	1647	241	65
	210.28	6,075	1.501	40.8	59.2	105.80	19.67	338.69	946.56	1515	223	65
	210.14	5,943	1.116	40.0	60.0	102.52	23.26	327.85	854.56	1637	245	65
	209.97	4,439	1.343	40.2	59.8	103.52	22.55	330.82	883.96	1630	240	65
	209.69	5,860	1.138	40.0	60.0	102.49	23.66	327.79	854.16	1667	245	65
	209.07	5,143	1.147	40.0	60.0	102.51	24.17	327.85	860.01	1678	249	65
	207.89	4,030	1.659	41.0	59.0	106.83	21.50	341.20	941.61	1599	229	65

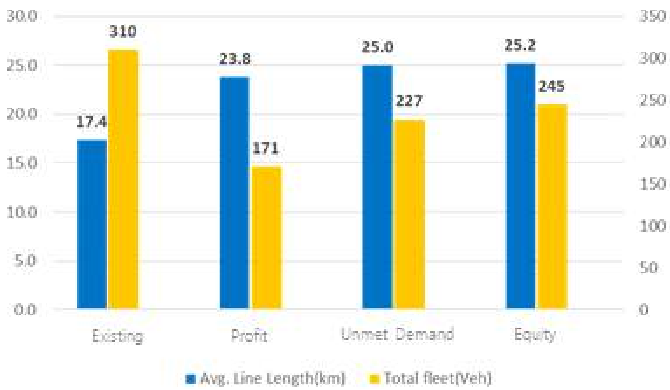
* is Profit-optimized bus network



(a) Modal Split and Passenger per km



(b) Line and Deviations per Link



(c) Line Length and Frequency

Table 5.17 Comparison with Existing Bus Network

5.2.3 Marginal Effect

Table 5.9 shows the results of analyzing the average marginal effects of changes between the index in the large network. The marginal effect on equity was high, and the unmet demand and the profit were low. Compared with the toy Network, equity similar to the radial circular network pattern and profit and unmet demand a similar to grid network pattern. Even if the service is equally increased due to the characteristic that the traffic volume is concentrated in the CBD at the radial circular network, the improvement in equity is large because it exhibits a higher congestion alleviation effect than the grid network. The grid network is a feature in which traffic volume is distributed, so the change in profit is not significant, but the line circuity is high, so it is possible to reduce transfer demand. Because a large network has a grid and radial circular network's feature, the marginal effect of the index is also considered a complex characteristic.

Table 5.10 Marginal Effect between Indexes

Network Type	Index					
	P-U	P-E	U-P	U-E	E-P	E-U
Large	0.047	0.439	0.080	0.621	0.367	0.665

P: Profit, U: Unmet Demand, E: Equity

A-B: Marginal Effect of A on B

5.2.4 Comparison with Previous Study

A comparative analysis was conducted between the bus network maximizing the profit based on the operator generally used in the previous study and the methodology of this study. Table 5.10 summarizes the bus network results considering only profit and the optimal value of each index within pareto solutions, which is considered profit, unmet demand and equity at the same time. In the toy network experiment, the profit was found when considering only the profit was slightly higher than that of applying the algorithm of this study. However, in the actual network showed higher profit using the algorithm of this study. If only profit is considered, there are service variations between areas as the network are concentrated around demand concentrated areas. The diversity of lines is limited when the network size is small, such as toy Network, but increases as the size increases. Therefore, while considering equity simultaneously, various lines are applied to reduce the deviations between areas, thereby increasing the modal split of transit and profits.

Confirmed that it is possible to provide a balanced bus network by considering both unmet demand and equity, compared to only considering profit from the large network. Also confirmed that possible to improving equity as well as profit.

Table 5.11 Analysis Result by objective

Division	Profit (M-won)	Unmet Demand (Person)	Equity	Modal Split(%)		Operate Cost(M-won)		Travel Time Cost(M-won)		# of Lines/seg	Passenger /km	Total Length (km)	# of Lines
				Car	Transit	Car	Transit	Car	Transit				
Profit Only	211.15	13,515	1.516	42.5	57.5	110.25	12.19	352.57	1449.60	1.1	52.15	1205	51
Pareto Solution*	207.51	3,306	1.679	41.1	58.9	107.26	21.39	342.58	950.42	1.5	30.45	1624	65
	214.76	16,885	1.345	40.9	59.1	105.18	15.05	336.18	945.36	1.0	43.47	1214	51
	210.14	5,943	1.116	40.0	60.0	102.52	23.26	327.85	854.56	1.4	28.56	1637	65

* is Results of Optimal Bus Network by Profit, Unmet Demand and Equity

5.3 Discussion

In this study, a multi-objective transit network design simultaneously reflects the stakeholders(operators, users, and the public). The operator aimed to maximize profits, excluding operating costs. In the previous study, the purpose of the user was generally applied to minimize the travel time, but the higher the direct demand, the lower the average travel time (Buba and Lee, 2018). It was aimed at minimizing transfer demand. Lastly, the public sector aimed to maximize the equity in order to provide a balanced bus network. Equity assessed through variations in public transportation competitiveness among regions.

Table 5.12 Characteristics of Optimal Bus Network for each Object

Object	Features of Optimal Bus network
Profit	• Bus Network with higher number of passengers compared to line length
Unmet Demand	• Bus network that can be transferred to various line in a specific area • A higher deviation of number of lines per link
Equity	• Bus network has various lines and with high frequency of service that can travel between multiple regions

To get a solution set that satisfies the three objective functions simultaneously is calculated, when profit, unmet demand, and equity are considered simultaneously. Pareto Solution is a set of solutions with the same value. Among them, there is a solution that has an optimal value for each objective function. The bus network characteristics in which each index has an optimal value are summarized in the Table 5.11.

This study's bus network design algorithm found that to decrease the total operating cost and travel time by mode compared to the existing bus network and increase the modal split of transit. This is considered possible by reducing road congestion and getting transit competitiveness by considering regional traffic levels and establishing a reasonable bus network.

Considering profits only in many previous studies, so did a comparative analysis of the bus network with optimal profit in Pareto solutions. Table 5.12 shows the analysis results for the toy network and the large network. If considered profit only as previously analyzed, the bus network will only create a demand concentrated area. As a result, the modal split of transit is low, and congestion of roads and the travel time cost by mode are increased. In a small network, can get a high profit by considering profit only. However, if profit is considered only in a large-scale network, the profit obtained is limited as the service is concentrated in a high-demand area. Therefore, higher profits can be obtained by considering both unmet demand and equity. It is possible to improve the competitiveness of transit and the modal split of transit by providing a balanced service. However, the unmet demand increased slightly because the line has an excessive length, or detour could not be created due to length constraint.

Table 5.13 Analysis Result by objective

Division		Profit (M-won)	Unmet Demand (Person)	Equity	Modal Split(%)		Operate Cost(M-won)		Travel Time Cost(M-won)		Total Length (km)	# of Lines
					Car	Transit	Car	Transit	Car	Transit		
Toy Network	Profit Only	30.86	592	0.708	67.0	33.0	76.05	3.42	420.24	492.78	236	7
	Profit*	30.68	428	0.666	66.8	33.2	75.83	3.86	418.87	493.70	292	9
Large Network	Profit Only	211.15	13,515	1.516	42.5	57.5	110.25	12.19	352.57	1449.60	1205	51
	Profit*	214.76	16,885	1.345	40.9	59.1	105.18	15.05	336.18	945.36	1214	51

* is Profit-optimized bus network among multi-object optimization results

Chapter 6. Result and Future Research

Transit network design has been considered as a multi-objective problem in nature because its objectives vary according to policy or social needs. In the previous study, the problems were solved combined them into one by applying weights to multiple objectives.

In this study, three objective functions were established to consider the interests of operators, users, and the public sector. The operator aims to maximize profit, excluding operating expenses from operating income. Users evaluated the inconvenience by maximization of unmet demand, which is the demand for transfer more than twice, and the public through the competitiveness between area, and aimed to maximize the equity. Here, the unmet demand was set as an acceptable standard for the number of transfers through the smart card data, which is actual traffic data. Also, when evaluating equity, the limitations that resulted in service imbalances between regions were compensated for applying the deviation of travel time between regions.

Considering the various network topology and traffic patterns of the city, conducted an experiment on the algorithm of this study on grid and radial circular network. Also, experiments on large networks confirmed the applicability of the algorithm. A method for selecting a reasonable bus network in a limited resource, in reality, was suggested by using characteristics of the bus network according to each index, and analysis of the marginal effects between the index. Through the comparison of this study with the previous ones, it was found that the application of the algorithm of this study is to get high profit and improve the modal split of transit as the network size increases. It is confirmed that a balanced bus network design is possible by considering both users and the public in addition to the operator.

The contribution to this study is as follows. First, the objective function was established to form a conflicted relationship for each stakeholder, considering an actual traffic pattern and city characteristics in a car-centered society. Second, by considering each stakeholder simultaneously, it is possible to increase the modal split and reduce the total cost of the network through an efficient bus network design compared to the previous study. Third, it is possible to provide design criteria to planners' according to the network topology and demand pattern.

In this study, we develop an algorithm that reflects the purpose of the most representative operators, users, and public sectors simultaneously that can be considered when transit network design. It is possible to supply a balanced bus network to regions with limited resources, such as new cities and sub-urban. It is Expected that a network suitable for reality can be applied based on the marginal effects of each index.

In this study, a bus network design was developed based on the average daily traffic volume. However, there are different traffic patterns between peak and non-peak times, in reality. Nevertheless, these dynamic patterns are not reflected in this study. Besides, there was no clear indicator for network evaluation, so evaluation of the optimal bus network was limited. Therefore, in the future, it is necessary to establish the evaluation system for the bus network using a comprehensive network that reflects real-time demand changes and the network evaluation indicators. Also, it would be possible to design an integrated transit network considering tram, rail, and new public transportation. Lastly, since the efficiency of the genetic algorithm varies depending on the expression of the gene, it is considered that additional research on the network input method is necessary.

Reference

1. Agrawal, J., &Mathew, T. V. (2004). Transit route network design using parallel genetic algorithm. Journal of Computing in Civil Engineering, 18(3), 248-256.
2. Arbex, R. O., &da Cunha, C. B. (2015). Efficient transit network design and frequencies setting multi-objective optimization by alternating objective genetic algorithm. Transportation Research Part B: Methodological, 81, 355-376.
3. Baaj, M. H., &Mahmassani, H. S. (1990). TRUST: A LISP program for the analysis of transit route configurations. Transportation Research Record, 1283(1990), 125-135.
4. Baaj, M. H., &Mahmassani, H. S. (1995). Hybrid route generation heuristic algorithm for the design of transit networks. Transportation Research Part C: Emerging Technologies, 3(1), 31-50.
5. Barbati, M. (2012). The design of transportation networks: a multi objective model combining equity, efficiency and efficacy. OASIcs: Open Access Series in Informatics, 22, 75-83.
6. Beimborn, E. A., Greenwald, M. J., &Jin, X. (2003, January). Transit accessibility and connectivity impacts on transit choice and captivity. In Transportation Research Board 82nd Annual Meeting, Washington, DC.
7. Bertolaccini, K. L. (2015). Designing Transit Networks for Equity and Accessibility.
8. Blum, J. J., &Mathew, T. V. (2011). Intelligent agent optimization of urban bus transit system design. Journal of Computing in Civil Engineering, 25(5), 357-369.
9. Bok, J., &Kwon, Y. (2016). Comparable measures of accessibility to public transport using the general transit feed specification.

Sustainability, 8(3), 224.

10. Buba, A. T., &Lee, L. S. (2018). A differential evolution for simultaneous transit network design and frequency setting problem. Expert Systems with Applications, 106, 277-289.
11. Buba, A. T., &Lee, L. S. (2018). A differential evolution for simultaneous transit network design and frequency setting problem. Expert Systems with Applications, 106, 277-289.
12. Camporeale, R., Caggiani, L., &Ottomanelli, M. (2019). Modeling horizontal and vertical equity in the public transport design problem: A case study. Transportation Research Part A: Policy and Practice, 125, 184-206.
13. Camporeale, R., Caggiani, L., Fonzone, A., &Ottomanelli, M. (2017). Quantifying the impacts of horizontal and vertical equity in transit route planning. Transportation Planning and Technology, 40(1), 28-44.
14. Canca, D., De-Los-Santos, A., Laporte, G., &Mesa, J. A. (2016). A general rapid network design, line planning and fleet investment integrated model. Annals of Operations Research, 246(1-2), 127-144.
15. Canca, D., De-Los-Santos, A., Laporte, G., &Mesa, J. A. (2019). Integrated railway rapid transit network design and line planning problem with maximum profit. Transportation Research Part E: Logistics and Transportation Review, 127, 1-30.
16. Ceder, A., &Israeli, Y. (1997). Creation of Objective functions for transit network design. IFAC Proceedings Volumes, 30(8), 667-673.
17. Chen, A., and C. Yang. Stochastic Transportation Network Design Problem with Spatial Equity Constraint. In Transportation Research Record: Journal of the Transportation Research Board, No. 1882, Transportation Research Board of the National Academies, Washington, D.C., 2004,pp. 97 - 104.

18. Chew, J. S. C., Lee, L. S., &Seow, H. V. (2013). Genetic algorithm for biobjective urban transit routing problem. Journal of Applied Mathematics, 2013.
19. Chien, S., Yang, Z., &Hou, E. (2001). Genetic algorithm approach for transit route planning and design. Journal of transportation engineering, 127(3), 200-207.
20. Cipriani, E., Gori, S., &Petrelli, M. (2012). A bus network design procedure with elastic demand for large urban areas. Public Transport, 4(1), 57-76.
21. Cipriani, E., Gori, S., &Petrelli, M. (2012). Transit network design: A procedure and an application to a large urban area. Transportation Research Part C: Emerging Technologies, 20(1), 3-14.
22. Cooper, I. M., John, M. P., Lewis, R., Mumford, C. L., &Olden, A. (2014, July). Optimising large scale public transport network design problems using mixed-mode parallel multi-objective evolutionary algorithms. In 2014 IEEE Congress on Evolutionary Computation (CEC) (pp. 2841-2848). IEEE.
23. Deb, K., Agrawal, S., Pratap, A., &Meyarivan, T. (2000, September). A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II. In International conference on parallel problem solving from nature (pp. 849-858). Springer, Berlin, Heidelberg.
24. Deb, K., Pratap, A., Agarwal, S., &Meyarivan, T. A. M. T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE transactions on evolutionary computation, 6(2), 182-197
25. Dou, X., Wang, H., &Meng, Q. (2019). Parallel shuttle bus service design for planned mass rapid transit shutdown: The Singapore experience. Transportation Research Part C: Emerging Technologies, 108, 340-356.
26. Duran, J., Pradenas, L., &Parada, V. (2019). Transit network

design with pollution minimization. Public Transport, 11(1), 189-210.
27. Duran-Micco, J., Vermeir, E., &Vansteenwegen, P. (2020). Considering emissions in the transit network design and frequency setting problem with a heterogeneous fleet. European Journal of Operational Research, 282(2), 580-592.
28. El-Geneidy, A., Levinson, D., Diab, E., Boisjoly, G., Verbich, D., &Loong, C. (2016). The cost of equity: Assessing transit accessibility and social disparity using total travel cost. Transportation Research Part A: Policy and Practice, 91, 302-316.
29. Fan, L., Mumford, C. L., &Evans, D. (2009, May). A simple multi-objective optimization algorithm for the urban transit routing problem. In 2009 IEEE Congress on Evolutionary Computation (pp. 1-7). IEEE.
30. Fan, W., &Machemehl, R. B. (2006a). Optimal transit route network design problem with variable transit demand: genetic algorithm approach. Journal of transportation engineering, 132(1), 40-51.
31. Fan, W., &Machemehl, R. B. (2006b). Using a simulated annealing algorithm to solve the transit route network design problem. Journal of transportation engineering, 132(2), 122-132.
32. Fan, W., &Machemehl, R. B. (2008). Tabu search strategies for the public transportation network optimizations with variable transit demand. Computer AidedCivilandInfrastructureEngineering,23(7),502-520.
33. Fan, W., &Machemehl, R. B. (2011). Bi-level optimization model for public transportation network redesign problem: Accounting for equity issues. Transportation Research Record, 2263(1), 151-162.
34. Ferguson, E. M., Duthie, J., Unnikrishnan, A., &Waller, S. T. (2012). Incorporating equity into the transit frequency-setting problem. Transportation Research Part A: Policy and Practice,

46(1), 190-199.
35. Gallo, M., Montella, B., &D'Acierno, L. (2011). The transit network design problem with elastic demand and internalisation of external costs: An application to rail frequency optimisation. Transportation Research Part C: Emerging Technologies, 19(6), 1276-1305.
36. Guihaire, V., &Hao, J. K. (2008). Transit network design and scheduling: A global review. Transportation Research Part A: Policy and Practice, 42(10), 1251-1273.
37. Hosapujari, A. B., &Verma, A. (2013). Development of a hub and spoke model for bus transit route network design. Procedia-Social and Behavioral Sciences, 104(0), 835-844.
38. Ibeas, Á., dell'Olio, L., Alonso, B., &Sainz, O. (2010). Optimizing bus stop spacing in urban areas. Transportation research part E: logistics and transportation review, 46(3), 446-458.
39. Jha, S. B., Jha, J. K., &Tiwari, M. K. (2019). A multi-objective meta-heuristic approach for transit network design and frequency setting problem in a bus transit system. Computers &Industrial Engineering, 130, 166-186.
40. Jiang, Y. (2018). Equitable Transit Network Design Under Uncertainty. In Conference on Advanced Systems in Public Transport.
41. Kepaptsoglou, K., &Karlaftis, M. (2009). Transit route network design problem. Journal of transportation engineering, 135(8), 491-505.
42. Khanzad, I., Seyedabrishami, S., Nazemi, M., &Zarrinmehr, A. (2016). Transit network design problem: An expansion of the route generation algorithm. In Advanced Concepts, Methodologies and Technologies for Transportation and Logistics , pp. 183-197.
43. Kim, M., Kho, S. Y., &Kim, D. K. (2019). A Transit Route Network Design Problem Considering Equity. Sustainability, 11(13), 3527.

44. Konak, A., Coit, D. W., &Smith, A. E. (2006). Multi-objective optimization using genetic algorithms: A tutorial. Reliability Engineering &System Safety, 91(9), 992-1007.
45. Kuan, S. N., Ong, H. L., &Ng, K. M. (2006). Solving the feeder bus network design problem by genetic algorithms and ant colony optimization. Advances in Engineering Software, 37(6), 351-359.
46. Li, Z. C., Lam, W. H., Wong, S. C., &Sumalee, A. (2012). Design of a rail transit line for profit maximization in a linear transportation corridor. Transportation Research Part E: Logistics and Transportation Review, 48(1), 50-70.
47. Liu, J., &Chen, X. (2019). An Improved NSGA-II Algorithm Based on Crowding Distance Elimination Strategy. International Journal of Computational Intelligence Systems, 12(2), 513-518.
48. Mahdavi Moghaddam, S. H., Rao, K. R., Tiwari, G., &Biyani, P. (2019). Simultaneous bus transit route network and frequency setting search algorithm. Journal of Transportation Engineering, Part A: Systems, 145(4), 04019011.
49. Martens, K., Golub, A., &Robinson, G. (2012). A justice-theoretic approach to the distribution of transportation benefits: Implications for transportation planning practice in the United States. Transportation research part A: policy and practice, 46(4), 684-695.
50. Mauttone, A., &Urquhart, M. E. (2009). A multi-objective metaheuristic approach for the transit network design problem. Public Transport, 1(4), 253-273.
51. Meng, Q., and H. Yang. Benefit Distribution and Equity in Road Network Design. Transportation Research Part B, Vol. 36, No. 1, 2002, pp. 19 - 35
52. Mortazavi, S. A. H., & Akbarzadeh, M. (2017). A framework for measuring the spatial equity in the distribution of public transportation benefits. Journal of Public Transportation, 20(1), 3.
53. Mumford, C. L. (2013, June). New heuristic and evolutionary

operators for the multi-objective urban transit routing problem. In 2013 IEEE Congress on Evolutionary Computation (pp. 939-946). IEEE.

54. Nayeem, M. A., Islam, M. M., &Yao, X. (2018). Solving Transit Network Design Problem Using Many-Objective Evolutionary Approach. IEEE Transactions on Intelligent Transportation Systems, 20(10), 3952-3963.
55. Nayeem, M. A., Rahman, M. K., &Rahman, M. S. (2014). Transit network design by genetic algorithm with elitism. Transportation Research Part C: Emerging Technologies, 46, 30-45.
56. Nikolić, M., &Teodorović, D. (2013). Transit network design by bee colony optimization. Expert Systems with Applications, 40(15), 5945-5955.
57. Nikolić, M., &Teodorović, D. (2014). A simultaneous transit network design and frequency setting: Computing with bees. Expert Systems with Applications, 41(16), 7200-7209.
58. Owais, M., Osman, M. K., &Moussa, G. (2015). Multi-objective transit route network design as set covering problem. IEEE Transactions on Intelligent Transportation Systems, 17(3), 670-679.
59. Patel, R., Raghuwanshi, M. M., &Malik, L. G. (2011, June). An improved ranking scheme for selection of parents in multi-objective genetic algorithm. In 2011 International Conference on Communication Systems and Network Technologies (pp. 734-739). IEEE.
60. Pternea, M., Kepaptsoglou, K., &Karlaftis, M. G. (2015). Sustainable urban transit network design. Transportation Research Part A: Policy and Practice, 77, 276-291.
61. Ranjbari, A., Hickman, M., &Chiu, Y. C. (2020). A network design problem formulation and solution procedure for intercity transit services. Transportmetrica A: Transport Science, 16(3), 1156-1175.

62. Roca-Riu, M., Estrada, M., &Trapote, C. (2012). The design of interurban bus networks in city centers. Transportation research part A: policy and practice, 46(8), 1153-1165.
63. Sharma, S., Ukkusuri, S. V., &Mathew, T. V. (2009). Pareto optimal multiobjective optimization for robust transportation network design problem. Transportation Research Record, 2090(1), 95-104.
64. Spasovic, L. N., Boile, M. P., &Bladikas, A. K. (1993, August). A methodological framework for optimizing bus transit service coverage. In 73rd Annual Meeting of the Transportation Research Board.
65. Spasovic, L., Boile, M. P., &Bladikas, A. K. (1994). Bus transit service coverage for maximum profit and social welfare. Transportation Research Record, (1451).
66. Stern, R. 1996. "Passenger transfer system review." Synthesis of Transit Practice 19, Transportation Research Board, Washington, D.C.
67. Szeto, W. Y., &Jiang, Y. (2014). Transit route and frequency design: Bi-level modeling and hybrid artificial bee colony algorithm approach. Transportation Research Part B: Methodological, 67, 235-263.
68. Szeto, W. Y., &Wu, Y. (2011). A simultaneous bus route design and frequency setting problem for Tin Shui Wai, Hong Kong. European Journal of Operational Research, 209(2), 141-155.
69. Van Nes, R. (2002). Multilevel network optimization for public transport networks. Transportation research record, 1799(1), 50-57.
70. van Nes, R., Hamerslag, R., &Immers, L. H. (1988). The design of public transport networks (Vol. 1202). National Research Council, Transportation Research Board.
71. Welch, T.F., 2013. Equity in transport: the distribution of transit access and connectivity among affordable housing units. Transp.

Pol. 30, 283 - 293.
72. Won, J. M., Lee, K. M., Lee, J. S., &Karray, F. (2006, July). Guideway network design of personal rapid transit system: A multiobjective genetic algorithm approach. In 2006 IEEE International Conference on Evolutionary Computation (pp. 2215-2221). IEEE.
73. Yan, Y., Liu, Z., Meng, Q., &Jiang, Y. (2013). Robust optimization model of bus transit network design with stochastic travel time. Journal of Transportation Engineering, 139(6), 625-634.
74. Yan, Y., Liu, Z., Meng, Q., &Jiang, Y. (2013). Robust optimization model of bus transit network design with stochastic travel time. Journal of Transportation Engineering, 139(6), pp. 625-634.
75. Yijie, S., &Gongzhang, S. (2008). Improved NSGA-II multi-objective genetic algorithm based on hybridization-encouraged mechanism. Chinese Journal of Aeronautics, 21(6), 540-549.
76. Yu, B., Yang, Z., Sun, X., Yao, B., Zeng, Q., &Jeppesen, E. (2011). Parallel genetic algorithm in bus route headway optimization. Applied Soft Computing, 11(8), 5081-5091.
77. Zhang, T., Ren, G., &Yang, Y. (2020). Transit Route Network Design for Low-Mobility Individuals Using a Hybrid Metaheuristic Approach. Journal of Advanced Transportation, 2020.
78. Zhao, F. (2006). Large-scale transit network optimization by minimizing user cost and transfers. Journal of Public Transportation, 9(2), 6.
79. Zhao, F., &Zeng, X. (2006). Simulated annealing genetic algorithm for transit network optimization. Journal of Computing In Civil Engineering, 20(1),57-68.
80. Zhao, F., &Zeng, X. (2007). Optimization of user and operator cost for large-scale transit network. Journal of Transportation Engineering, 133(4), 240-251.

81. Zhao, F., and I. Ubaka. 2004. Transit network optimization－minimizingtransfersandoptimizingroutedirectness.JournalofPublicTransportation7,1:67 - 82.
82. Zhao, H., &Jiang, R. (2015). The memetic algorithm for the optimization of urban transit network. Expert Systems with Applications, 42(7), 3760-3773.

Appendix

Appendix A. OD Matrix

CBD

Table A.2 O/D Matrix(Grid, CBD Demand: -90%)

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.0	570.9	570.9	570.9	570.9	43.0	43.0	570.9	570.9	43.0	43.0	570.9	570.9	570.9	570.9	570.9
2	570.9	0.0	570.9	570.9	570.9	43.0	43.0	570.9	570.9	43.0	43.0	570.9	570.9	570.9	570.9	570.9
3	570.9	570.9	0.0	570.9	570.9	43.0	43.0	570.9	570.9	43.0	43.0	570.9	570.9	570.9	570.9	570.9
4	570.9	570.9	570.9	0.0	570.9	43.0	43.0	570.9	570.9	43.0	43.0	570.9	570.9	570.9	570.9	570.9
5	570.9	570.9	570.9	570.9	0.0	43.0	43.0	570.9	570.9	43.0	43.0	570.9	570.9	570.9	570.9	570.9
6	43.0	43.0	43.0	43.0	43.0	0.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0
7	43.0	43.0	43.0	43.0	43.0	43.0	0.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0
8	570.9	570.9	570.9	570.9	570.9	43.0	43.0	0.0	570.9	43.0	43.0	570.9	570.9	570.9	570.9	570.9
9	570.9	570.9	570.9	570.9	570.9	43.0	43.0	570.9	0.0	43.0	43.0	570.9	570.9	570.9	570.9	570.9
10	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	0.0	43.0	43.0	43.0	43.0	43.0	43.0
11	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	0.0	43.0	43.0	43.0	43.0	43.0
12	570.9	570.9	570.9	570.9	570.9	43.0	43.0	570.9	570.9	43.0	43.0	0.0	570.9	570.9	570.9	570.9
13	570.9	570.9	570.9	570.9	570.9	43.0	43.0	570.9	570.9	43.0	43.0	570.9	0.0	570.9	570.9	570.9
14	570.9	570.9	570.9	570.9	570.9	43.0	43.0	570.9	570.9	43.0	43.0	570.9	570.9	0.0	570.9	570.9
15	570.9	570.9	570.9	570.9	570.9	43.0	43.0	570.9	570.9	43.0	43.0	570.9	570.9	570.9	0.0	570.9
16	570.9	570.9	570.9	570.9	570.9	43.0	43.0	570.9	570.9	43.0	43.0	570.9	570.9	570.9	570.9	0.0

Table A.3 O/D Matrix(Grid, CBD Demand: -60%)

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.0	477.7	477.7	477.7	477.7	156.9	156.9	477.7	477.7	156.9	156.9	477.7	477.7	477.7	477.7	477.7
2	477.7	0.0	477.7	477.7	477.7	156.9	156.9	477.7	477.7	156.9	156.9	477.7	477.7	477.7	477.7	477.7
3	477.7	477.7	0.0	477.7	477.7	156.9	156.9	477.7	477.7	156.9	156.9	477.7	477.7	477.7	477.7	477.7
4	477.7	477.7	477.7	0.0	477.7	156.9	156.9	477.7	477.7	156.9	156.9	477.7	477.7	477.7	477.7	477.7
5	477.7	477.7	477.7	477.7	0.0	156.9	156.9	477.7	477.7	156.9	156.9	477.7	477.7	477.7	477.7	477.7
6	156.9	156.9	156.9	156.9	156.9	0.0	156.9	156.9	156.9	156.9	156.9	156.9	156.9	156.9	156.9	156.9
7	156.9	156.9	156.9	156.9	156.9	156.9	0.0	156.9	156.9	156.9	156.9	156.9	156.9	156.9	156.9	156.9
8	477.7	477.7	477.7	477.7	477.7	156.9	156.9	0.0	477.7	156.9	156.9	477.7	477.7	477.7	477.7	477.7
9	477.7	477.7	477.7	477.7	477.7	156.9	156.9	477.7	0.0	156.9	156.9	477.7	477.7	477.7	477.7	477.7
10	156.9	156.9	156.9	156.9	156.9	156.9	156.9	156.9	156.9	0.0	156.9	156.9	156.9	156.9	156.9	156.9
11	156.9	156.9	156.9	156.9	156.9	156.9	156.9	156.9	156.9	156.9	0.0	156.9	156.9	156.9	156.9	156.9
12	477.7	477.7	477.7	477.7	477.7	156.9	156.9	477.7	477.7	156.9	156.9	0.0	477.7	477.7	477.7	477.7
13	477.7	477.7	477.7	477.7	477.7	156.9	156.9	477.7	477.7	156.9	156.9	477.7	0.0	477.7	477.7	477.7
14	477.7	477.7	477.7	477.7	477.7	156.9	156.9	477.7	477.7	156.9	156.9	477.7	477.7	0.0	477.7	477.7
15	477.7	477.7	477.7	477.7	477.7	156.9	156.9	477.7	477.7	156.9	156.9	477.7	477.7	477.7	0.0	477.7
16	477.7	477.7	477.7	477.7	477.7	156.9	156.9	477.7	477.7	156.9	156.9	477.7	477.7	477.7	477.7	0.0

Table A.4 O/D Matrix(Grid, CBD Demand: -30%)

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.0	399.7	399.7	399.7	399.7	252.3	252.3	399.7	399.7	252.3	252.3	399.7	399.7	399.7	399.7	399.7
2	399.7	0.0	399.7	399.7	399.7	252.3	252.3	399.7	399.7	252.3	252.3	399.7	399.7	399.7	399.7	399.7
3	399.7	399.7	0.0	399.7	399.7	252.3	252.3	399.7	399.7	252.3	252.3	399.7	399.7	399.7	399.7	399.7
4	399.7	399.7	399.7	0.0	399.7	252.3	252.3	399.7	399.7	252.3	252.3	399.7	399.7	399.7	399.7	399.7
5	399.7	399.7	399.7	399.7	0.0	252.3	252.3	399.7	399.7	252.3	252.3	399.7	399.7	399.7	399.7	399.7
6	252.3	252.3	252.3	252.3	252.3	0.0	252.3	252.3	252.3	252.3	252.3	252.3	252.3	252.3	252.3	252.3
7	252.3	252.3	252.3	252.3	252.3	252.3	0.0	252.3	252.3	252.3	252.3	252.3	252.3	252.3	252.3	252.3
8	399.7	399.7	399.7	399.7	399.7	252.3	252.3	0.0	399.7	252.3	252.3	399.7	399.7	399.7	399.7	399.7
9	399.7	399.7	399.7	399.7	399.7	252.3	252.3	399.7	0.0	252.3	252.3	399.7	399.7	399.7	399.7	399.7
10	252.3	252.3	252.3	252.3	252.3	252.3	252.3	252.3	252.3	0.0	252.3	252.3	252.3	252.3	252.3	252.3
11	252.3	252.3	252.3	252.3	252.3	252.3	252.3	252.3	252.3	252.3	0.0	252.3	252.3	252.3	252.3	252.3
12	399.7	399.7	399.7	399.7	399.7	252.3	252.3	399.7	399.7	252.3	252.3	0.0	399.7	399.7	399.7	399.7
13	399.7	399.7	399.7	399.7	399.7	252.3	252.3	399.7	399.7	252.3	252.3	399.7	0.0	399.7	399.7	399.7
14	399.7	399.7	399.7	399.7	399.7	252.3	252.3	399.7	399.7	252.3	252.3	399.7	399.7	0.0	399.7	399.7
15	399.7	399.7	399.7	399.7	399.7	252.3	252.3	399.7	399.7	252.3	252.3	399.7	399.7	399.7	0.0	399.7
16	399.7	399.7	399.7	399.7	399.7	252.3	252.3	399.7	399.7	252.3	252.3	399.7	399.7	399.7	399.7	0.0

Table A.5 O/D Matrix(Grid, CBD Demand: 0%)

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.0	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3
2	333.3	0.0	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3
3	333.3	333.3	0.0	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3
4	333.3	333.3	333.3	0.0	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3
5	333.3	333.3	333.3	333.3	0.0	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3
6	333.3	333.3	333.3	333.3	333.3	0.0	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3
7	333.3	333.3	333.3	333.3	333.3	333.3	0.0	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3
8	333.3	333.3	333.3	333.3	333.3	333.3	333.3	0.0	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3
9	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	0.0	333.3	333.3	333.3	333.3	333.3	333.3	333.3
10	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	0.0	333.3	333.3	333.3	333.3	333.3	333.3
11	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	0.0	333.3	333.3	333.3	333.3	333.3
12	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	0.0	333.3	333.3	333.3	333.3
13	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	0.0	333.3	333.3	333.3
14	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	0.0	333.3	333.3
15	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	0.0	333.3
16	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	333.3	0.0

Table A.6 O/D Matrix(Grid, CBD Demand: 30%)

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.0	276.3	276.3	276.3	276.3	403.1	403.1	276.3	276.3	403.1	403.1	276.3	276.3	276.3	276.3	276.3
2	276.3	0.0	276.3	276.3	276.3	403.1	403.1	276.3	276.3	403.1	403.1	276.3	276.3	276.3	276.3	276.3
3	276.3	276.3	0.0	276.3	276.3	403.1	403.1	276.3	276.3	403.1	403.1	276.3	276.3	276.3	276.3	276.3
4	276.3	276.3	276.3	0.0	276.3	403.1	403.1	276.3	276.3	403.1	403.1	276.3	276.3	276.3	276.3	276.3
5	276.3	276.3	276.3	276.3	0.0	403.1	403.1	276.3	276.3	403.1	403.1	276.3	276.3	276.3	276.3	276.3
6	403.1	403.1	403.1	403.1	403.1	0.0	403.1	403.1	403.1	403.1	403.1	403.1	403.1	403.1	403.1	403.1
7	403.1	403.1	403.1	403.1	403.1	403.1	0.0	403.1	403.1	403.1	403.1	403.1	403.1	403.1	403.1	403.1
8	276.3	276.3	276.3	276.3	276.3	403.1	403.1	0.0	276.3	403.1	403.1	276.3	276.3	276.3	276.3	276.3
9	276.3	276.3	276.3	276.3	276.3	403.1	403.1	276.3	0.0	403.1	403.1	276.3	276.3	276.3	276.3	276.3
10	403.1	403.1	403.1	403.1	403.1	403.1	403.1	403.1	403.1	0.0	403.1	403.1	403.1	403.1	403.1	403.1
11	403.1	403.1	403.1	403.1	403.1	403.1	403.1	403.1	403.1	403.1	0.0	403.1	403.1	403.1	403.1	403.1
12	276.3	276.3	276.3	276.3	276.3	403.1	403.1	276.3	276.3	403.1	403.1	0.0	276.3	276.3	276.3	276.3
13	276.3	276.3	276.3	276.3	276.3	403.1	403.1	276.3	276.3	403.1	403.1	276.3	0.0	276.3	276.3	276.3
14	276.3	276.3	276.3	276.3	276.3	403.1	403.1	276.3	276.3	403.1	403.1	276.3	276.3	0.0	276.3	276.3
15	276.3	276.3	276.3	276.3	276.3	403.1	403.1	276.3	276.3	403.1	403.1	276.3	276.3	276.3	0.0	276.3
16	276.3	276.3	276.3	276.3	276.3	403.1	403.1	276.3	276.3	403.1	403.1	276.3	276.3	276.3	276.3	0.0

Table A.7 O/D Matrix(Grid, CBD Demand: 60%)

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.0	226.6	226.6	226.6	226.6	463.8	463.8	226.6	226.6	463.8	463.8	226.6	226.6	226.6	226.6	226.6
2	226.6	0.0	226.6	226.6	226.6	463.8	463.8	226.6	226.6	463.8	463.8	226.6	226.6	226.6	226.6	226.6
3	226.6	226.6	0.0	226.6	226.6	463.8	463.8	226.6	226.6	463.8	463.8	226.6	226.6	226.6	226.6	226.6
4	226.6	226.6	226.6	0.0	226.6	463.8	463.8	226.6	226.6	463.8	463.8	226.6	226.6	226.6	226.6	226.6
5	226.6	226.6	226.6	226.6	0.0	463.8	463.8	226.6	226.6	463.8	463.8	226.6	226.6	226.6	226.6	226.6
6	463.8	463.8	463.8	463.8	463.8	0.0	463.8	463.8	463.8	463.8	463.8	463.8	463.8	463.8	463.8	463.8
7	463.8	463.8	463.8	463.8	463.8	463.8	0.0	463.8	463.8	463.8	463.8	463.8	463.8	463.8	463.8	463.8
8	226.6	226.6	226.6	226.6	226.6	463.8	463.8	0.0	226.6	463.8	463.8	226.6	226.6	226.6	226.6	226.6
9	226.6	226.6	226.6	226.6	226.6	463.8	463.8	226.6	0.0	463.8	463.8	226.6	226.6	226.6	226.6	226.6
10	463.8	463.8	463.8	463.8	463.8	463.8	463.8	463.8	463.8	0.0	463.8	463.8	463.8	463.8	463.8	463.8
11	463.8	463.8	463.8	463.8	463.8	463.8	463.8	463.8	463.8	463.8	0.0	463.8	463.8	463.8	463.8	463.8
12	226.6	226.6	226.6	226.6	226.6	463.8	463.8	226.6	226.6	463.8	463.8	0.0	226.6	226.6	226.6	226.6
13	226.6	226.6	226.6	226.6	226.6	463.8	463.8	226.6	226.6	463.8	463.8	226.6	0.0	226.6	226.6	226.6
14	226.6	226.6	226.6	226.6	226.6	463.8	463.8	226.6	226.6	463.8	463.8	226.6	226.6	0.0	226.6	226.6
15	226.6	226.6	226.6	226.6	226.6	463.8	463.8	226.6	226.6	463.8	463.8	226.6	226.6	226.6	0.0	226.6
16	226.6	226.6	226.6	226.6	226.6	463.8	463.8	226.6	226.6	463.8	463.8	226.6	226.6	226.6	226.6	0.0

Table A.8 O/D Matrix(Grid, CBD Demand: 90%)

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.0	183.1	183.1	183.1	183.1	517.0	517.0	183.1	183.1	517.0	517.0	183.1	183.1	183.1	183.1	183.1
2	183.1	0.0	183.1	183.1	183.1	517.0	517.0	183.1	183.1	517.0	517.0	183.1	183.1	183.1	183.1	183.1
3	183.1	183.1	0.0	183.1	183.1	517.0	517.0	183.1	183.1	517.0	517.0	183.1	183.1	183.1	183.1	183.1
4	183.1	183.1	183.1	0.0	183.1	517.0	517.0	183.1	183.1	517.0	517.0	183.1	183.1	183.1	183.1	183.1
5	183.1	183.1	183.1	183.1	0.0	517.0	517.0	183.1	183.1	517.0	517.0	183.1	183.1	183.1	183.1	183.1
6	517.0	517.0	517.0	517.0	517.0	0.0	517.0	517.0	517.0	517.0	517.0	517.0	517.0	517.0	517.0	517.0
7	517.0	517.0	517.0	517.0	517.0	517.0	0.0	517.0	517.0	517.0	517.0	517.0	517.0	517.0	517.0	517.0
8	183.1	183.1	183.1	183.1	183.1	517.0	517.0	0.0	183.1	517.0	517.0	183.1	183.1	183.1	183.1	183.1
9	183.1	183.1	183.1	183.1	183.1	517.0	517.0	183.1	0.0	517.0	517.0	183.1	183.1	183.1	183.1	183.1
10	517.0	517.0	517.0	517.0	517.0	517.0	517.0	517.0	517.0	0.0	517.0	517.0	517.0	517.0	517.0	517.0
11	517.0	517.0	517.0	517.0	517.0	517.0	517.0	517.0	517.0	517.0	0.0	517.0	517.0	517.0	517.0	517.0
12	183.1	183.1	183.1	183.1	183.1	517.0	517.0	183.1	183.1	517.0	517.0	0.0	183.1	183.1	183.1	183.1
13	183.1	183.1	183.1	183.1	183.1	517.0	517.0	183.1	183.1	517.0	517.0	183.1	0.0	183.1	183.1	183.1
14	183.1	183.1	183.1	183.1	183.1	517.0	517.0	183.1	183.1	517.0	517.0	183.1	183.1	0.0	183.1	183.1
15	183.1	183.1	183.1	183.1	183.1	517.0	517.0	183.1	183.1	517.0	517.0	183.1	183.1	183.1	0.0	183.1
16	183.1	183.1	183.1	183.1	183.1	517.0	517.0	183.1	183.1	517.0	517.0	183.1	183.1	183.1	183.1	0.0

Table A.9 O/D Matrix(Radial Circular, CBD Demand: -90%)

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0
2	42.0	0.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0
3	42.0	42.0	0.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0
4	42.0	42.0	42.0	0.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0
5	42.0	42.0	42.0	42.0	0.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0
6	42.0	42.0	42.0	42.0	42.0	0.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0
7	42.0	42.0	42.0	42.0	42.0	42.0	0.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4
8	42.0	42.0	42.0	42.0	42.0	42.0	626.4	0.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4
9	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	0.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4
10	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	0.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4
11	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	626.4	0.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4
12	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	626.4	626.4	0.0	626.4	626.4	626.4	626.4	626.4	626.4
13	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	626.4	626.4	626.4	0.0	626.4	626.4	626.4	626.4	626.4
14	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	0.0	626.4	626.4	626.4	626.4
15	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	0.0	626.4	626.4	626.4
16	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	0.0	626.4	626.4
17	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	0.0	626.4
18	42.0	42.0	42.0	42.0	42.0	42.0	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	626.4	0.0

Table A.10 O/D Matrix(Radial Circular, CBD Demand: -60%)

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0.0	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1
2	147.1	0.0	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1
3	147.1	147.1	0.0	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1
4	147.1	147.1	147.1	0.0	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1
5	147.1	147.1	147.1	147.1	0.0	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1
6	147.1	147.1	147.1	147.1	147.1	0.0	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1	147.1
7	147.1	147.1	147.1	147.1	147.1	147.1	0.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0
8	147.1	147.1	147.1	147.1	147.1	147.1	488.0	0.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0
9	147.1	147.1	147.1	147.1	147.1	147.1	488.0	488.0	0.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0
10	147.1	147.1	147.1	147.1	147.1	147.1	488.0	488.0	488.0	0.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0
11	147.1	147.1	147.1	147.1	147.1	147.1	488.0	488.0	488.0	488.0	0.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0
12	147.1	147.1	147.1	147.1	147.1	147.1	488.0	488.0	488.0	488.0	488.0	0.0	488.0	488.0	488.0	488.0	488.0	488.0
13	147.1	147.1	147.1	147.1	147.1	147.1	488.0	488.0	488.0	488.0	488.0	488.0	0.0	488.0	488.0	488.0	488.0	488.0
14	147.1	147.1	147.1	147.1	147.1	147.1	488.0	488.0	488.0	488.0	488.0	488.0	488.0	0.0	488.0	488.0	488.0	488.0
15	147.1	147.1	147.1	147.1	147.1	147.1	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	0.0	488.0	488.0	488.0
16	147.1	147.1	147.1	147.1	147.1	147.1	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	0.0	488.0	488.0
17	147.1	147.1	147.1	147.1	147.1	147.1	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	0.0	488.0
18	147.1	147.1	147.1	147.1	147.1	147.1	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	488.0	0.0

Table A.11 O/D Matrix(Radial Circular, CBD Demand: －30%)

O\D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0.0	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8
2	228.8	0.0	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8
3	228.8	228.8	0.0	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8
4	228.8	228.8	228.8	0.0	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8
5	228.8	228.8	228.8	228.8	0.0	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8
6	228.8	228.8	228.8	228.8	228.8	0.0	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8
7	228.8	228.8	228.8	228.8	228.8	228.8	0.0	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3
8	228.8	228.8	228.8	228.8	228.8	228.8	380.3	0.0	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3
9	228.8	228.8	228.8	228.8	228.8	228.8	380.3	380.3	0.0	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3
10	228.8	228.8	228.8	228.8	228.8	228.8	380.3	380.3	380.3	0.0	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3
11	228.8	228.8	228.8	228.8	228.8	228.8	380.3	380.3	380.3	380.3	0.0	380.3	380.3	380.3	380.3	380.3	380.3	380.3
12	228.8	228.8	228.8	228.8	228.8	228.8	380.3	380.3	380.3	380.3	380.3	0.0	380.3	380.3	380.3	380.3	380.3	380.3
13	228.8	228.8	228.8	228.8	228.8	228.8	380.3	380.3	380.3	380.3	380.3	380.3	0.0	380.3	380.3	380.3	380.3	380.3
14	228.8	228.8	228.8	228.8	228.8	228.8	380.3	380.3	380.3	380.3	380.3	380.3	380.3	0.0	380.3	380.3	380.3	380.3
15	228.8	228.8	228.8	228.8	228.8	228.8	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3	0.0	380.3	380.3	380.3
16	228.8	228.8	228.8	228.8	228.8	228.8	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3	0.0	380.3	380.3
17	228.8	228.8	228.8	228.8	228.8	228.8	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3	0.0	380.3
18	228.8	228.8	228.8	228.8	228.8	228.8	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3	380.3	0.0

Table A.12 O/D Matrix(Radial Circular, CBD Demand: 0%)

O\D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0.0	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1
2	294.1	0.0	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1
3	294.1	294.1	0.0	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1
4	294.1	294.1	294.1	0.0	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1
5	294.1	294.1	294.1	294.1	0.0	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1
6	294.1	294.1	294.1	294.1	294.1	0.0	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1
7	294.1	294.1	294.1	294.1	294.1	294.1	0.0	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1
8	294.1	294.1	294.1	294.1	294.1	294.1	294.1	0.0	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1
9	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	0.0	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1
10	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	0.0	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1
11	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	0.0	294.1	294.1	294.1	294.1	294.1	294.1	294.1
12	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	0.0	294.1	294.1	294.1	294.1	294.1	294.1
13	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	0.0	294.1	294.1	294.1	294.1	294.1
14	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	0.0	294.1	294.1	294.1	294.1
15	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	0.0	294.1	294.1	294.1
16	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	0.0	294.1	294.1
17	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	0.0	294.1
18	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	294.1	0.0

Table A.13 O/D Matrix(Radial Circular, CBD Demand: 30%)

O D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0.0	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6
2	347.6	0.0	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6
3	347.6	347.6	0.0	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6
4	347.6	347.6	347.6	0.0	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6
5	347.6	347.6	347.6	347.6	0.0	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6
6	347.6	347.6	347.6	347.6	347.6	0.0	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6	347.6
7	347.6	347.6	347.6	347.6	347.6	347.6	0.0	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6
8	347.6	347.6	347.6	347.6	347.6	347.6	223.6	0.0	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6
9	347.6	347.6	347.6	347.6	347.6	347.6	223.6	223.6	0.0	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6
10	347.6	347.6	347.6	347.6	347.6	347.6	223.6	223.6	223.6	0.0	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6
11	347.6	347.6	347.6	347.6	347.6	347.6	223.6	223.6	223.6	223.6	0.0	223.6	223.6	223.6	223.6	223.6	223.6	223.6
12	347.6	347.6	347.6	347.6	347.6	347.6	223.6	223.6	223.6	223.6	223.6	0.0	223.6	223.6	223.6	223.6	223.6	223.6
13	347.6	347.6	347.6	347.6	347.6	347.6	223.6	223.6	223.6	223.6	223.6	223.6	0.0	223.6	223.6	223.6	223.6	223.6
14	347.6	347.6	347.6	347.6	347.6	347.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	0.0	223.6	223.6	223.6	223.6
15	347.6	347.6	347.6	347.6	347.6	347.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	0.0	223.6	223.6	223.6
16	347.6	347.6	347.6	347.6	347.6	347.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	0.0	223.6	223.6
17	347.6	347.6	347.6	347.6	347.6	347.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	0.0	223.6
18	347.6	347.6	347.6	347.6	347.6	347.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	223.6	0.0

Table A.14 O/D Matrix(Radial Circular, CBD Demand: 60%)

O D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0.0	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2
2	392.2	0.0	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2
3	392.2	392.2	0.0	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2
4	392.2	392.2	392.2	0.0	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2
5	392.2	392.2	392.2	392.2	0.0	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2
6	392.2	392.2	392.2	392.2	392.2	0.0	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2	392.2
7	392.2	392.2	392.2	392.2	392.2	392.2	0.0	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9
8	392.2	392.2	392.2	392.2	392.2	392.2	164.9	0.0	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9
9	392.2	392.2	392.2	392.2	392.2	392.2	164.9	164.9	0.0	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9
10	392.2	392.2	392.2	392.2	392.2	392.2	164.9	164.9	164.9	0.0	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9
11	392.2	392.2	392.2	392.2	392.2	392.2	164.9	164.9	164.9	164.9	0.0	164.9	164.9	164.9	164.9	164.9	164.9	164.9
12	392.2	392.2	392.2	392.2	392.2	392.2	164.9	164.9	164.9	164.9	164.9	0.0	164.9	164.9	164.9	164.9	164.9	164.9
13	392.2	392.2	392.2	392.2	392.2	392.2	164.9	164.9	164.9	164.9	164.9	164.9	0.0	164.9	164.9	164.9	164.9	164.9
14	392.2	392.2	392.2	392.2	392.2	392.2	164.9	164.9	164.9	164.9	164.9	164.9	164.9	0.0	164.9	164.9	164.9	164.9
15	392.2	392.2	392.2	392.2	392.2	392.2	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9	0.0	164.9	164.9	164.9
16	392.2	392.2	392.2	392.2	392.2	392.2	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9	0.0	164.9	164.9
17	392.2	392.2	392.2	392.2	392.2	392.2	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9	0.0	164.9
18	392.2	392.2	392.2	392.2	392.2	392.2	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9	164.9	0.0

Table A.15 O/D Matrix(Radial Circular, CBD Demand: 90%)

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0.0	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9
2	429.9	0.0	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9
3	429.9	429.9	0.0	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9
4	429.9	429.9	429.9	0.0	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9
5	429.9	429.9	429.9	429.9	0.0	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9
6	429.9	429.9	429.9	429.9	429.9	0.0	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9	429.9
7	429.9	429.9	429.9	429.9	429.9	429.9	0.0	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2
8	429.9	429.9	429.9	429.9	429.9	429.9	115.2	0.0	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2
9	429.9	429.9	429.9	429.9	429.9	429.9	115.2	115.2	0.0	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2
10	429.9	429.9	429.9	429.9	429.9	429.9	115.2	115.2	115.2	0.0	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2
11	429.9	429.9	429.9	429.9	429.9	429.9	115.2	115.2	115.2	115.2	0.0	115.2	115.2	115.2	115.2	115.2	115.2	115.2
12	429.9	429.9	429.9	429.9	429.9	429.9	115.2	115.2	115.2	115.2	115.2	0.0	115.2	115.2	115.2	115.2	115.2	115.2
13	429.9	429.9	429.9	429.9	429.9	429.9	115.2	115.2	115.2	115.2	115.2	115.2	0.0	115.2	115.2	115.2	115.2	115.2
14	429.9	429.9	429.9	429.9	429.9	429.9	115.2	115.2	115.2	115.2	115.2	115.2	115.2	0.0	115.2	115.2	115.2	115.2
15	429.9	429.9	429.9	429.9	429.9	429.9	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	0.0	115.2	115.2	115.2
16	429.9	429.9	429.9	429.9	429.9	429.9	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	0.0	115.2	115.2
17	429.9	429.9	429.9	429.9	429.9	429.9	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	0.0	115.2
18	429.9	429.9	429.9	429.9	429.9	429.9	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	0.0

Appendix B. Optima Network by Index

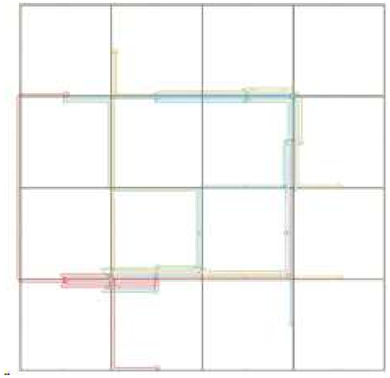
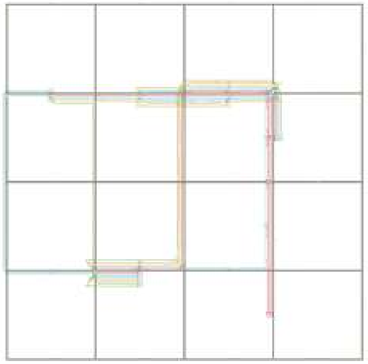
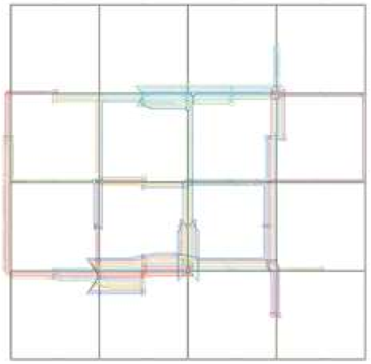
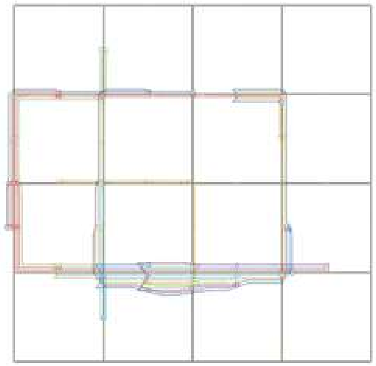
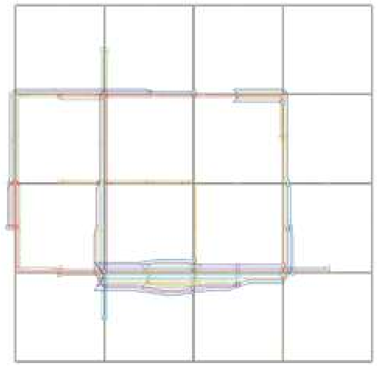
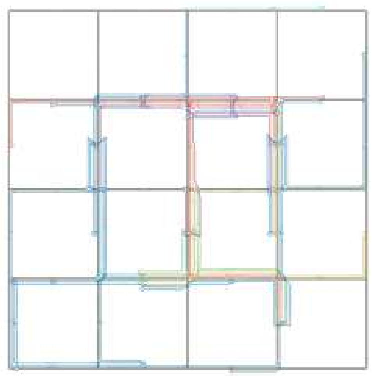
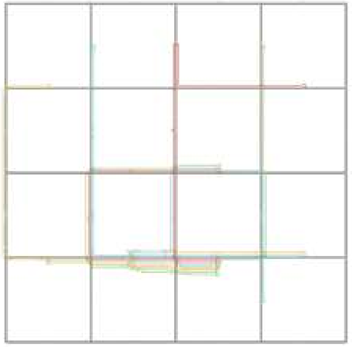
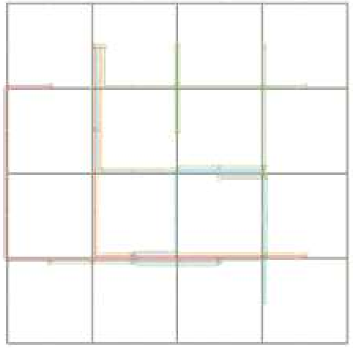
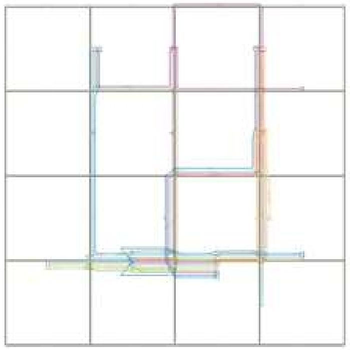
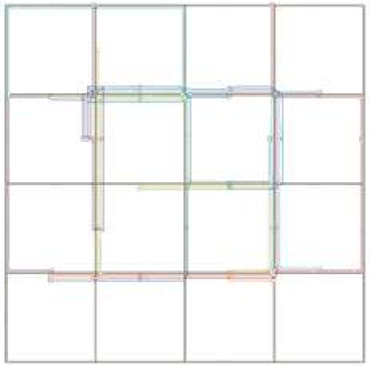
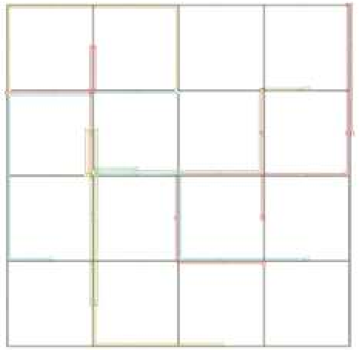
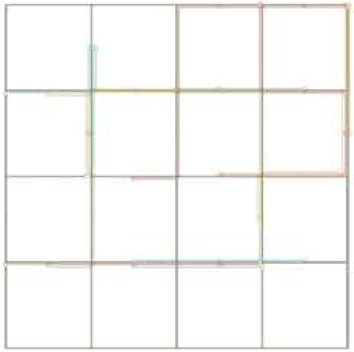
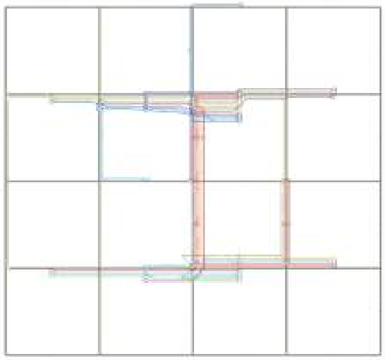
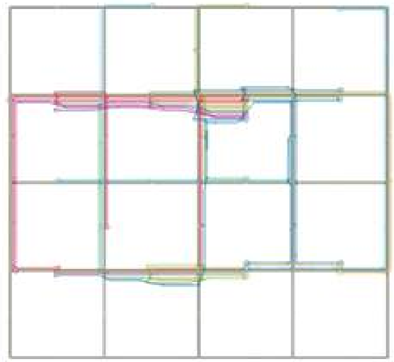
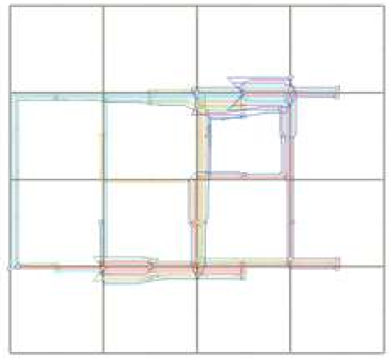
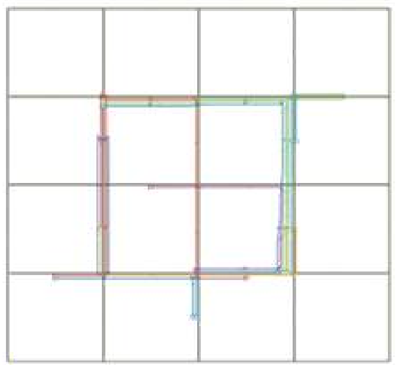
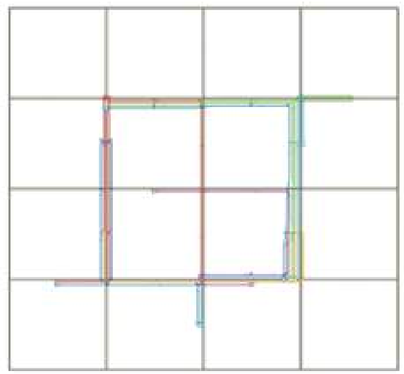
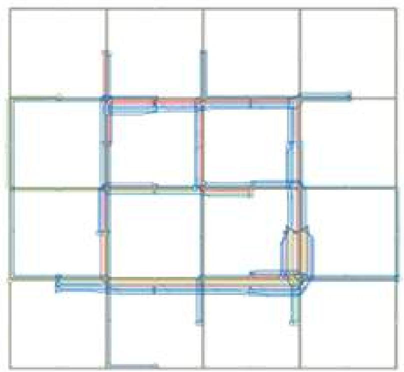
Profit	Unmet Demand	Equity
		
Demand ratio of CBD : -90%		
		
Demand ratio of CBD : -60%		

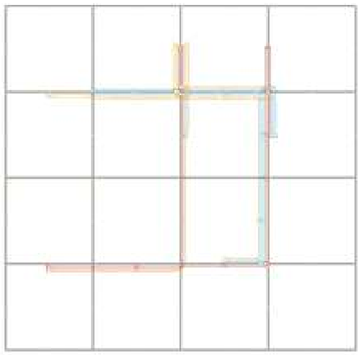
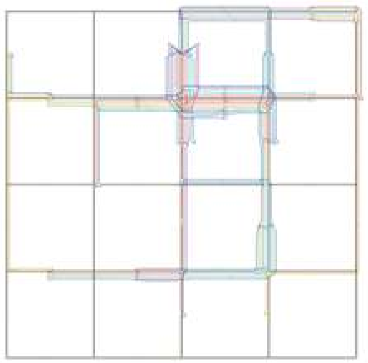
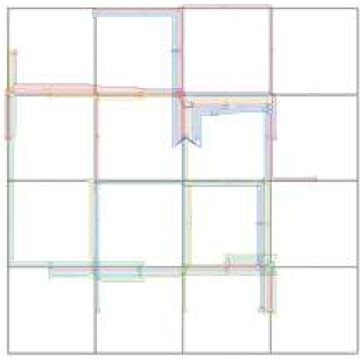
Figure B.1 Optimal Network by Index (Grid Network)

Profit	Unmet Demand	Equity
		
Demand ratio of CBD : -30%		
		
Demand ratio of CBD : 0%		

Continue Figure B.1

Profit	Unmet Demand	Equity
		
Demand ratio of CBD : 30%		
		
Demand ratio of CBD : 60%		

Continue Figure B.1

<table>
<tr><td>Profit</td><td>Unmet Demand</td><td>Equity</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3">Demand ratio of CBD : 90%</td></tr>
</table>

Continue Figure B.1

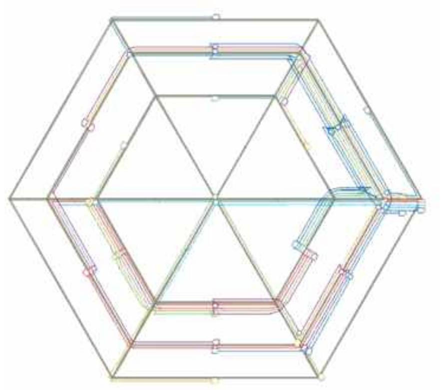
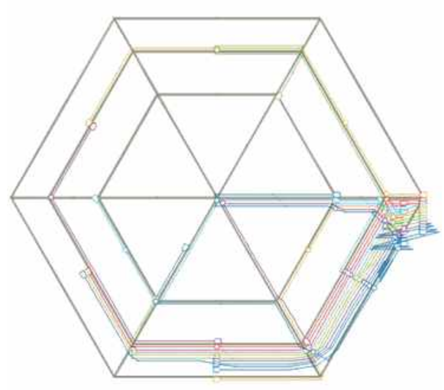
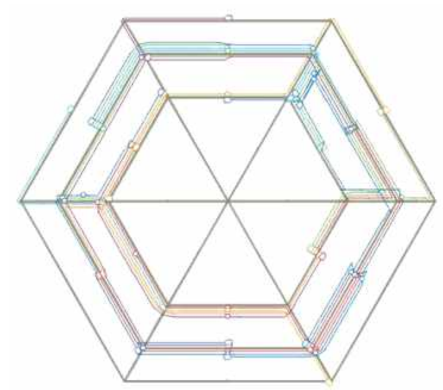
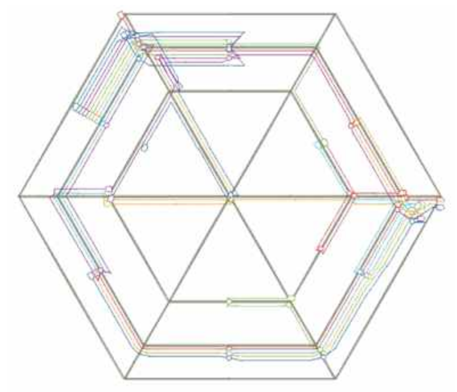
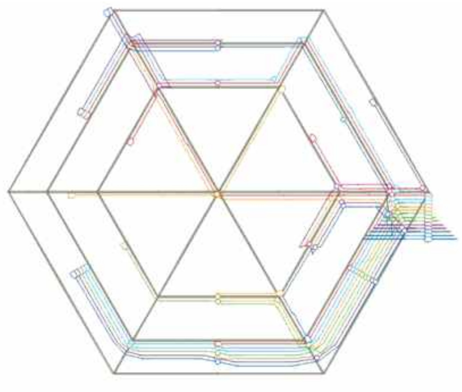
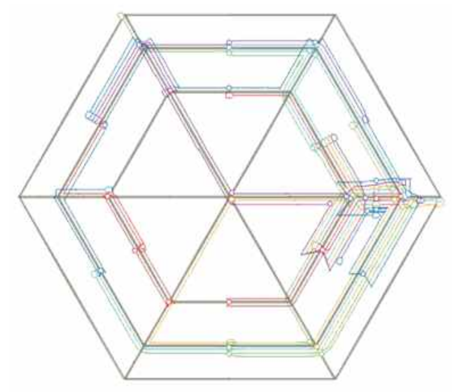
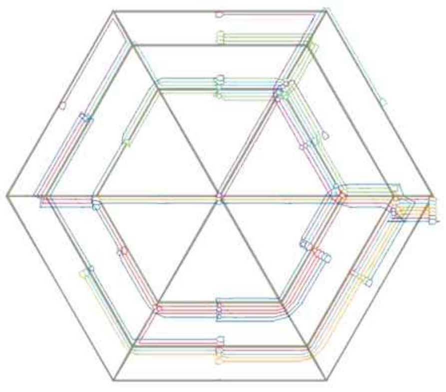
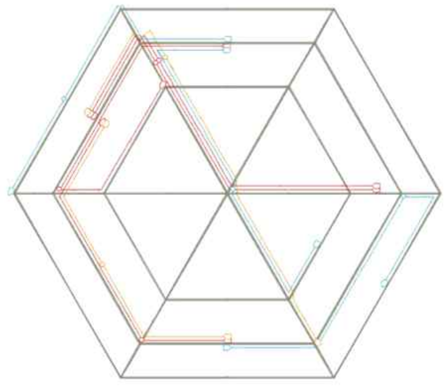
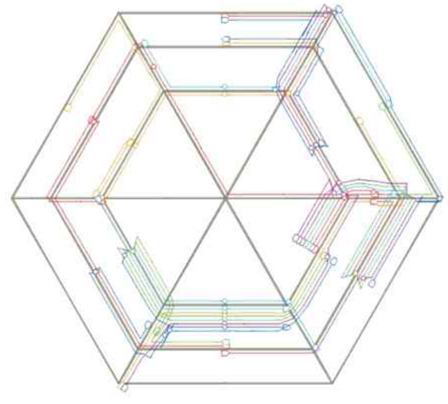
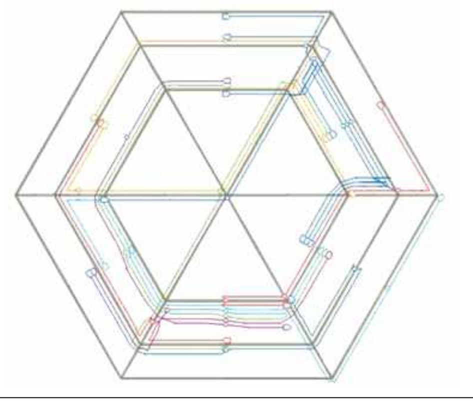
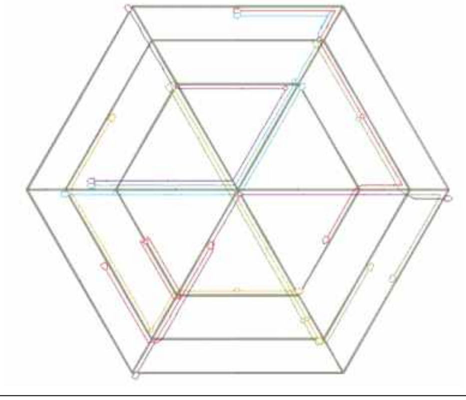
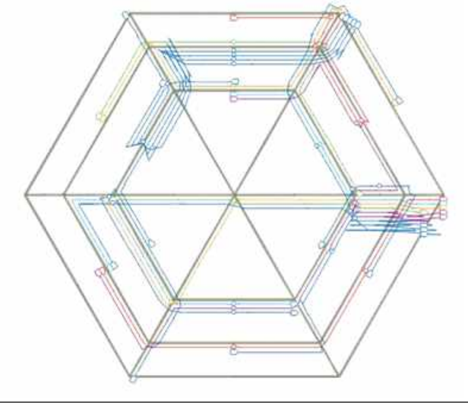
<table>
<tr><th>Profit</th><th>Unmet Demand</th><th>Equity</th></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3">Demand ratio of CBD : -90%</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3">Demand ratio of CBD : -60%</td></tr>
</table>

Figure B.2 Optimal Network by Index (Radial Circular Network)

<table>
<tr><th>Profit</th><th>Unmet Demand</th><th>Equity</th></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3">Demand ratio of CBD : -30%</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3">Demand ratio of CBD : 0%</td></tr>
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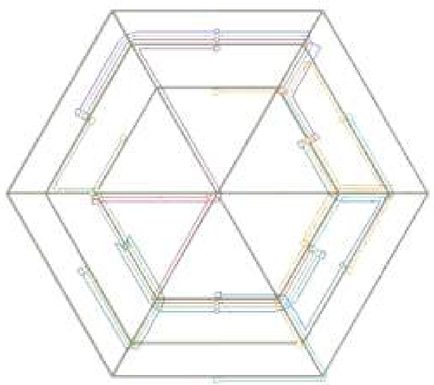
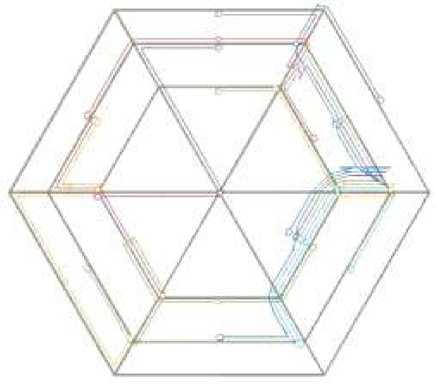
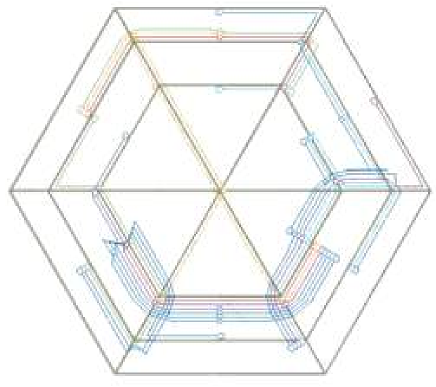
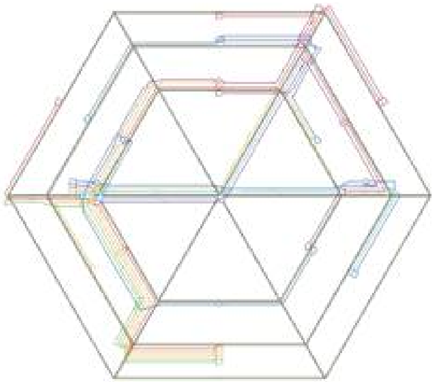
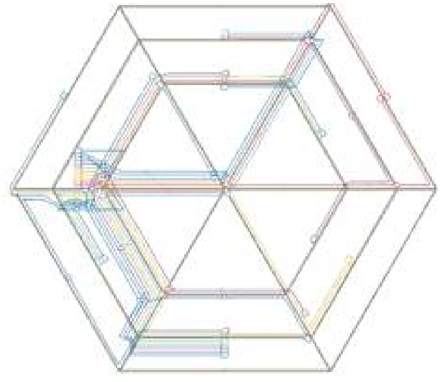
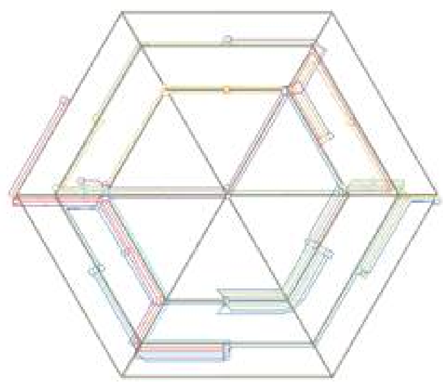
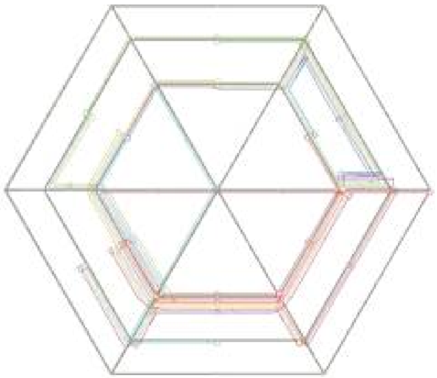
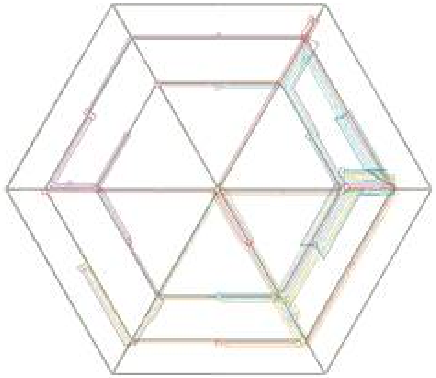
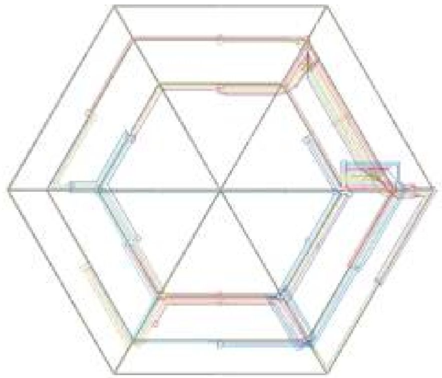
Continue Figure B.2

Profit	Unmet Demand	Equity
		
Demand ratio of CBD : 30%		
		
Demand ratio of CBD : 60%		

Continue Figure B.2

Profit	Unmet Demand	Equity
		
Demand ratio of CBD : 90%		

Continue Figure B.2

Appendix C. Result of Optimal Network

Table C.1 Result of Optimal Network(Grid Network, Ratio of CBD Demand:-90%)

Profit (M-won)	Unmet Demand (Person)	Equity	Car OD(%)	Transit OD (%)	Avg. lines/seg	Dev.Line /seg	Person /km	# oflines/seg (center, %)		# oflines/seg (other, %)		Avg. OD Travel dist (km)	Avg.Wait (min)	Total Fleet	Total Length (km)	# Lines
30.06	908	0.706	68.8	31.2	1.09	1.72	38.97	132	75.9	42	24.1	7.60	22.59	38	348	10
30.03	58	0.701	67.5	32.5	1.66	2.97	25.32	190	71.4	76	28.6	8.56	23.72	64	532	17
29.80	-	0.743	68.2	31.8	1.11	2.16	29.01	150	84.3	28	15.7	7.91	20.73	50	356	10
29.65	-	0.727	68.6	31.4	1.13	1.94	31.08	138	76.7	42	23.3	8.03	22.59	44	360	10
29.59	230	0.673	66.2	33.8	1.71	3.10	17.98	224	81.8	50	18.2	8.03	18.65	92	548	17
29.53	49	0.698	66.9	33.1	1.05	1.63	20.11	104	61.9	64	38.1	8.95	10.84	74	336	10
29.47	49	0.698	66.9	33.1	1.06	1.63	19.87	104	61.2	66	38.8	9.04	10.80	74	340	10
29.12	222	0.657	66.2	33.8	1.83	2.59	16.57	220	75.3	72	24.7	8.10	16.08	100	584	17
28.11	841	0.655	66.2	33.8	1.84	2.61	14.25	218	74.1	76	25.9	7.72	15.61	112	588	17
26.91	664	0.657	66.7	33.3	1.64	2.59	12.82	194	74.0	68	26.0	8.06	11.11	134	524	17
24.75	203	0.668	65.9	34.1	2.05	3.12	9.45	272	82.9	56	17.1	8.05	7.91	148	656	17
24.75	203	0.668	65.9	34.1	2.05	3.12	9.45	272	82.9	56	17.1	8.04	7.91	148	656	17

Table C.2 Result of Optimal Network(Grid Network, Ratio of CBD Demand:-60%)

Profit (M-won)	Unmet Demand (Person)	Equity	Car OD(%)	Transit OD (%)	Avg. lines/seg	Dev.Line /seg	Person /km	# oflines/seg (center, %)		# oflines/seg (other, %)		Avg. OD Travel dist (km)	Avg.Wait (min)	Total Fleet	Total Length (km)	# Lines
23.66	819	0.661	66.7	33.3	1.85	2.23	9.01	184	62.2	112	37.8	7.48	7.53	202	592	20
29.21	312	0.671	66.3	33.7	1.31	2.37	17.03	174	82.9	36	17.1	7.53	8.71	108	420	14
23.56	1,106	0.657	66.6	33.4	1.89	2.22	8.84	184	60.9	118	39.1	7.84	7.48	202	604	20
23.63	1,292	0.658	66.7	33.3	1.95	2.31	8.95	208	66.7	104	33.3	7.00	6.94	192	624	20
28.40	156	0.664	66.7	33.3	1.44	2.55	15.88	196	85.2	34	14.8	7.31	8.76	104	460	14
24.36	2,914	0.658	66.0	34.0	1.91	2.72	9.18	232	75.8	74	24.2	7.84	6.90	194	612	20
24.64	2,631	0.662	66.6	33.4	1.90	2.57	9.78	230	75.7	74	24.3	7.53	7.20	182	608	20
29.20	107	0.735	68.8	31.2	1.16	1.66	28.03	122	65.6	64	34.4	8.05	19.38	66	372	14
28.98	234	0.680	66.7	33.3	1.28	2.50	17.36	180	88.2	24	11.8	7.17	8.73	108	408	14
25.96	22	0.683	67.5	32.5	1.50	2.00	12.28	174	72.5	66	27.5	6.78	8.15	122	480	14
29.27	527	0.702	67.4	32.6	1.45	2.48	20.89	152	65.5	80	34.5	8.13	15.78	76	464	14
28.70	101	0.700	67.9	32.1	1.44	2.58	20.48	168	73.0	62	27.0	7.76	15.48	76	460	14
22.47	2,773	0.644	66.4	33.6	1.99	2.28	7.95	212	66.7	106	33.3	7.65	6.04	216	636	20
22.65	3,590	0.655	66.5	33.5	1.99	2.34	8.12	232	73.0	86	27.0	7.47	6.22	208	636	20
28.61	185	0.679	66.7	33.3	1.36	2.37	16.30	160	73.4	58	26.6	8.21	11.06	104	436	14

Table C.3 Result of Optimal Network(Grid Network, Ratio of CBD Demand:-30%)

Profit (M-won)	Unmet Demand (Person)	Equity	Car OD(%)	Transit OD (%)	Avg. lines/seg	Dev.Line /seg	Person /km	# oflines/seg (center, %)		# oflines/seg (other, %)		Avg. OD Travel dist (km)	Avg.Wait (min)	Total Fleet	Total Length (km)	# Lines
30.52	615	0.754	67.4	32.6	0.90	1.63	28.59	112	77.8	32	22.2	9.24	10.35	50	288	8
30.46	-	0.707	66.6	33.4	0.95	1.42	23.33	112	73.7	40	26.3	8.49	8.55	60	304	8
29.69	568	0.700	67.8	32.2	0.89	1.33	24.97	112	78.9	30	21.1	8.31	8.97	58	284	8
29.64	334	0.687	66.3	33.7	1.36	2.25	18.29	172	78.9	46	21.1	8.46	9.72	88	436	13
29.56	429	0.680	67.2	32.8	1.45	2.24	21.30	174	75.0	58	25.0	8.12	12.24	70	464	13
29.27	364	0.673	66.9	33.1	1.34	2.05	18.93	158	73.8	56	26.2	8.17	10.62	84	428	13
29.26	-	0.668	65.6	34.4	1.39	2.12	15.66	172	77.5	50	22.5	8.38	7.88	104	444	13
28.51	2,409	0.657	66.7	33.3	1.31	1.76	16.19	142	67.6	68	32.4	8.21	8.29	100	420	13
28.09	376	0.663	65.6	34.4	2.10	3.28	13.22	246	73.2	90	26.8	7.89	10.74	118	672	19
27.58	772	0.654	66.3	33.7	2.04	2.40	13.37	204	62.6	122	37.4	7.66	11.74	116	652	19
27.05	688	0.660	66.3	33.7	2.01	2.80	12.48	224	69.6	98	30.4	8.32	10.08	128	644	19
26.16	950	0.646	65.8	34.2	2.09	2.64	10.74	228	68.3	106	31.7	8.19	8.55	144	668	19
25.87	1,888	0.646	66.0	34.0	2.11	2.65	10.58	232	68.6	106	31.4	8.15	8.57	144	676	19
25.67	271	0.661	65.9	34.1	2.18	2.48	10.31	224	64.4	124	35.6	8.18	9.39	144	696	19
25.64	249	0.665	66.0	34.0	2.11	2.85	10.36	222	65.7	116	34.3	8.44	8.57	148	676	19
25.64	520	0.659	65.8	34.2	2.04	3.10	10.22	254	77.9	72	22.1	7.93	7.91	156	652	19
25.54	772	0.658	66.0	34.0	2.05	3.11	10.22	254	77.4	74	22.6	7.97	7.98	156	656	19

Table C.4 Result of Optimal Network(Grid Network, Ratio of CBD Demand: 0%)

Profit (M-won)	Unmet Demand (Person)	Equity	Car OD(%)	Transit OD (%)	Avg. lines/seg	Dev.Line /seg	Person /km	# oflines/seg (center, %)		# oflines/seg (other, %)		Avg. OD Travel dist (km)	Avg.Wait (min)	Total Fleet	Total Length (km)	# Lines
26.79	289	0.662	66.4	33.6	1.55	2.381701	12.18	208	83.9	40	16.1	8.05	7.46	136	496	15
27.31	333	0.661	66.1	33.9	1.5	2.19089	12.63	180	75.0	60	25.0	7.82	7.28	130	480	15
27.93	619	0.664	67.3	32.7	1.525	2.25818	15.85	180	73.8	64	26.2	7.83	9.17	102	488	15
28.43	799	0.664	67.0	33.0	1.4625	2.196268	16.65	176	75.2	58	24.8	7.80	9.17	102	468	15
28.27	1,253	0.652	67.1	32.9	1.4	1.991231	16.47	178	79.5	46	20.5	7.22	9.90	108	448	15
28.32	-	0.777	68.5	31.5	0.9125	1.014812	21.06	72	49.3	74	50.7	9.18	12.12	76	292	9
28.01	-	0.772	68.8	31.2	0.9125	1.002419	20.86	72	49.3	74	50.7	8.55	12.12	76	292	9
27.85	1,092	0.649	67.3	32.7	1.4375	2.072702	15.78	182	79.1	48	20.9	7.17	9.80	108	460	15
27.52	1,021	0.649	67.2	32.8	1.4625	1.612015	14.71	150	64.1	84	35.9	7.95	9.60	114	468	15
27.54	274	0.664	66.8	33.2	1.525	2.397785	14.04	210	86.1	34	13.9	7.31	8.48	118	488	15
27.44	564	0.645	66.1	33.9	1.5	2.313007	12.80	206	85.8	34	14.2	7.80	7.58	136	480	15
28.99	296	0.721	68.0	32.0	1.4125	1.895348	21.87	150	66.4	76	33.6	7.33	18.32	80	452	14
27.25	503	0.644	66.9	33.1	1.5	1.923538	13.70	178	74.2	62	25.8	7.76	9.49	120	480	15
27.19	68	0.679	66.2	33.8	1.525	2.31827	12.60	208	85.2	36	14.8	7.75	7.62	136	488	15
29.04	353	0.664	67.1	32.9	1.575	1.835586	18.76	166	65.9	86	34.1	7.64	18.63	88	504	15
28.16	1,162	0.640	66.8	33.2	1.4125	1.663534	15.38	158	69.9	68	30.1	7.76	9.33	114	452	15
26.14	63	0.680	67.0	33.0	1.525	2.371576	11.95	206	84.4	38	15.6	7.38	7.34	136	488	15
29.59	993	0.672	67.7	32.3	0.8625	0.984172	24.00	70	50.7	68	49.3	8.33	12.87	76	276	9

Table C.5 Result of Optimal Network(Grid Network, Ratio of CBD Demand: 30%)

Profit (M-won)	Unmet Demand (Person)	Equity	Car OD(%)	Transit OD (%)	Avg. lines/seg	Dev.Line /seg	Person /km	# oflines/seg (center, %)		# oflines/seg (other, %)		Avg. OD Travel dist (km)	Avg.Wait (min)	Total Fleet	Total Length (km)	# Lines
30.33	539	0.673	67.1	32.9	1.30	2.37	24.94	166	79.8	42	20.2	8.23	12.45	86	416	17
30.28	427	0.715	67.3	32.7	1.31	2.87	25.86	176	83.8	34	16.2	8.68	13.29	80	420	17
30.16	433	0.708	67.1	32.9	1.39	2.78	24.01	182	82.0	40	18.0	8.26	13.20	82	444	17
30.14	430	0.693	67.0	33.0	1.59	3.02	23.18	186	73.2	68	26.8	8.67	14.00	78	508	17
29.99	346	0.704	67.1	32.9	1.46	2.85	22.80	190	81.2	44	18.8	8.37	13.18	82	468	17
29.97	154	0.680	66.9	33.1	1.50	2.64	21.99	188	78.3	52	21.7	8.23	12.75	86	480	17
29.93	573	0.672	66.6	33.4	1.43	2.37	20.61	188	82.5	40	17.5	8.17	11.10	94	456	17
29.87	-	0.704	66.9	33.1	1.50	3.03	21.62	196	81.7	44	18.3	7.97	12.77	84	480	17
29.71	580	0.669	66.7	33.3	1.48	2.37	20.00	188	79.7	48	20.3	8.15	11.19	94	472	17
29.57	137	0.702	67.2	32.8	1.70	3.11	21.55	196	72.1	76	27.9	8.79	14.03	78	544	17
29.57	300	0.671	67.1	32.9	1.64	2.69	20.90	196	74.8	66	25.2	8.36	13.13	82	524	17
29.36	403	0.666	66.5	33.5	1.75	2.78	18.06	206	73.6	74	26.4	8.28	12.21	90	560	17
29.25	58	0.669	66.2	33.8	1.83	2.87	17.05	224	76.7	68	23.3	8.48	11.90	92	584	17
29.24	109	0.661	66.3	33.7	1.74	3.02	17.26	228	82.0	50	18.0	8.50	11.38	96	556	17
29.23	462	0.658	67.0	33.0	1.69	2.49	19.14	206	76.3	64	23.7	8.35	12.63	88	540	17
28.94	-	0.679	66.6	33.4	1.68	2.18	16.97	170	63.4	98	36.6	8.74	11.38	96	536	17
28.89	-	0.679	66.6	33.4	1.66	2.18	17.02	168	63.2	98	36.8	8.81	11.35	96	532	17
28.58	139	0.660	66.0	34.0	1.76	2.72	14.87	218	77.3	64	22.7	8.33	9.91	112	564	17

Table C.6 Result of Optimal Network(Grid Network, Ratio of CBD Demand: 60%)

Profit (M-won)	Unmet Demand (Person)	Equity	Car OD(%)	Transit OD (%)	Avg. lines/seg	Dev.Line /seg	Person /km	# oflines/seg (center, %)		# oflines/seg (other, %)		Avg. OD Travel dist (km)	Avg.Wait (min)	Total Fleet	Total Length (km)	# Lines
30.68	428	0.666	66.8	33.2	0.91	1.59	25.45	134	91.8	12	8.2	7.47	14.11	64	292	9
30.67	91	0.658	67.0	33.0	0.95	1.77	26.92	138	90.8	14	9.2	7.39	14.05	58	304	9
30.63	74	0.649	66.0	34.0	0.93	1.61	21.08	132	89.2	16	10.8	7.68	8.71	78	296	9
30.62	4	0.650	66.5	33.5	0.95	1.54	23.43	138	90.8	14	9.2	7.63	12.11	66	304	9
30.21	91	0.643	65.9	34.1	0.94	1.44	19.17	118	78.7	32	21.3	7.63	6.92	84	300	9
30.02	69	0.648	66.2	33.8	0.91	1.44	19.53	118	80.8	28	19.2	7.48	6.95	84	292	9
29.91	-	0.733	67.8	32.2	0.94	1.79	26.91	120	80.0	30	20.0	8.33	16.40	56	300	9
27.85	15	0.647	65.5	34.5	1.90	2.77	12.71	250	82.2	54	17.8	7.61	11.56	136	608	19
27.83	18	0.639	65.6	34.4	1.89	2.77	12.83	250	82.8	52	17.2	7.51	11.64	136	604	19
27.08	319	0.634	65.7	34.3	1.94	2.51	11.84	234	75.5	76	24.5	7.71	10.94	136	620	19
27.04	-	0.685	66.4	33.6	1.95	3.22	12.64	248	79.5	64	20.5	7.92	14.22	126	624	19
26.99	346	0.634	65.7	34.3	1.98	2.49	11.67	232	73.4	84	26.6	7.72	10.96	136	632	19

Table C.7 Result of Optimal Network(Grid Network, Ratio of CBD Demand: 90%)

Profit (M-won)	Unmet Demand (Person)	Equity	Car OD(%)	Transit OD (%)	Avg. lines/seg	Dev.Line /seg	Person /km	# oflines/seg (center, %)		# oflines/seg (other, %)		Avg. OD Travel dist (km)	Avg.Wait (min)	Total Fleet	Total Length (km)	# Lines
30.22	775	0.689	67.4	32.6	0.86	1.66	26.10	112	81.2	26	18.8	7.95	8.57	64	276	9
30.08	453	0.717	68.1	31.9	0.91	1.48	30.13	102	69.9	44	30.1	8.42	15.45	52	292	9
30.07	224	0.658	67.3	32.7	0.88	1.59	24.34	96	68.6	44	31.4	7.82	8.25	68	280	9
29.35	-	0.707	67.3	32.7	0.98	1.24	20.88	90	57.7	66	42.3	7.92	8.15	72	312	9
29.26	-	0.694	67.6	32.4	0.91	1.45	21.73	98	67.1	48	32.9	7.78	7.91	72	292	9
28.79	175	0.693	67.5	32.5	0.90	1.31	19.18	82	56.9	62	43.1	8.47	6.91	84	288	9
28.42	1,070	0.656	67.3	32.7	1.88	3.18	17.42	206	68.7	94	31.3	7.96	19.21	98	600	19
27.48	1,583	0.654	66.6	33.4	1.88	2.77	13.56	194	64.7	106	35.3	8.36	11.85	122	600	19
27.44	1,248	0.655	66.6	33.4	1.88	2.72	13.62	192	64.0	108	36.0	8.38	11.90	122	600	19
26.86	427	0.654	66.1	33.9	1.84	2.58	11.99	210	71.4	84	28.6	7.81	10.25	144	588	19
26.60	491	0.641	65.8	34.2	1.96	2.63	11.29	220	70.1	94	29.9	7.92	8.31	146	628	19
26.57	57	0.687	66.8	33.2	2.04	2.79	12.31	196	60.1	130	39.9	8.13	13.39	132	652	19
26.25	456	0.652	66.2	33.8	1.95	2.46	11.26	218	69.9	94	30.1	7.98	8.33	146	624	19
25.67	160	0.673	66.0	34.0	2.06	3.15	10.41	276	83.6	54	16.4	7.41	8.17	148	660	19
25.55	424	0.655	66.6	33.4	1.94	2.59	10.73	204	65.8	106	34.2	7.94	9.79	154	620	19
25.53	197	0.656	66.0	34.0	1.96	2.57	10.22	218	69.4	96	30.6	8.20	9.82	164	628	19
25.20	183	0.652	66.7	33.3	1.98	2.63	10.44	204	64.6	112	35.4	8.11	9.73	154	632	19
24.84	32	0.655	66.0	34.0	1.90	2.75	9.58	212	69.7	92	30.3	8.18	7.02	174	608	19
24.53	1,295	0.639	66.7	33.3	1.94	2.76	9.79	216	69.7	94	30.3	8.22	8.48	166	620	19
23.92	-	0.684	66.4	33.6	2.16	2.89	9.00	190	54.9	156	45.1	7.86	7.53	174	692	20
23.35	901	0.639	66.5	33.5	1.95	2.48	8.63	198	63.5	114	36.5	8.45	6.67	188	624	19
23.27	31	0.658	66.7	33.3	2.01	2.37	8.65	214	66.5	108	33.5	8.11	6.70	184	644	19

Table C.8 Result of Optimal Network(Radial Circular Network, Ratio of CBD Demand: -90%)

Profit (M-won)	Unmet Demand (Person)	Equity	Car OD(%)	Transit OD (%)	Avg. lines/seg	Dev.Line /seg	Person /km	# oflines/seg (center, %)		# oflines/seg (other, %)		Avg. OD Travel dist (km)	Avg.Wait (min)	Total Fleet	Total Length (km)	# Lines
43.03	382	0.822	57.1	42.9	2.11	1.92	20.09	58	21.0	218	79.0	10.52	12.32	120	646.90	20
42.58	-	1.060	59.4	40.6	3.57	1.82	27.66	12	4.6	250	95.4	10.71	14.52	86	602.14	20
41.82	1,738	0.785	58.8	41.2	1.91	2.00	21.45	74	25.7	214	74.3	10.93	15.56	106	653.48	20
41.45	275	0.857	59.0	41.0	2.67	2.11	21.03	70	23.0	234	77.0	10.27	12.86	110	642.50	20
40.48	934	0.795	58.8	41.2	2.70	1.90	17.73	86	31.4	188	68.6	10.97	11.41	128	649.26	20
40.15	2,942	0.740	58.8	41.2	2.24	1.89	17.05	58	21.3	214	78.7	10.18	11.38	130	655.84	20
39.56	2,085	0.736	57.9	42.1	2.20	2.01	14.43	90	31.0	200	69.0	10.86	9.93	154	684.14	20
39.21	2,367	0.707	58.3	41.7	2.02	1.88	14.47	74	27.4	196	72.6	10.74	9.46	154	669.52	20
38.69	134	0.787	59.6	40.4	2.13	1.97	15.77	72	25.4	212	74.6	10.34	10.96	134	681.52	20
38.60	1,408	0.786	58.4	41.6	2.35	2.06	13.79	68	23.0	228	77.0	10.92	9.40	162	677.58	20
38.38	950	0.745	59.0	41.0	2.19	2.04	14.30	78	26.5	216	73.5	10.23	8.65	154	677.00	20
38.22	1,133	0.738	59.2	40.8	2.11	2.07	14.32	76	25.5	222	74.5	10.14	9.07	154	674.88	20
36.89	1,406	0.731	58.4	41.6	2.00	2.14	11.73	66	21.4	242	78.6	10.79	7.14	192	661.46	20
36.84	74	0.744	58.5	41.5	2.15	2.17	11.79	76	24.4	236	75.6	10.39	8.45	188	676.82	20
36.44	3	0.761	58.8	41.2	2.08	2.21	11.68	68	21.4	250	78.6	10.45	8.40	188	678.12	20
35.85	1,646	0.728	59.2	40.8	2.17	2.22	11.47	62	19.4	258	80.6	10.77	7.47	188	674.52	20

Table C.9 Result of Optimal Network(Radial Circular Network, Ratio of CBD Demand: -60%)

Profit (M-won)	Unmet Demand (Person)	Equity	Car OD(%)	Transit OD (%)	Avg. lines/seg	Dev.Line /seg	Person /km	# oflines/seg (center, %)		# oflines/seg (other, %)		Avg. OD Travel dist (km)	Avg.Wait (min)	Total Fleet	Total Length (km)	# Lines
41.85	577	0.859	60.2	39.8	2.15	1.58	27.91	20	8.8	208	91.2	9.53	13.84	82	573.92	18
41.80	1,152	0.840	59.6	40.4	2.17	1.58	24.57	28	12.3	200	87.7	10.13	13.02	90	581.34	18
41.48	136	0.868	60.1	39.9	2.03	1.61	25.57	24	10.3	208	89.7	10.59	13.04	88	581.46	18
41.44	890	0.828	60.4	39.6	2.17	1.68	26.95	24	9.9	218	90.1	10.24	13.86	86	575.18	18
41.43	315	0.845	59.7	40.3	2.24	1.75	23.37	28	11.1	224	88.9	10.50	12.99	92	623.26	18
41.43	2,015	0.822	60.3	39.7	2.15	1.75	26.27	34	13.5	218	86.5	10.22	13.63	86	579.18	18
41.29	738	0.805	60.1	39.9	2.08	1.86	24.39	32	11.9	236	88.1	9.54	13.88	86	622.96	18
41.27	622	0.832	60.2	39.8	2.07	1.85	25.02	32	12.0	234	88.0	9.74	13.95	86	615.88	18
40.36	2,363	0.751	60.8	39.2	1.97	1.75	23.57	50	19.8	202	80.2	10.50	12.54	94	588.84	18
40.30	613	0.824	60.3	39.7	2.24	1.74	21.44	38	15.2	212	84.8	10.67	12.17	98	602.20	18
40.17	481	0.844	60.4	39.6	2.28	1.75	21.30	36	14.3	216	85.7	10.53	12.19	98	605.86	18
40.09	1,572	0.783	61.0	39.0	1.95	1.76	23.22	44	17.3	210	82.7	10.43	12.52	94	593.84	18
40.06	615	0.817	60.9	39.1	2.47	1.79	22.95	32	12.4	226	87.6	11.01	13.25	94	608.92	18
39.92	218	0.774	60.0	40.0	2.29	1.76	19.37	32	12.6	222	87.4	10.20	11.80	108	617.10	18
39.91	3,382	0.722	61.1	38.9	2.19	1.81	23.16	54	20.8	206	79.2	10.56	13.24	94	581.70	18
39.87	204	0.784	60.7	39.3	2.38	1.82	21.36	34	13.0	228	87.0	10.76	12.58	96	618.72	18
39.82	174	0.809	60.2	39.8	2.20	1.96	19.51	34	12.1	248	87.9	9.96	12.27	104	624.96	18
39.72	1,857	0.738	60.8	39.2	2.05	1.92	21.19	50	18.1	226	81.9	10.22	12.95	98	617.26	18
39.37	1,801	0.708	60.5	39.5	2.28	1.90	19.26	66	24.1	208	75.9	10.16	11.26	106	632.04	18
39.33	45	0.818	60.6	39.4	2.59	1.93	19.28	38	13.7	240	86.3	11.24	12.08	106	604.38	18
39.27	1,383	0.727	60.4	39.6	2.26	1.90	18.57	48	17.5	226	82.5	10.74	10.67	116	586.20	18
39.23	1,257	0.748	60.5	39.5	2.24	1.96	18.95	46	16.3	236	83.7	11.11	11.79	114	600.72	18
39.09	498	0.758	60.6	39.4	2.23	2.01	18.64	40	13.8	250	86.2	11.25	11.81	114	610.94	18
37.94	8	0.815	61.2	38.8	2.73	1.94	17.35	34	12.1	246	87.9	12.27	11.69	120	603.38	18
37.83	23	0.811	61.0	39.0	2.70	1.97	16.56	38	13.4	246	86.6	12.27	11.52	120	624.38	18
36.44	-	0.883	62.2	37.8	2.96	1.99	16.10	34	11.9	252	88.1	13.28	11.50	122	612.04	18

Table C.10 Result of Optimal Networkn(Radial Circular Network, Ratio of CBD Demand: -30%)

Profit (M-won)	Unmet Demand (Person)	Equity	Car OD(%)	Transit OD (%)	Avg. lines/seg	Dev.Line /seg	Person /km	# oflines/seg (center, %)		# oflines/seg (other, %)		Avg. OD Travel dist (km)	Avg.Wait (min)	Total Fleet	Total Length (km)	# Lines
38.87	2,404	0.788	61.0	39.0	2.21	2.08	19.37	104	34.7	196	65.3	10.84	18.87	106	662.98	20
38.61	760	0.810	60.6	39.4	2.72	2.08	17.60	146	48.7	154	51.3	11.59	12.65	122	667.90	20
37.71	1,644	0.789	60.8	39.2	2.25	2.01	16.10	124	42.8	166	57.2	11.56	10.90	138	642.80	20
37.31	1,128	0.721	60.2	39.8	2.21	2.03	14.32	108	37.0	184	63.0	11.17	8.12	162	619.62	20
37.26	760	0.721	60.0	40.0	2.63	2.22	14.00	108	33.8	212	66.3	11.08	9.62	152	674.56	20
36.71	621	0.932	62.1	37.9	2.41	2.11	16.56	110	36.2	194	63.8	11.85	13.83	128	659.06	20
36.37	420	0.910	61.9	38.1	2.51	2.21	15.52	110	34.6	208	65.4	11.52	13.63	128	696.86	20
36.07	2,270	0.661	60.5	39.5	2.43	2.13	12.91	108	35.3	198	64.7	10.97	7.45	172	632.74	20
35.75	387	0.791	60.3	39.7	2.28	2.08	12.35	106	35.3	194	64.7	10.48	8.47	176	668.38	20
34.57	939	0.708	60.7	39.3	2.93	2.24	11.44	152	47.2	170	52.8	11.23	6.76	184	672.60	20
34.52	605	0.777	61.3	38.7	2.78	2.26	12.03	136	41.7	190	58.3	11.15	7.61	172	669.88	20
33.67	-	1.493	68.2	31.8	1.18	0.82	30.37	54	45.8	64	54.2	10.05	9.49	62	268.52	9
32.43	288	1.406	69.5	30.5	1.17	0.81	30.77	12	10.3	104	89.7	9.28	15.52	56	292.88	9
32.03	340	1.400	69.3	30.7	1.27	0.85	26.58	12	9.8	110	90.2	9.19	14.18	64	298.58	9
31.99	278	1.370	69.4	30.6	1.35	0.79	26.91	34	29.8	80	70.2	9.19	11.05	68	274.54	9
31.94	265	1.333	68.8	31.2	1.16	0.81	22.84	6	5.2	110	94.8	9.30	10.65	78	288.60	9
31.24	-	1.325	69.4	30.6	1.17	0.82	22.20	6	5.1	112	94.9	8.98	10.55	78	290.66	9
30.75	367	1.238	70.6	29.4	1.07	0.82	26.65	10	8.5	108	91.5	9.47	14.07	64	288.08	9

Table C.11 Result of Optimal Network(Radial Circular Network, Ratio of CBD Demand: 0%)

Profit (M-won)	Unmet Demand (Person)	Equity	Car OD(%)	Transit OD (%)	Avg. lines/seg	Dev.Line /seg	Person /km	# oflines/seg (center, %)		# oflines/seg (other, %)		Avg. OD Travel dist (km)	Avg.Wait (min)	Total Fleet	Total Length (km)	# Lines
37.34	1,122	0.840	61.9	38.1	1.55	1.58	17.45	78	34.2	150	65.8	11.76	10.76	114	523.76	15
37.03	1,351	0.822	62.1	37.9	1.40	1.58	17.31	68	29.8	160	70.2	12.16	10.57	114	520.82	15
36.91	554	0.889	62.1	37.9	1.53	1.58	17.02	80	35.1	148	64.9	11.89	10.71	116	525.74	15
36.38	670	0.822	62.3	37.7	1.82	1.58	16.20	68	29.8	160	70.2	11.54	9.02	122	521.44	15
36.03	259	0.872	62.8	37.2	1.57	1.58	16.49	58	25.4	170	74.6	11.08	9.00	122	505.16	15
35.79	3,967	0.736	61.7	38.3	2.45	2.21	14.17	114	35.8	204	64.2	11.37	8.27	154	609.38	19
35.78	486	0.813	62.4	37.6	2.42	1.81	15.27	90	34.6	170	65.4	11.76	6.92	134	500.46	15
35.78	2,111	0.759	61.5	38.5	2.14	2.10	13.83	120	39.7	182	60.3	11.23	7.77	158	604.74	19
35.63	369	0.871	62.7	37.3	2.50	1.82	15.52	106	40.5	156	59.5	12.31	8.04	130	504.86	15
35.55	539	0.808	62.4	37.6	2.42	1.83	14.88	90	34.1	174	65.9	11.74	6.91	134	512.04	15
35.02	612	0.728	61.5	38.5	2.51	2.28	12.82	78	23.8	250	76.2	11.03	7.29	164	621.78	19
34.45	130	0.867	62.5	37.5	2.63	1.99	13.18	122	42.7	164	57.3	11.75	7.60	160	605.90	19
30.16	46	1.325	71.1	28.9	0.96	0.93	26.28	8	6.0	126	94.0	8.64	12.24	66	315.92	10
29.82	-	1.329	71.3	28.7	1.00	0.93	25.77	6	4.5	128	95.5	8.33	12.24	66	318.00	10
28.87	18	1.326	71.1	28.9	1.10	1.11	19.53	16	10.0	144	90.0	9.07	9.49	80	333.78	10
28.34	-	1.305	71.7	28.3	1.00	1.08	19.91	14	9.0	142	91.0	8.30	9.21	80	313.98	10

Table C.12 Result of Optimal Network(Radial Circular Network, Ratio of CBD Demand: 30%)

Profit (M-won)	Unmet Demand (Person)	Equity	Car OD(%)	Transit OD (%)	Avg. lines/seg	Dev.Line /seg	Person /km	# oflines/seg (center, %)		# oflines/seg (other, %)		Avg. OD Travel dist (km)	Avg.Wait (min)	Total Fleet	Total Length (km)	# Lines
37.82	2,142	0.887	62.3	37.7	1.42	1.22	20.05	56	31.8	120	68.2	12.53	8.72	104	388.14	12
37.72	510	0.934	63.7	36.3	1.02	0.93	25.55	34	25.4	100	74.6	11.37	7.49	80	283.04	9
37.39	1,011	0.834	62.6	37.4	1.27	1.18	19.58	62	36.5	108	63.5	11.54	6.67	114	360.18	12
37.20	1,272	0.741	61.0	39.0	2.60	1.97	15.34	132	46.5	152	53.5	11.66	8.98	136	608.42	18
37.02	268	0.821	62.9	37.1	1.32	1.25	19.40	44	24.4	136	75.6	11.77	7.71	108	376.48	12
36.97	111	0.856	63.3	36.7	1.47	1.25	20.39	48	26.7	132	73.3	12.16	8.31	102	372.32	12
36.89	647	0.770	61.2	38.8	2.67	1.85	15.13	126	47.4	140	52.6	11.39	9.00	142	581.40	18
35.86	144	0.763	62.1	37.9	2.65	1.88	14.81	80	29.6	190	70.4	11.69	8.55	144	568.86	18
35.67	315	0.756	61.7	38.3	2.29	1.85	14.00	98	36.8	168	63.2	11.61	7.63	156	557.44	18
35.56	109	0.743	61.3	38.7	2.30	1.85	13.30	82	30.8	184	69.2	11.76	7.03	166	565.12	18
35.53	312	0.733	61.9	38.1	2.51	1.89	14.07	86	31.6	186	68.4	11.40	7.10	156	556.64	18
35.53	606	0.731	61.7	38.3	2.24	1.64	13.77	94	39.8	142	60.2	12.27	6.50	166	511.44	17
35.32	-	0.889	64.2	35.8	1.57	1.22	18.25	40	22.7	136	77.3	10.69	6.71	118	354.72	12

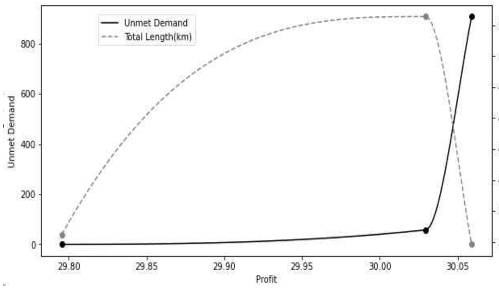
Table C.13 Result of Optimal Network(Radial Circular Network, Ratio of CBD Demand: 60%)

Profit (M-won)	Unmet Demand (Person)	Equity	Car OD(%)	Transit OD (%)	Avg. lines/seg	Dev.Line /seg	Person /km	# oflines/seg (center, %)		# oflines/seg (other, %)		Avg. OD Travel dist (km)	Avg.Wait (min)	Total Fleet	Total Length (km)	# Lines
37.50	340	0.825	63.4	36.6	2.02	1.72	22.76	66	26.6	182	73.4	11.84	12.33	90	518.20	16
37.39	1,731	0.753	63.1	36.9	1.92	1.69	21.25	86	35.2	158	64.8	11.38	11.43	94	527.90	16
36.90	332	0.719	62.3	37.7	2.08	1.76	17.46	64	25.2	190	74.8	10.79	9.77	116	536.64	16
36.80	1,376	0.699	62.5	37.5	2.06	1.76	17.62	82	32.3	172	67.7	10.86	10.23	112	546.32	16
36.75	267	0.923	64.0	36.0	2.47	1.79	22.50	110	42.6	148	57.4	11.13	12.64	86	536.24	16
36.48	-	0.913	63.9	36.1	2.40	1.81	20.77	86	33.1	174	66.9	11.97	12.19	92	544.42	16
35.27	-	0.904	65.2	34.8	2.94	2.18	21.26	82	26.1	232	73.9	11.64	13.90	92	638.86	20

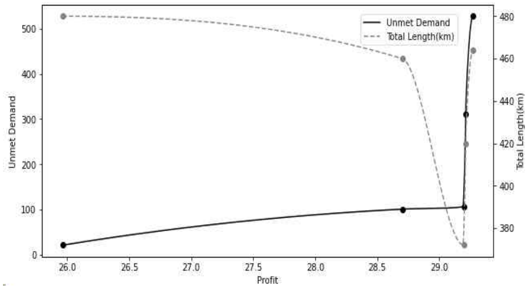
Table C.14 Result of Optimal Network(Radial Circular Network, Ratio of CBD Demand: 90%)

Profit (M-won)	Unmet Demand (Person)	Equity	Car OD(%)	Transit OD (%)	Avg. lines/seg	Dev.Line /seg	Person /km	# oflines/seg (center, %)		# oflines/seg (other, %)		Avg. OD Travel dist (km)	Avg.Wait (min)	Total Fleet	Total Length (km)	# Lines
36.51	2,692	0.754	62.6	37.4	2.31	1.78	17.24	112	43.8	144	56.3	11.67	9.62	116	561.32	17
36.44	182	0.813	64.8	35.2	1.61	1.18	24.71	42	24.7	128	75.3	11.42	10.19	80	383.04	12
35.84	1,986	0.794	62.1	37.9	2.81	2.21	14.89	122	38.4	196	61.6	12.07	9.45	132	691.80	20
35.75	28	0.777	64.9	35.1	1.98	1.35	21.98	46	23.7	148	76.3	11.63	9.05	84	409.72	12
35.43	1,746	0.723	62.9	37.1	2.82	2.24	15.49	94	29.2	228	70.8	11.51	10.75	128	678.28	20
35.38	2,163	0.664	62.5	37.5	2.73	2.25	14.77	90	27.8	234	72.2	12.19	9.23	136	670.06	20
35.33	147	0.749	64.0	36.0	2.52	1.72	17.72	70	28.2	178	71.8	10.91	9.69	114	540.58	17
35.27	760	0.720	63.9	36.1	2.42	1.79	17.31	62	24.0	196	76.0	11.45	9.85	116	548.06	17
35.22	1,134	0.715	62.9	37.1	2.97	2.31	15.18	92	27.7	240	72.3	11.43	9.45	132	665.24	20
34.98	-	0.774	65.1	34.9	2.37	1.83	19.73	70	26.5	194	73.5	11.59	13.01	98	551.80	17
34.95	601	0.688	62.5	37.5	2.36	2.14	13.93	88	28.6	220	71.4	11.24	8.53	150	647.82	20
34.86	548	0.690	62.3	37.7	2.29	2.19	13.60	86	27.2	230	72.8	11.47	8.52	150	663.92	20
34.18	386	0.733	63.6	36.4	3.03	2.32	14.38	86	25.7	248	74.3	11.02	9.12	138	659.10	20

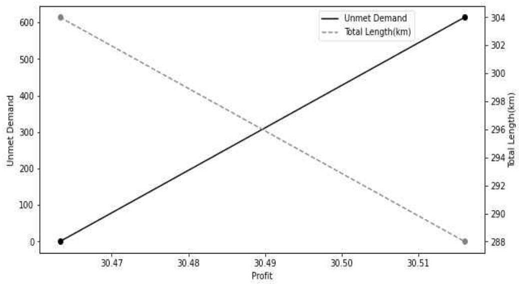
Appendix D. Changes between Index



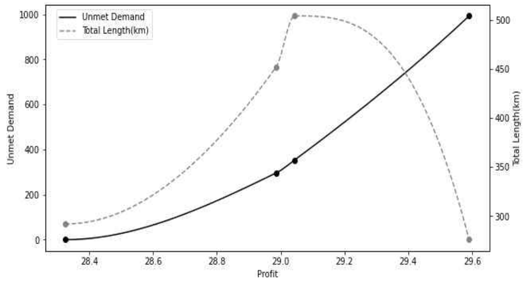
(a) Demand ratio of CBD : -90%



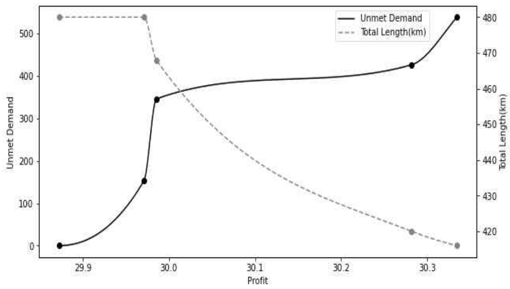
(b) Demand ratio of CBD : -60%



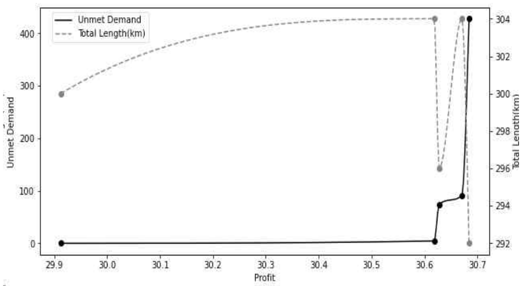
(c) Demand ratio of CBD : -30%



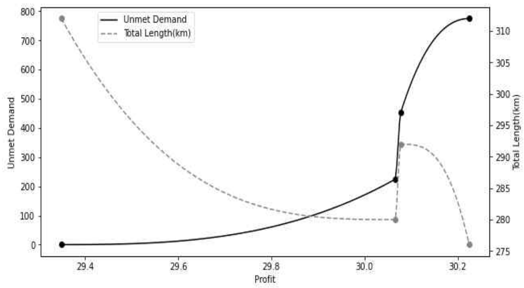
(d) Demand ratio of CBD : 0%



(e) Demand ratio of CBD : 30%

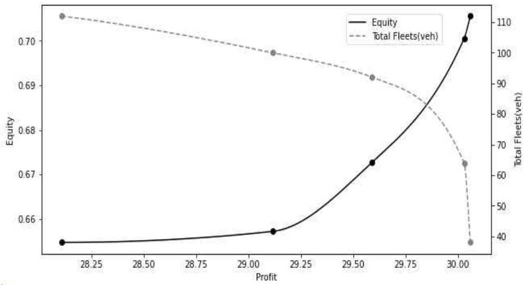


(f) Demand ratio of CBD : 60%

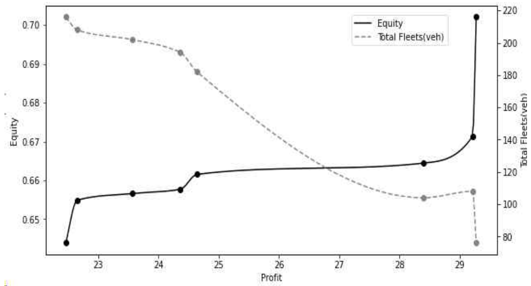


(g) Demand ratio of CBD : 90%

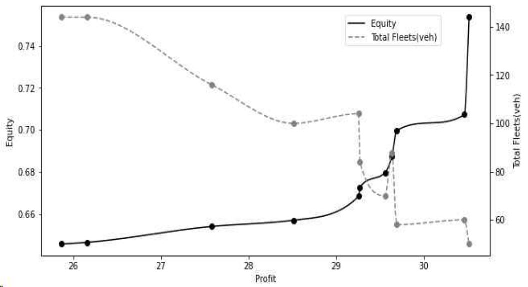
Figure D.1 Changes between Profit and Unmet Demand
(Grid Network)



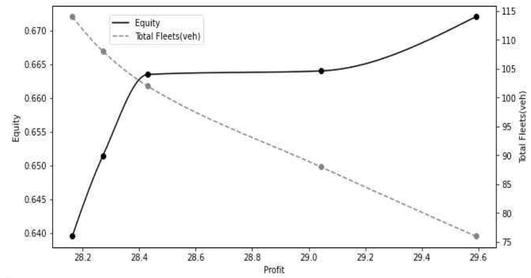
(a) Demand ratio of CBD : -90%



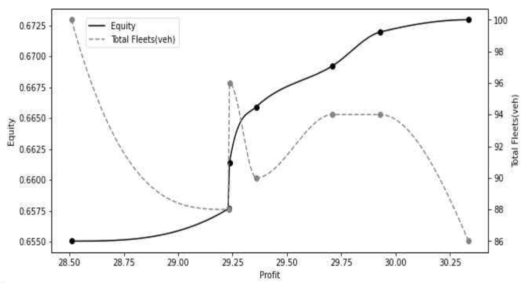
(b) Demand ratio of CBD : -60%



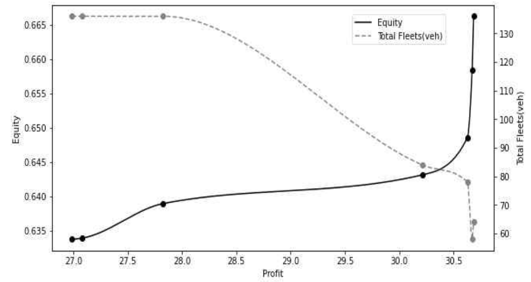
(c) Demand ratio of CBD : -30%



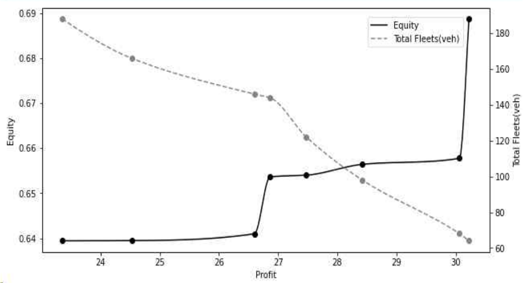
(d) Demand ratio of CBD : 0%



(e) Demand ratio of CBD : 30%

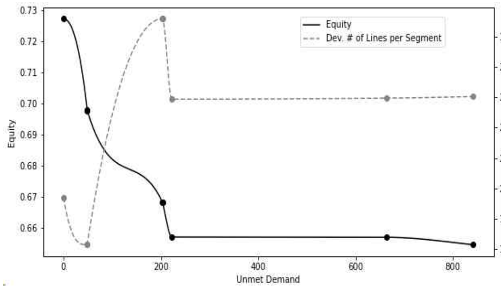


(f) Demand ratio of CBD : 60%

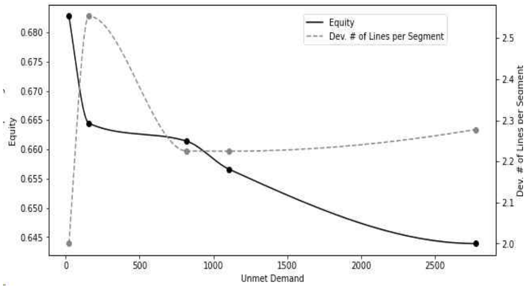


(g) Demand ratio of CBD : 90%

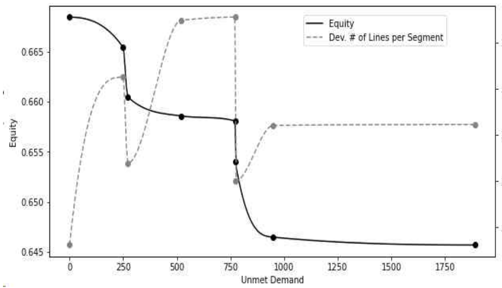
Figure D.2 Changes between Profit and Equity (Grid Network)



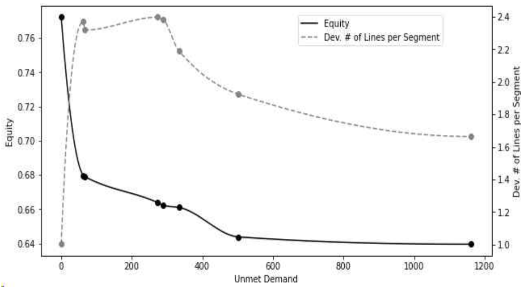
(a) Demand ratio of CBD : -90%



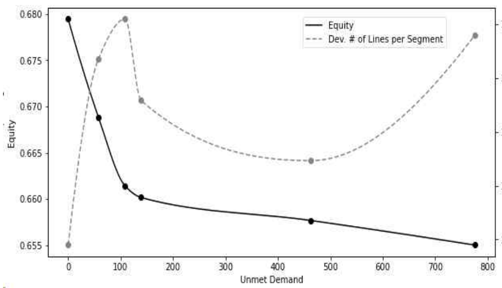
(b) Demand ratio of CBD : -60%



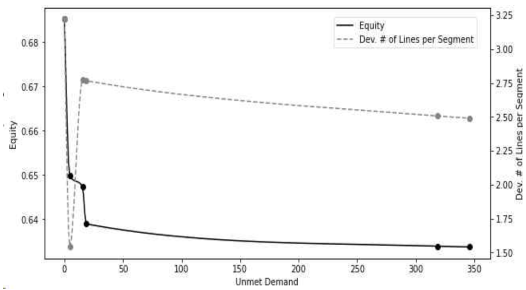
(c) Demand ratio of CBD : -30%



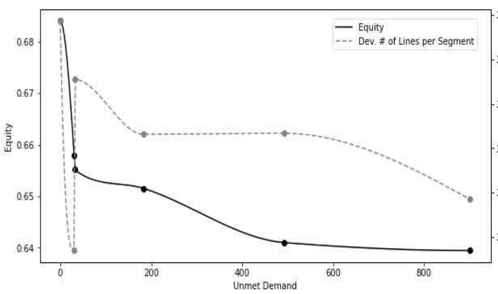
(d) Demand ratio of CBD : 0%



(e) Demand ratio of CBD : 30%

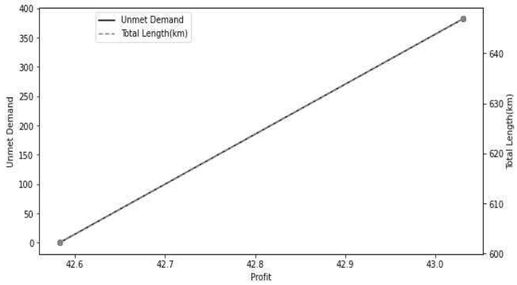


(f) Demand ratio of CBD : 60%

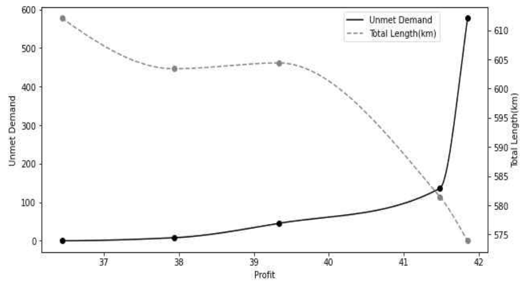


(g) Demand ratio of CBD : 90%

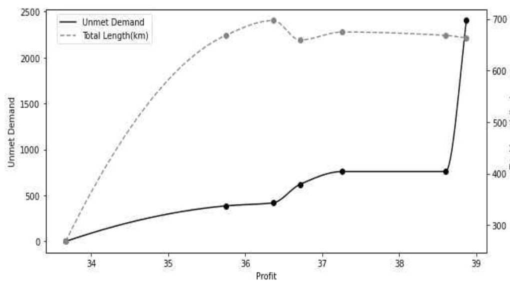
Figure D.3 Changes between Unmet Demand and Equity
(Grid Network)



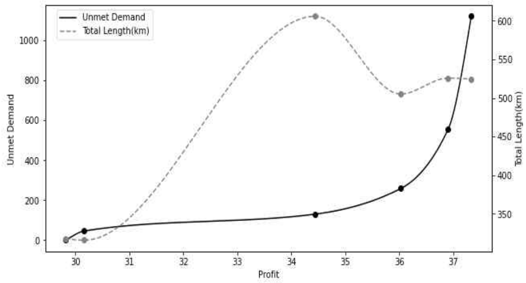
(a) Demand ratio of CBD : -90%



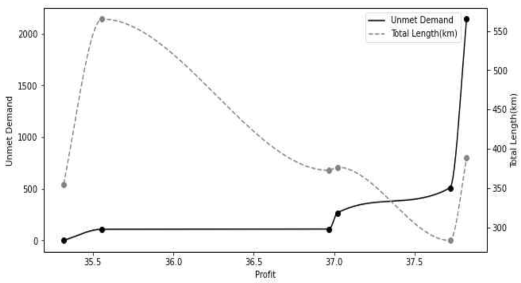
(b) Demand ratio of CBD : -60%



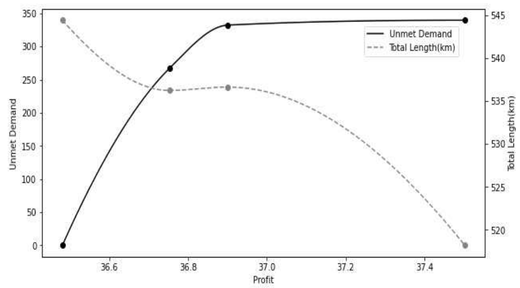
(c) Demand ratio of CBD : -30%



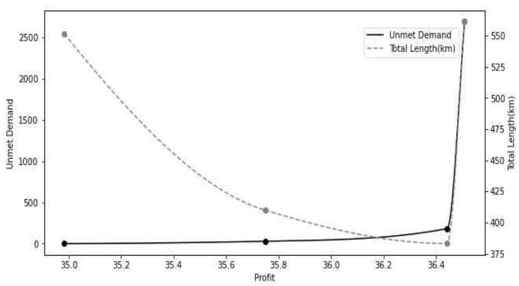
(d) Demand ratio of CBD : 0%



(e) Demand ratio of CBD : 30%

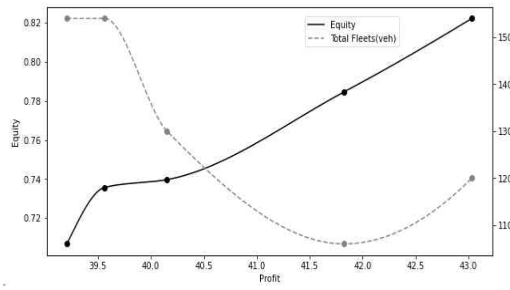


(f) Demand ratio of CBD : 60%

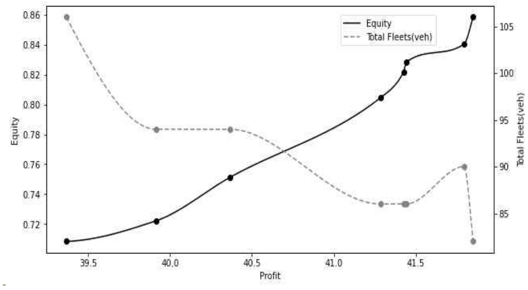


(g) Demand ratio of CBD : 90%

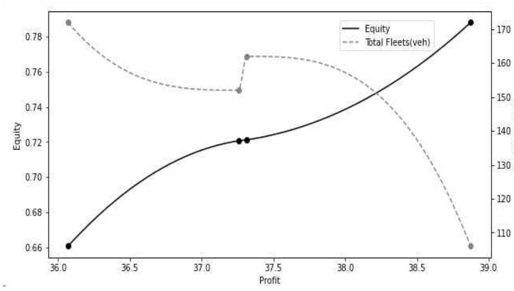
Figure D.4 Changes between Profit and Unmet Demand
(Radial Circular Network)



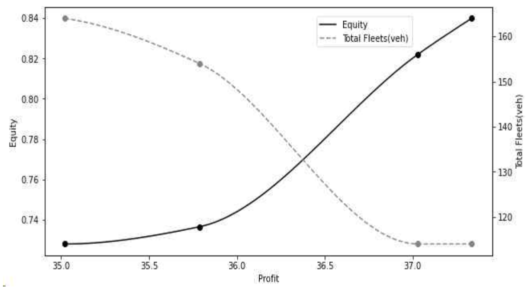
(a) Demand ratio of CBD : -90%



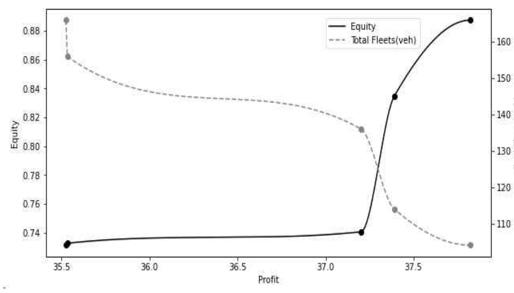
(b) Demand ratio of CBD : -60%



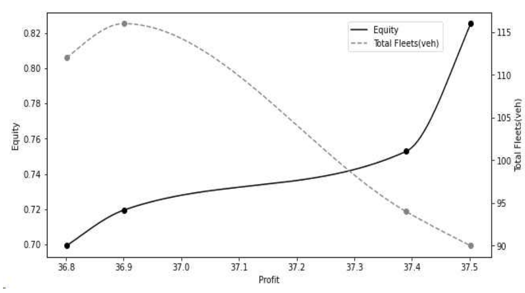
(c) Demand ratio of CBD : -30%



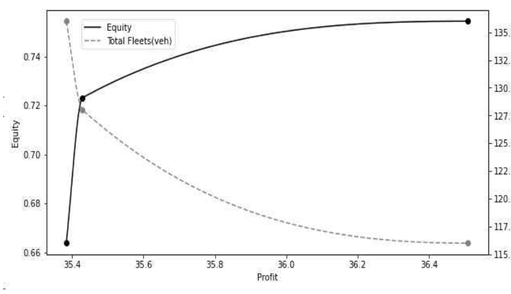
(d) Demand ratio of CBD : 0%

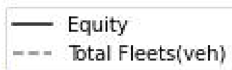


(e) Demand ratio of CBD : 30%



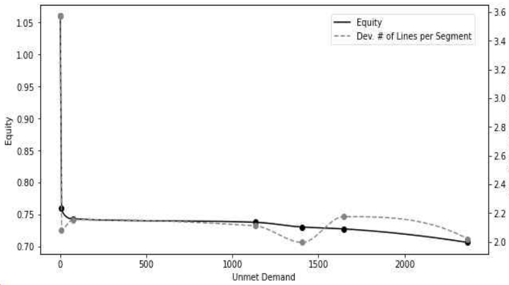
(f) Demand ratio of CBD : 60%



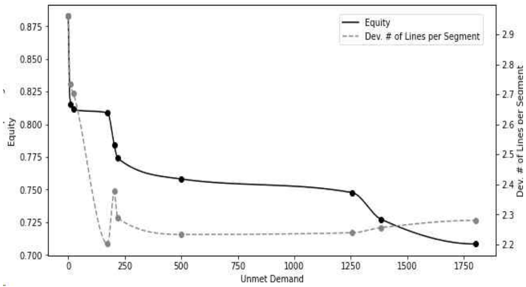


(g) Demand ratio of CBD : 90%

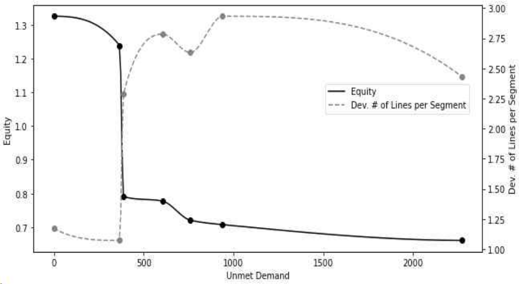
Figure D.5 Changes between Profit and Equity (Radial Circular Network)



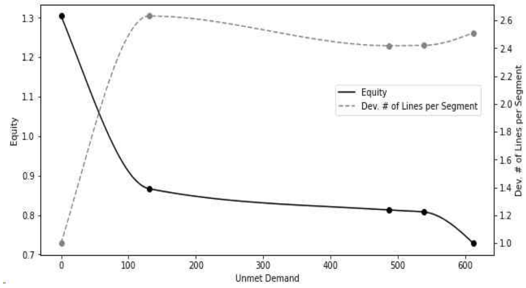
(a) Demand ratio of CBD : -90%



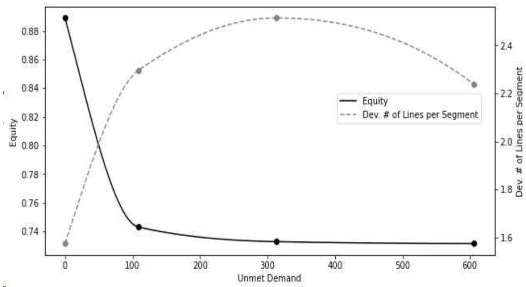
(b) Demand ratio of CBD : -60%



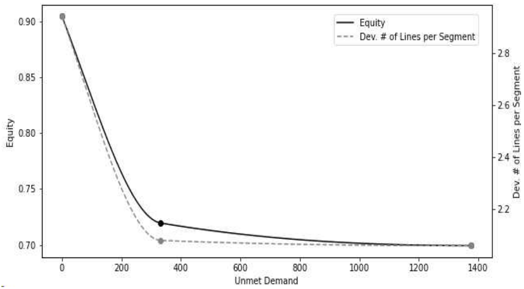
(c) Demand ratio of CBD : -30%



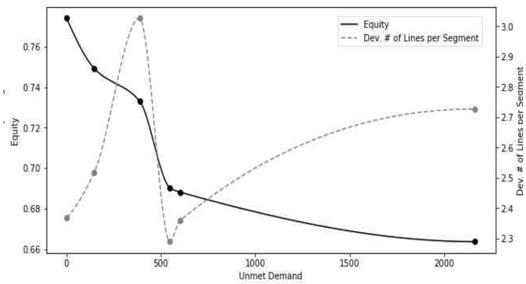
(d) Demand ratio of CBD : 0%



(e) Demand ratio of CBD : 30%



(f) Demand ratio of CBD : 60%



(g) Demand ratio of CBD : 90%

Figure D.6 Changes between Unmet Demand and Equity (Radial Circular Network)

Appendix D. Result of Optimal Network in Large Network

Table D.1 Result of Optimization(Large Network)

Profit (M-won)	Unmet Demand (Person)	Equity	Car OD(%)	Transit OD (%)	Avg. lines/seg	Dev.Line /seg	Person /km	# oflines/seg (center, %)		# oflines/seg (other, %)		Avg. OD Travel dist (km)	Avg.Wait (min)	Total Fleet	Total Length (km)	# Lines
214.76	16,885	1.345	40.88	59.12	1.05	2.31	43.47	6223	67.3	3017	32.7	11.11	12.66	171	1214.38	51
214.42	14,437	1.374	41.03	58.97	1.06	2.3	44.06	6542	69.8	2827	30.2	11.94	13.36	168	1220.49	51
214.36	13,892	1.316	40.76	59.24	1.1	2.45	41.17	6540	67.8	3110	32.2	10.73	12.30	176	1240.69	51
213.92	12,493	1.321	40.69	59.31	1.34	2.93	39.45	8726	74.0	3066	26.0	13.85	12.92	196	1489.52	65
213.46	14,226	1.216	40.47	59.53	1.38	3.02	36.71	8833	72.9	3286	27.1	12.95	12.76	202	1546.58	65
213.31	12,097	1.349	40.7	59.3	1.34	3	38.16	9015	76.3	2798	23.7	12.92	12.99	204	1444.04	65
213.27	8,222	1.441	40.63	59.37	1.39	3	37.48	8910	72.8	3332	27.2	13.24	12.20	200	1540.33	65
213.14	13,137	1.266	40.56	59.44	1.39	3.03	36.75	8851	72.1	3433	27.9	13.03	12.55	200	1565.65	65
212.85	12,249	1.284	40.55	59.45	1.33	2.77	36.05	8030	68.6	3675	31.4	12.16	12.77	214	1516.42	65
212.79	9,631	1.254	40.48	59.52	1.45	3.19	35.49	9344	73.4	3388	26.6	13.34	12.92	204	1597.15	65
212.66	9,264	1.262	40.47	59.53	1.46	3.28	35.18	9641	74.8	3248	25.2	12.99	12.94	207	1591.13	65
212.66	9,043	1.284	40.43	59.57	1.36	2.93	34.85	8450	70.6	3518	29.4	12.33	13.10	213	1514.54	65
212.24	13,970	1.234	40.3	59.7	1.36	2.95	33.34	8128	68.0	3822	32.0	11.71	13.24	214	1615.24	65
212.21	9,031	1.187	40.07	59.93	1.38	2.98	31.96	8209	67.7	3917	32.3	10.87	12.58	227	1589.40	65
211.92	6,733	1.392	40.53	59.47	1.39	3.08	34.17	9117	74.7	3094	25.3	12.58	12.57	216	1550.64	65
211.88	7,515	1.254	40.3	59.7	1.38	2.94	32.75	8393	68.8	3800	31.2	11.66	12.75	219	1577.90	65
211.78	7,617	1.248	40.29	59.71	1.4	2.98	32.5	8489	68.7	3873	31.3	11.71	12.78	218	1601.17	65
211.75	7,421	1.259	40.27	59.73	1.39	2.93	32.36	8288	67.6	3972	32.4	11.57	12.64	221	1586.16	65
211.37	6,697	1.169	40.02	59.98	1.39	2.9	30.46	8095	66.3	4114	33.7	9.94	12.60	237	1597.38	65
210.49	7,766	1.159	39.97	60.03	1.43	3.16	29.07	8658	68.5	3976	31.5	10.17	12.23	239	1644.43	65
210.43	6,441	1.127	39.94	60.06	1.44	3.12	28.85	8626	67.9	4079	32.1	9.96	12.29	241	1646.93	65

국문초록

대중교통은 다양한 기회에 대한 접근성을 제공하는 서비스로써 효율적인 노선망 설계를 통해 이동성 격차의 감소가 가능하다. 그러나 경제적 효율성을 중점적으로 고려하면서 특정지역으로 서비스 집중되어 서비스의 공간적 불균형 및 이용자의 비효율이 발생하기도 한다. 따라서 효율성뿐만 아니라 수단 또는 공간에 대한 불균형을 고려한 노선망 설계 알고리즘을 제시하였다.

본 연구에서는 운영자, 이용자, 공공 측면을 모두 고려한 노선망 설계 알고리즘을 제시하였으며, 이때 운영자 및 이용자의 효율성뿐만 아니라 수단 및 지역간 대중교통 경쟁력을 고려하였다. 도시의 네트워크 형태 및 수요패턴에 따라 예제네트워크를 구성하여 본 연구의 알고리즘을 적용하여 분석을 수행하였으며, 실제 네트워크를 통해 알고리즘의 확장성을 확인하였다. 운영 효율성을 중점적으로 고려한 기존의 방법론 대비 운영자와 공공 측면에서 개선된 노선망을 도출할 수 있었다. 또한 단일해가 아닌 다목적 함수를 동시에 만족시키는 최적해 집합을 도출함으로써 설계자의 판단에 따라 적절한 노선망 적용방안을 제시하였다. 각 이해관계를 동시에 고려한 본 연구의 대중교통 노선망 설계 알고리즘은 도시의 다양한 형태 및 통행패턴에 따른 설계 기준을 제공함으로써 의사결정 지원수단으로 활용이 가능하고, 제한된 자원으로 균형적인 네트워크 공급이 필요한 도시에 적용이 가능하다는 점에서 큰 의의가 있다.

주요어 : TNDFSP, Equity, Unmet Demand, Multi-Object, Pareto Optimal

학번 : 2016-30286