An Accessibility-based Framework for Enhancing a Socially-Sustainable Urban Built Environment for Seniors

by

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ABSTRACT

Population ageing has a significant impact on the age structure of the population of an entire country and can introduce regional differences with respect to demographic measures, such as the rate of population growth, geographic distribution of elderly people, and the degree of population ageing, especially in developing countries. These long-standing and increasingly evident differences can hinder effective resource distribution among regions. In addition to the social influences, the rapid growth of the older-adult segment of the population also has a profound effect on city infrastructure needs and urban design. In general, the current urban built environment is not well developed to cope with the unprecedented challenges related to the increase in senior population. For instance, the location of age-restricted communities that serve older adults aged 65 or older can influence accessibility to goods and services and further affect the health and quality of life of seniors. However, few quantitative indicators are available to judge whether the accessibility of neighboring facilities to these communities is appropriate, and few studies focus on improving accessibility of urban facilities and services for seniors. Furthermore, not all residents in a city, especially socially disadvantaged groups (SDGs) (e.g., seniors or children), can benefit from similar levels of accessibility given existing urban resources such as public transportation. Therefore, this research proposes an accessibility-based framework in order to enhance a socially-sustainable urban built environment for seniors. Five primary modules are involved in the research: (1) a methodology is developed for exploring differences in regional population ageing from both temporal and spatial perspectives; (2) a spatial analysis framework is established for age-restricted communities to analyze their spatial distribution, identify age-friendly communities, and measure and evaluate accessibility of different types of age-restricted communities to neighboring facilities that are important to seniors; (3) a methodology supported by the geographic information system (GIS) is developed to identify the relative spatial gaps in public transport supply and demand from seniors at the statistical area (SA) level, such as gaps among census tracts (CTs), traffic analysis zones (TAZs), and neighborhoods; (4) a systematic methodology is developed to assess the accessibility-based service effectiveness (ABSEV) of urban bus transit in consideration of social equity; and (5) a bi-level decision support model (BLDSM) is developed to optimize bus route distribution and enhance the level of accessibility for seniors in age-restricted communities. The outcome of this research is expected to propose a systematic approach to enhance accessibility of seniors to urban facilities and services in the built environment within the context of population ageing from the perspective of social sustainability.

PREFACE

This thesis is the original work of Yuan Chen. Five journal papers and one conference papers related to this thesis have been submitted or published and are listed below. This thesis is organized in paper format following the guidelines for paper-based theses.

1. Chen, Y., Bouferguene, A., Shen, Y.H., and Al-Hussein, M. 2019. A bi-level decision support model (BLDSM) for bus route optimization and accessibility improvement for seniors. *Journal of Computing in Civil Engineering* (Under review). Dr. Bouferguene and Dr. Al-Hussein were the supervisory authority and involved with concept formation and manuscript composition. Yinghua Shen was responsible for improving code quality in the implementation of an algorithm.
2. Chen, Y., Bouferguene, A., Shirgaokar, M., and Al-Hussein, M. 2019. Spatial analysis framework for age-restricted communities integrating spatial distribution and accessibility evaluation. *Journal of Urban Planning and Development* (Under review). Dr. Bouferguene and Dr. Al-Hussein were the supervisory authority and involved with concept formation and manuscript composition. Dr. Shirgaokar gave some suggestions on manuscript composition and guidance regarding urban planning.
3. Chen, Y., Bouferguene, A., Shen, Y.H., and Al-Hussein, M. 2019. Difference analysis of regional population ageing from temporal and spatial perspectives: a case study in China. *Regional Studies*, **53**(6): 849–860. Dr. Bouferguene and Dr. Al-Hussein were the supervisory authority and involved with concept formation and manuscript composition. Yinghua Shen was responsible for improving code quality in the implementation of an algorithm.

4. Chen, Y., Bouferguene, A., Shen, Y.H., and Al-Hussein, M. 2019. Assessing accessibility-based service effectiveness (ABSEV) and social equity for urban bus transit: A sustainability perspective. *Sustainable Cities and Society*, **44**: 499–510. Dr. Bouferguene and Dr. Al-Hussein were the supervisory authority and involved with concept formation and manuscript composition. Yinghua Shen was responsible for improving code quality in the implementation of an algorithm.
5. Chen, Y., Bouferguene, A., Li, H.X., Liu, H.X., Shen, Y.H., and Al-Hussein, M. 2018. Spatial gaps in urban public transport supply and demand from the perspective of sustainability. *Journal of Cleaner Production*, **195**: 1237–1248. Dr. Bouferguene and Dr. Al-Hussein were the supervisory authority and involved with concept formation and manuscript composition. Hongxian Li and Hexu Liu gave some suggestions on response to reviewers' comments. Yinghua Shen was responsible for improving code quality in the implementation of an algorithm.
6. Chen, Y., Bouferguene, A., and Al-Hussein, M. 2018. Neighborhood design and regional accessibility of age-restricted communities from resiliency and spatial perspectives. In *Proceedings, Construction Research Congress*. ASCE, New Orleans, LA, USA, pp. 9–18. Dr. Bouferguene and Dr. Al-Hussein were the supervisory authority and involved with concept formation and manuscript composition.

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ABSEV	Accessibility-based service effectiveness
BLDSM	Bi-level decision support model
CT	Census tract
CV	Coefficient of variation
CRS	Constant returns to scale
DEA	Data envelopment analysis
DMU	Decision making unit
GA	Genetic algorithm
GC	Gini coefficient
GTFS	General transit feed specification
GIS	Geographic information system
LEED	Leadership in energy and environmental design
LLM	Lower-level model
OEV	Operational effectiveness
PLS	Partial least squares
PE	Production efficiency
PTDI	Public transport demand index
PTSI	Public transport supply index
PTE	Pure technical efficiency
SE	Scale efficiency
SEV	Service effectiveness
SDG	Socially disadvantaged group
SD	Standard deviation
SA	Statistical area
SFA	Stochastic frontier analysis
TE	Technical efficiency
TAZ	Traffic analysis zone
TSP	Traveling salesman problem
ULM	Upper-level model
VRS	Variable returns to scale
WHO	World health organization

Chapter 1: INTRODUCTION

1.1 Background and Motivation

"We are ageing—not just as individuals or communities but as a world" (National Institutes on Aging and National Institutes of Health 2007). In 2017, the global population aged 60 years or over reached 962 million, which was more than double that of 1980; this number is expected to increase to 1.4 billion by 2030 and 2.1 billion by 2050, accounting for 16% and 22% of the total population, respectively (United Nations 2017). Furthermore, the growth rate of the senior population in developing regions far exceeds that of the corresponding demographic in developed regions. This point indicates that even though global population ageing is primarily attributed to a reduction in fertility and an increased in life expectancies, ageing trends are diverse in all countries.

Within this context, tremendous challenges related to the increase in the senior population are emerging and gaining attention from academia and industry. The more frequently debated topics with respect to population ageing focus on social insurance (Tamiya et al. 2011), pension systems (Roseveare et al. 1996, Blake and Mayhew 2006), health care (Lloyd-Sherlock 2000, Werblow et al. 2007), migration (Warnes et al. 2004, Bijak et al. 2007), the impact on economic growth (Bloom et al. 2010, Prettner 2013), and the labor market (Dixon 2003, Tang and MacLeod 2006). These topics can be broadly classified into social or economic issues.

In addition to the challenges mentioned above, population ageing also presents significant challenges in relation to the built environment, which, despite its importance, has received little attention from scientists and engineers. Luckily, over the past few years, the thinking paradigm has shifted among scholars to become more holistic in nature thus allowing social elements to be included in the design phase of an engineering project. In this respect, it turns out that many urban design features, which can seem ordinary or unnoticeable to healthy individuals, can become insurmountable challenges for a segment of population having special needs due to limited physical abilities or other conditions. For instance, most sidewalks are designed without ramps, which in turn triggers mobility issues for residents using wheelchairs. The new design (i.e., adding more ramps per year) has been employed by the City of Edmonton in order to better accommodate wheelchairs and strollers. In fact, a large part of the current built environment is not necessarily tailored to accommodate the needs of an increasing senior population in the near future. As such, the notion put forward by Prof. Bernard Isaacs, has become a useful design principle for urban development: "Design for the young and you exclude the old; design for the old and you include everyone".

1.1.1 Sustainability in built environment

Countries worldwide have been promoting the concept of sustainability and attempting to implement it in all kinds of industries after this concept was first mentioned in the Brundtland Report (WCED 1987). In general, sustainability requires effectively managing the influences stemming from environmental, economic, and social systems. The built environment is defined as "an environment that includes man-made buildings (e.g., facilities, residential buildings, and industrial plants), infrastructures (e.g., transportation, water supply and drainage systems), and cultural landscapes that constitute the physical, natural, economic, social, and cultural capital of a society"[1], which is distinguishable from any other concept in the natural environment (or unbuilt environment). The lifecycle of man-made structures, whether buildings or infrastructure, often includes similar phases starting from planning, to design, to construction, to operation and

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[1] This definition is proposed in a workshop on Built Environment Resilience held at ETH Zurich in January 2013.

maintenance, and finally to the end of service life, which may require decommissioning. As such, the concept of sustainability should be implemented into each stage of the project lifecycle and requires a balance between environmental protection, economic development, and social care (Vanegas 2003).

Compared with the first two aspects (i.e., environment and economy), social sustainability in the built environment has garnered relatively little attention (Kohler 1999, U.S. Green Building Council 2000, Kua and Lee 2002, Pearce and Vanegas 2002a, 2002b, Vanegas 2003, Doughty and Hammond 2004, Atkinson 2008). With the rapid increase in the senior population, an age-friendly built environment is becoming a practical and pressing need. The World Health Organization (WHO) (2002) stated that age-friendly built environments can make the difference between independence and dependence for all individuals, but the importance is significantly higher for older adults. In fact, it has been recognized that the built environment not only influences seniors' mobility, independence, quality of life, and autonomy, but also facilitates or hinders the quest for a healthy lifestyle at all ages (PMSEIC 2003). Examples of efficient and useful built environments include a safe and secure pedestrian environment (e.g., sidewalks, street crossings, and street amenities), good access to facilities and services (e.g., parks, public transport, health services, and recreation facilities), housing design and choices satisfying customers at different ages (e.g., senior housing and general housing), facility design and usage supporting older adults (e.g., adequate signage and public toilets with handicap access), and age-friendly design at different scales (e.g., home, neighborhood, and community).

Besides the above-mentioned items that are easily observed in the existing built environment, other issues such as social equity, as one component of social sustainability, tend to be ignored. In other words, do all residents in a city including seniors receive similar benefits from resources and services provided in the built environment in order to reduce adverse effects on different population groups and enhance their social inclusion? If we take public transportation in urban areas as an example, the following questions are thought-provoking: (a) Do the seniors in a city have equal opportunities for public transport? (b) What differences exist between seniors and other populations in terms of transport service usage? (c) If seniors do not have good access to nearby bus transit, what should we do to improve the status quo? It is a worthwhile endeavor, therefore, to explore how to facilitate a socially-sustainable urban built environment for seniors within the context of population ageing.

1.1.2 Senior housing

Housing is one component of the built environment, and the shift in demographics is predicted to lead to changes in housing needs and design. Currently, there exist several different types of lifestyles of the elderly. First, "ageing in place", an emerging paradigm in ageing policy, aims to help older people to continue living at home, and fundamentally and positively contributes to an increase in well-being, independence, social participation, and healthy ageing (Sixsmith and Sixsmith 2008). Second, age-restricted communities, defined as communities restricted to residents of a minimum age (primarily 55 and over), have become a popular residential option for older adults (Ginzler 2009). Some scholars have conducted a study of interior architectural design for senior housing. Afifi et al. (2014) employed evidence-based assessment to evaluate staircase elements (e.g., handrail and step) and investigated the degree of falling risk resulting from these elements by means of an established rating system in order to create age-friendly and safe architectural design for senior housing. Similarly, the proposed methodology was also applied to redesign the bathrooms in senior housing, including multiple elements (i.e., toilet, bathtub, lavatory, lighting, and flooring) (Afifi and Al-Hussein 2014). Nagananda et al. (2010)

conducted a structured questionnaire and in-depth interview to summarize the problems and limitations of using existing bathing and toileting facilities in the daily life of elderly persons with or without disability. These studies can inform the redesign of these facilities to decrease accidents in senior housing and provide a comfortable indoor environment for elderly people. Additionally, community development surrounding senior housing is yet another critical issue. Currently, many guides for building age-friendly communities have been proposed (WHO 2007, Neal 2014, Public Health Agency of Canada 2015); however, these guides lack quantitative indicators, resulting in difficulties in evaluating accessibility of senior housing to neighboring facilities and services. Here, accessibility is largely understood as the ease with which people can reach destinations (Hansen 1959). Furthermore, young individuals can easily overcome minor physical barriers to reach the desired destination, while the mobility of older adults is influenced by many factors including physical ability, general health, and environmental challenges (Webber et al. 2010). In fact, older adults prefer to do outdoor activities, such as walking or jogging, sports and physical activities (Szanton et al. 2015), rather than always staying at home. As a result, appropriate housing and access to facilities and services can have an influence on seniors' independence and quality of life (WHO 2007). Therefore, quantifying the accessibility between senior housing and neighboring facilities and services can facilitate implementation of guides for building age-friendly communities, and it also enhances social interaction and community involvement for older adults.

1.1.3 Resilience in older adults

According to the Oxford dictionary, "resilience" may be interpreted in two ways: (a) "the capacity to recover quickly from difficulties"; (b) "the ability of a substance or object to spring back into shape" (Oxford University Press 2013). In the past few decades, the resilience concept has been extended to various disciplines, such as engineering (Bruneau et al. 2003, McAllister 2016), ecology (Gunderson 2000), economy (Simmie and Martin 2010), and society (Keck and Sakdapolrak 2013). As such, a corresponding new definition of resilience has emerged in this discipline as well as in multiple other disciplines such as social-ecological systems (Smith and Stirling 2010).

Similarly, in the context of older adults (or ageing), a senior-centered concept of resilience has been introduced in order to clearly emphasize the way in which this segment of the population copes with day-to-day challenges (e.g., physical, mental, or social challenges). van Kessel (2013) stated the definition as the ability of seniors to bounce back and recover physical and psychological health when facing adversity, and listed influencing factors of resilience in older people that were derived from the 41 screened articles. In addition to seven internal factors related to the individual, the author pointed out five environmental factors: social support, ability to access care, social policy, societal responses, and availability of resources. Wiles et al. (2012) conducted interviews and participant-led focus groups with seniors in order to investigate their understandings and experiences of resilience. The findings emphasized two factors as having an important role in resilience in old age: social support and places for growing older, where convenient access to community facilities and services is highlighted. Furthermore, Östh et al. (2015) conducted an analysis at the municipality level and found that proxies of resilience had a significantly positive correlation with accessibility in general. More importantly, resilience in older adults, along with quality of life and level of activity, has a great influence on subjective ratings of successful ageing (Montross et al. 2006). Housing provides seniors with a living place, but it is not isolated from the neighboring built environment. Previous studies indicate that the built environment will influence seniors' wellness, quality of life, and resilience (Oswald and Wahl 2004, Shaw 2004, Netherland et al. 2011).

1.2 Research Objective

The research presented herein is built upon the following hypothesis:

"Integrating quantitative analysis and mathematical optimization to investigate accessibility-related issues of the urban built environment will assist in improving seniors' accessibility to urban facilities and services in the built environment considering social sustainability."

The research identifies, in the context of population ageing, the limitations of current practices in the design of and resource distribution in the built environment, including facilities and services that are important to seniors. An accessibility-based framework is proposed in this research to enhance a socially-sustainable urban built environment for seniors. In addition to knowledge of construction, this research also integrates knowledge of other disciplines, such as urban planning, regional economics, spatial econometrics, and computational science. Specifically, this study primarily focuses on developing a set of methods with respect to accessibility-relevant evaluation and improvement for urban facilities and services in the built environment as well as social equity assessment for urban resources in the interest of seniors. The proposed framework can provide a basis for the strategic development of urban built environments involving multiple stakeholders at different stages (e.g., for design, construction, or renewal) with a view to provide the conditions that help older adults develop resiliency. The framework can also address the status quo for urban facilities and services, promote greater equality of resource opportunities and service effectiveness (SEV) for socially disadvantaged groups (SDGs), and provide a reference for policy making pertaining to the sustainable planning and development of urban built environment.

To attain this underlying goal, the following objectives are pursued in this research:

1) Development of a temporal-spatial analysis to explore change trends and regional differences in population ageing in order to provide the basis for regional population strategies and address the challenges associated with population ageing.
2) Development of a spatial analysis for age-restricted communities using both regional and local perspectives in order to explore the community distribution and identify age-friendly communities by accessibility measures and evaluation.
3) Development of a set of methods based on geographic information system (GIS) technology in order to quantify public transport supply and demand from seniors as well as investigate public transport gaps considering social equity.
4) Development of assessment approaches for measuring the SEV of urban bus transit from an accessibility perspective and analyzing social equity in SEV among various population groups, including seniors, in order to balance the benefits that different population groups in regions receive from the SEV.
5) Development of an optimization model involving two stakeholders (i.e., seniors and transit agencies) in order to facilitate the redesign of an existing bus route with the purpose of maximizing accessibility of seniors to nearby bus stops and minimizing operation cost for transit agency.

Among the above objectives, the first objective provides, from a macro perspective, the theoretical basis and background for this research, namely, the significance of taking seniors into account and regional differences in population ageing. Within this context, some specific improvement strategies are needed to mitigate the issues that come with population ageing. As such, regions (or cities as micro units) implement the remaining objectives in order to enhance a socially-sustainable urban built environment for seniors based on accessibility.

1.3 Thesis Organization

This thesis consists of seven chapters and three appendices. Chapter 1 presents the background and motivation of this research. The hypothesis and objectives of this research are also outlined in this chapter. In Chapter 2, the ageing coefficient is selected as the index to evaluate population ageing, and some methods are proposed for analyzing differences in regional population ageing from temporal and spatial perspectives. Time-based differences of population ageing are reflected in population distribution, population ageing trends, regional variations and the concentration degree; whereas, spatial-based differences of population ageing are reflected in population ageing clusters, and global and local autocorrelation. China is then used as the case study over the period 1998–2014. In practice, the presented research methodology can be applied to other countries where regional differences in population ageing exist.

Chapter 3 highlights the limitation of the few quantitative indicators that are available to judge whether the level of accessibility of age-restricted communities to their neighboring facilities is appropriate. Therefore, this chapter presents a spatial analysis framework for age-restricted communities from a regional-local perspective. The regional analysis explores the spatial distribution of age-restricted communities, while the local analysis involves the accessibility measure of these communities to necessary neighboring facilities by type, age-friendly community identification, and a comprehensive accessibility evaluation. This framework is then applied to investigate three types of age-restricted communities in Edmonton, Canada. The proposed methodology can be used for accessibility analysis of age-restricted communities for different stakeholders, and can also lead to existing and proposed improvements to enhance age-friendliness in neighborhood design.

Chapter 4 considers that an imbalanced distribution of public transport services across a population may result in adverse effects for some social groups such as seniors. This chapter develops a systematic methodology, supported by GIS, to identify the relative spatial gaps in public transport supply and demand with respect to seniors, considering sustainability at the statistical area (SA) level. A case study of Edmonton, Canada is described to demonstrate the novelty and practical capabilities of this methodology. The findings provide policy makers with evidence to validate a quantitative method for evaluating the relative spatial gaps in public transport services for individual SAs in order to promote greater equality of transport opportunities and increased transport service efficiency among SDGs.

Chapter 5 presents, in consideration of the fact that in any given city not all residents enjoy the same level of accessibility to transit supply (with SDGs such as seniors having more limited access), a systematic methodology integrating the cumulative opportunity measure and data envelopment analysis (DEA) in order to assess the accessibility-based service effectiveness (ABSEV) of bus transit, employing Lorenz curves and Gini coefficients (GCs) to explore social equity in ABSEV. Using the elderly as an example of an SDG, an empirical application of Edmonton, Canada is provided. The findings can provide policy makers with evidence on how to balance the ABSEV distribution of bus transit, improve benefits of bus transit to SDGs, and enhance sustainable development of urban bus transit systems.

Chapters 2–5 primarily focus on assessing the accessibility-relevant issues of urban built environments in the interest of seniors. As such, the key problem to be solved in Chapter 6 is how to improve the accessibility seniors have to urban resources if the status quo is not good (e.g., when the distance between senior housing and the nearest bus stop exceeds 400 m). This chapter introduces an optimization methodology for bus route redesign in order to facilitate transit operation management and enhance the benefits that seniors receive from transit services. A bi-level decision support model (BLDSM) for two schemes is formulated for the identified problem. In the proposed model, transit agencies, as lower-level decision makers, locate appropriate bus stops and generate bus routes using the shortest distance as an optimization criterion. Meanwhile, the decision with regards to the maximum accessibility provision to seniors is taken into account at the upper level. To address this problem, the location-routing-allocation strategy is proposed and implemented in scheme I using exact methods, while in scheme II, exact methods are integrated with a genetic algorithm (GA) to identify a near-optimal solution. Finally, a numerical example is provided to assess the feasibility of the proposed method for the two schemes, and a discussion is conducted for the adjustment of the roles of transit agencies and seniors in the built BLDSM. Finally, conclusions based on the findings of the research are summarized and future research recommendations are offered in Chapter 7.

Appendix A and Appendix B present supplementary data for Chapter 2 and Chapter 4, respectively. Appendix C demonstrates a study conducted on the regional accessibility measurement of age-restricted communities to various facilities, including hospitals, recreation facilities, shopping centers, and parks, from resiliency and spatial perspectives. A set of methods is proposed based on a GIS at the neighborhood level, which involves distribution exploration of age-restricted communities, spatial analysis of facility locations by type, and gravity accessibility measures to each type of facility in a given neighborhood. These methods are then applied to age-restricted communities for independent living in Edmonton, Canada. Suggestions and policy implementations are then proposed pertaining to neighborhood design and location selection of age-restricted communities in order to improve regional accessibility. Appendix D presents a list of research papers published during the PhD research program.

Chapter 2: DIFFERENCE ANALYSIS OF REGIONAL POPULATION AGEING FROM TEMPORAL AND SPATIAL PERSPECTIVES[2]

2.1 Introduction

As of 2015, the global population of people aged 60 years or over had increased by 48% from the year 2000, reaching 901 million worldwide; this number is projected to grow to 1.4 billion by 2030 and 2.1 billion by 2050, accounting for 16% and 22% of the total population respectively (United Nations 2015). This phenomenon is often referred to as population ageing, also known as the "silver tsunami". Although declining fertility and increasing longevity are the key drivers of global population ageing, ageing trends are not identical in all countries. Available statistics indicate that older adults living in developing regions account for 66.7% of the world's aged population, with a growth rate far exceeding that of the corresponding demographic in developed regions (United Nations 2015). China, as a developing country, has a total population of more than 1.37 billion as of 2015, of which those aged 60 years and over account for 16.1% (222 million) and those aged 65 years and over account for 10.5% (144 million) (National Bureau of Statistics of China 2016). These figures indicate that China is already a greying society, and older persons are projected to comprise at least 30% of the population by 2050 (United Nations 2015). Furthermore, with a wealth of land and considerable regional economic disparity, China is also characterized by regional differences with respect to such demographic measures as the rate of population development, distribution of elderly people and the degree of population ageing. These long-standing and increasingly pronounced differences influence the population structure of the entire country, and also hinder effective resource distribution. Within this context,

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[2] A version of this chapter has been published in the journal, *Regional Studies*, as follows. Chen, Y., Bouferguene, A., Shen, Y., and Al-Hussein, M. (2019). "Difference analysis of regional population ageing from the temporal and spatial perspectives: A case study in China." *Regional Studies*, 53(6): 849-860. It also has been reprinted with permission from Taylor & Francis.

difference analysis of population ageing among regions is significant and essential in order to aid understanding of the current state of population ageing and to provide a reference point for policy-making seeking to mitigate regional demographic differences.

From the existing body of research, three major avenues of study of population ageing can be identified:

1) *Time oriented*: Goodman (1987) uses Lorenz curves and GCs to measure population ageing in urban areas based on 1980 census data, but this is done from a static perspective and not taking into account temporal changes in urban elderly distributions. Several studies have sought to compare population ageing in various regions during the same period (Shrestha 2000, Chatterji et al. 2008, Chomik et al. 2016). However, these horizontal and temporal comparisons have been limited to higher-level comparisons between countries or continents, overlooking variations in population ageing among the regions within a given country. Dufek and Minařík (2009) choose two main factors out of 12 indicators related to demographic indicators using factor analysis and explore the development of population ageing in particular Czech regions during the period 1998–2007. Chen and Hao (2014) select two indicators based upon which to measure population ageing in China for the period 1995–2011 and examine the overall differences of population ageing, as well as the differences among three primary regions, using the Theil index.
2) *Space oriented:* the spatial distribution of population ageing has been analyzed in Poland by means of spatial clustering by Kurek (2003). In that study, several age groups, including seniors, are divided in order to assess the age structure and characterize the distribution of each group's proportion of the entire population. Yuan et al. (2007) compare spatial changes

in population ageing among rural regions of China for 1990 and 2000 and cluster these regions into four quantiles accordingly.

3) *Time and space oriented*: Lai (1999) uses simple *T*-statistics to measure the temporal changes of China's population ageing among provinces and applies *D*-statistics to assess its spatial autocorrelation for the period 1953–1994. Kacerova et al. (2014) examine data from 1950 to 2010 in order to analyze time-space differences in age structure of the population in 39 European countries by means of spatial clustering. Zhang and Chen (2014) collect census data from 1990 to 2010 in the Fujian province of China and use several indicators of spatial autocorrelation to describe population ageing in terms of spatial-temporal evolutionary features.

In spite of the efforts made in existing studies, gaps in the body of knowledge still exist in this area. The current methods focus primarily on a single feature of population ageing (e.g., spatial autocorrelation) from either the spatial or the temporal perspective; thus, the research tends to be one-dimensional in nature. Furthermore, few studies have explored the differences in population ageing among the regions within a given country, integrating the temporal and spatial perspectives. To address the above issues, the present research proposes a comprehensive and systematic methodology for difference analysis of regional population ageing. Specifically, two multidimensional research frameworks for population ageing are presented—temporal difference analysis and spatial difference analysis—using the corresponding methods. For the temporal perspective, features of population ageing such as ageing trends, regional variations and the concentration degree of population ageing are of significant interest, while the spatial clusters and spatial autocorrelation form the primary features of population ageing from the spatial perspective. In addition to the overall and regional differences of population ageing analyzed in a country, differences of population ageing in some aggregated regions of a country (e.g., classified based on economic strength) are explored from both the temporal and spatial perspectives.

The novel contributions of this study include: (1) integrating the temporal and spatial analysis of population ageing from multiple dimensions in terms of regional difference, thus achieving theoretical innovation in regional population ageing research; (2) exploring these ageing features in different regions (e.g., both the country and aggregated regions) in a manner that takes into account both holistic and individual aspects in order to refine the difference analysis; and (3) considering the effects of geographical location on population ageing, resulting in improvement measures that correspond more closely with reality. In practice, the presented research methodology can be applied to other countries where regional differences in population ageing exist. It can also help policy-makers to understand change trends and regional differences in population ageing and to provide the basis for regional population strategies in order to balance regional development and address the economic, social and public health challenges associated with population ageing.

2. 2 Methodology

This chapter explores differences in regional population ageing from both temporal and spatial perspectives. The temporal perspective entails analyzing the features of population ageing in a given region(s) during an observed period—that is, time-based differences of population ageing. The spatial perspective takes geographical properties (e.g., the location of a region and its neighboring regions) into account, and examines the spatial features in population ageing among regions. To achieve the above objectives, a comprehensive and systematic methodology is proposed and illustrated in Figure 2-1. It consists of three key components: (1) the measurement of regional population ageing by means of the ageing coefficient; (2) the temporal analysis of population distribution, population ageing trends, regional variations and the concentration degree using stacked column graphs, mean analysis, coefficient of variation (CV), Lorenz curves and GC; and (3) the spatial analysis of population ageing clusters, global and local autocorrelation, using spatial clustering, global Moran's *I* and a Moran scatterplot. A detailed introduction to these research methods will be presented in the following subsections. Figure 2-1 depicts the relationship between the research methods (rounded rectangles) and research objectives (rectangles), and facilitates an understanding of the potential application of the research methodology to areas of interest for measuring and comparing regional population ageing.

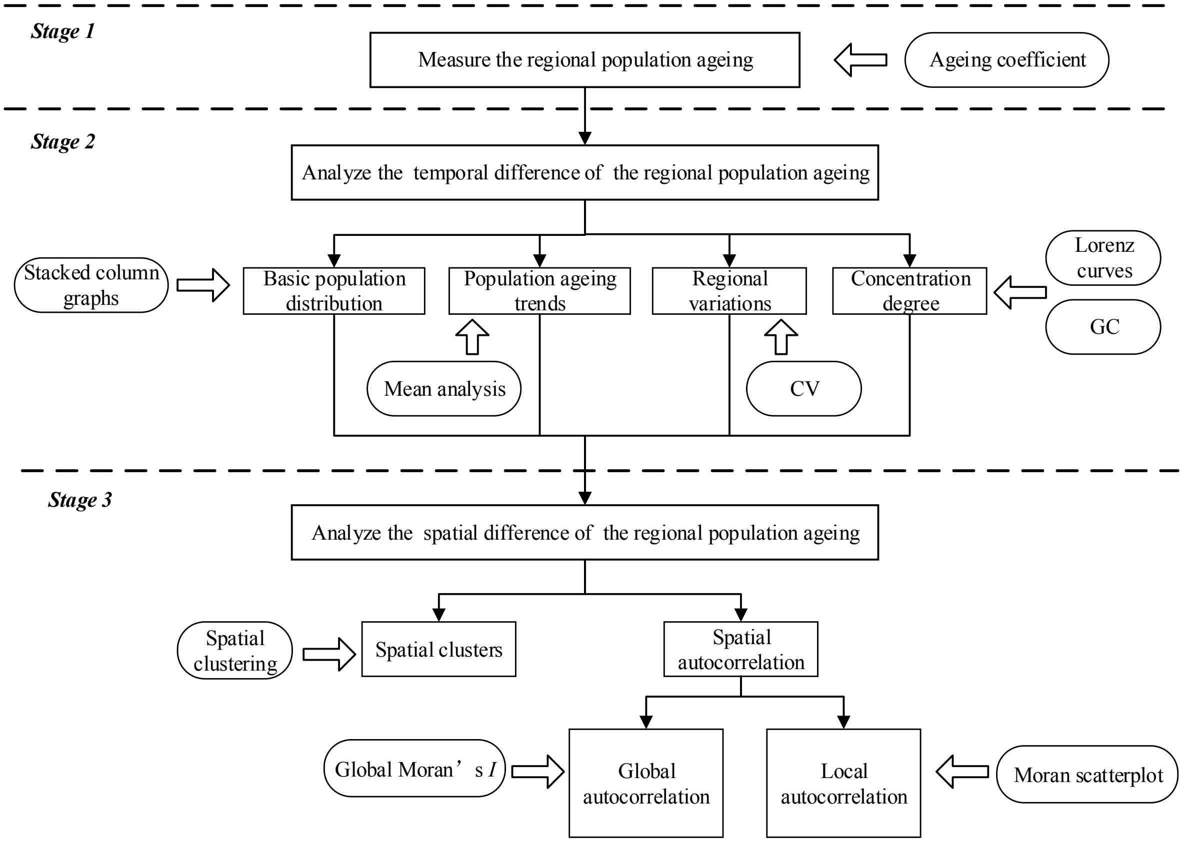

Figure 2-1. Research methodology.

Based on the above three components, the innovativeness of the proposed methodology is highlighted as follows:

1) A systematic process for population ageing analysis is developed that embraces population ageing measurement and regional difference analysis. Furthermore, this process simultaneously considers features of population ageing from the perspectives of time and space.
2) The research is multidimensional since multiple features of population ageing are involved from either the temporal or the spatial perspective. As such, compared with previous studies, this research provides a relatively comprehensive profile of regional population ageing in terms of temporal and spatial differences.
3) The whole country, aggregated regions and their component parts (e.g., provinces) are selected as research units, since the regional diversity underscores not only the imbalance in population ageing across the country but also the differences among and within the regions.

2.2.1 Measurements of population ageing

The conventional indicators to measure population ageing encompass the following:

1) Proportion of elderly persons (typically defined as those aged 65 and over)—this indicator directly reflects the absolute degree of ageing, which is the most frequently used as an index of demographic ageing (Cowgill 1974, Lutz et al. 2008, Ricciardi et al. 2015), and has also been applied in studies of population ageing in China (Chen and Hao 2014, Zhang and Chen 2014).
2) Median age of the population, which is an arbitrary metric, since it simply represents the age of persons who happen to be at the 50th percentile of the data set containing the ages of all individuals sorted in ascending (or descending) order (Shryock et al. 1973).

3) Ratio of the elderly (typically defined as those aged 65 years and over) to the young (typically those aged 15 years and under), where the latter is a relative index, the value of which is influenced by the proportion changes of two groups. However, there is some deficiency in using this ratio as the index of population ageing since it uses only the proportion of elderly people in a population (Kii 1982).
4) Dependency coefficients calculated based on three different age groups: youth (aged 0–14 years), productive (aged 15–64 years), and seniors (aged 65 and over years) (Dufek and Minařík 2009). Based on this classification, the youth (and senior) dependency ratios are the number of individuals aged 0–14 years (and aged 65 and over years) per 100 persons whose age lies within the range of 15–64 years. The sum of these ratios is known as the overall dependency coefficient. Since the variations in the whole age distribution of a population are not considered, the degree of ageing in a specific year will be exaggerated when fertility declines steeply (Kii 1982).

In this chapter, preference is given to the first indictor (i.e., the proportion of elderly people) as the ageing coefficient in order to measure regional population ageing. The reasons are two-fold: (a) considering the definitions and disadvantages of each of the above indicators, the proportion of elderly persons directly reflects the proportion of older adults in the total population with an extensive application; and (b) the selected ageing coefficient—which only involves two population groups, that is, the elderly and the total population—is better suited to serve as the foundation on which the other methods in the proposed methodology (Figure 2-1) could be used synergistically to analyze other features of population ageing.

2.2.2 Methods for temporal analysis

- *Lorenz curve and Gini coefficients*

The Lorenz curve can be employed to quantify precisely the concentration degree of population ageing, that is, the variations in the distribution of the elderly in the total population. By sorting region-level observations of elderly populations in ascending order, the cumulative percentage of elderly people is represented as the vertical axis and the cumulative percentage of the total population as the horizontal axis (Goodman 1987). If population ageing in each region is nearly identical—that is, if all the regions share uniform proportions of the elderly segment of the population—then the Lorenz curve is a diagonal line with equal distribution. Otherwise, the Lorenz curve is under the diagonal. A curve further from the diagonal indicates a more uneven distribution of population ageing, i.e., a higher concentration degree.

In reality, the GC is regarded as a relative index based on the Lorenz curve. Considering a Lorenz curve in which the cumulative percentage of the total population is plotted against the cumulative percentage of elderly people, the GC can be expressed by:

$$G = S / P \tag{2-1}$$

where S refers to the area between the diagonal (signifying equal distribution) and the Lorenz curve; and P denotes the entire area under the diagonal. If $G = 0$, then the distribution of population ageing is regionally equal; if $G = 1$, then population ageing represents complete inequity; if $0 < G < 1$ and closer to 1, this is indicative of more pronounced differences in regional population ageing; and if $0 < G < 1$ and closer to 0, then the regional population ageing tends to be uniform.

- *Coefficient of variation*

The CV metric is defined as the standard deviation (SD) of an indicator divided by its mean; it is the most widely used to measure differences in terms of regional development and imbalanced development (Wang et al. 2013). The CV is thus used to analyze fluctuations in population ageing in different regions over an observed period.

$$CV = \frac{\sigma}{\mu} = \frac{1}{\mu}[\frac{1}{n}\sum_{i=1}^{n}(AC_i - \mu)^2]^{\frac{1}{2}} \tag{2-2}$$

where CV denotes the CV; n indicates the number of regions; AC_i is the value of the ageing coefficient in region i; μ and σ represent the mean and the SD of ageing coefficients respectively; and, accordingly, where CV is larger, the larger is the difference in regional population ageing.

2.2.3 Methods for spatial analysis

- *Spatial clustering*

Clustering analysis is conducted on the basis of distance, and Euclidean distance (e.g., including location distance and attribute distance) is widely applied to traditional clustering analysis. The location distance reveals the degree of proximity between two objects, while the attribute distance reflects the similarity of attribute features between two objects (Wang et al. 2013). In consideration of similar objects with the above two features, spatial clustering is effective in solving the feature combination. If the location distance and the attribute distance are regarded equally, then spatial distance is expressed as:

$$D_s = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + \sum_{k=1}^{n}(a_{ik} - a_{jk})^2} \tag{2-3}$$

where (x_i, y_i) and (x_j, y_j) are two-plane Cartesian coordinates of points or regions' centers P_i and P_j respectively; and a_{ik} and $a_{jk} (k = 1,2,...,n)$ are their corresponding attribute vectors.

If the location distance and attribute distance are weighted, then the spatial distance, D_s, can be expressed in either of two ways:

$$D_s = \omega_l \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} + \omega_a \sqrt{\sum_{k=1}^{n} (a_{ik} - a_{jk})^2} \tag{2-4}$$

or

$$D_s = \sqrt{\omega_x (x_i - x_j)^2 + \omega_y (y_i - y_j)^2 + \sum_{k=1}^{n} \omega_k (a_{ik} - a_{jk})^2} \tag{2-5}$$

where ω_l, ω_x or ω_y is the weight of the location distance; ω_a or ω_k is the weight of the attribute distance; and $\omega_l + \omega_a = 1$ or $\omega_x + \omega_y + \sum_{k=1}^{n} \omega_k = 1$.

- *Global spatial autocorrelation*

It should be noted that CV is unrelated to the geographical location and only refers to the dispersion degree of data (Rey and Montouri 1999). A global Moran's *I* is used to indicate the global autocorrelation and difference degree of the observed values in spatial neighboring regions (Moran 1948). Therefore, global Moran's *I* is applied here in order to measure the regional imbalance of population ageing and its global spatial autocorrelation.

$$I_t = \frac{\sum_{i=1}^{n} \sum_{j \neq i}^{n} w_{ij} (x_{ti} - \overline{x}_t)(x_{tj} - \overline{x}_t)}{S_t^2 \sum_{i=1}^{n} \sum_{j \neq i}^{n} w_{ij}} \tag{2-6}$$

where I_t is the global Moran's *I* of the t^{th} year; x_{ti} is the ageing coefficient of region i in the t^{th} year; $\overline{x}_t = \frac{1}{n} \sum_{i=1}^{n} x_{ti}$ and $S_t^2 = \frac{1}{n} \sum_{i=1}^{n} (x_{ti} - \overline{x}_t)^2$ are the mean and variance of the ageing coefficients of all the regions in the t^{th} year, respectively; and w_{ij} represents the elements of the spatial weighting matrix $W_{n \times n}$ determined by the spatial adjacency and spatial distance. The spatial adjacency method is selected for the present research based on the Rook rule: if region i adjoins region j, then $w_{ij} = 1$; otherwise $w_{ij} = 0$, and no adjacency relationship exists between region i and itself, that is, $w_{ii} = 0$.

The range of global Moran's I-values is [−1, 1]. $I_t > 0$ expresses a positive spatial autocorrelation, that is, the regions of relative high or low population ageing tend to be significantly spatially conglomerated; $I_t < 0$ denotes a negative spatial autocorrelation, that is, there exist differences in population ageing between region i and its surrounding regions; and $I_t = 0$ denotes no spatial autocorrelation, that is, the regional population ageing has a random spatial distribution.

Normally, the z-test is used to verify whether the calculated global Moran's I meets the significance level (Cliff et al. 1981).

$$z_t = \frac{1 - E(I_t)}{\sqrt{VAR(I_t)}} \tag{2-7}$$

- *Local spatial autocorrelation*

To measure further the local spatial autocorrelation between a given region and its surrounding regions, the spatial degree of difference and the spatial pattern in terms of population ageing, a Moran scatterplot is used. A Moran scatterplot is two-dimensional and describes the correlation between a vector of observed ageing coefficients (y) and a weighted average of the neighboring values, or spatial lag, Wy (Anselin 1996):

$$Moran's\ I = (N / S_0) y' Wy / y' y \tag{2-8}$$

where N is the number of observed ageing coefficients; S_0 is the sum of all elements in the spatial weight matrix ($S_0 = \sum_i \sum_j w_{ij}$); y is the observed ageing coefficients in deviation from the mean; and Wy is the associated spatial lag, which is a weighted average of the neighboring values.

A Moran scatterplot divides the whole region into four types of spatial areas. The first quadrant (HH) and the third quadrant (LL) indicate the degree of population ageing in region i and its surrounding regions are high or low; the second quadrant (HL) denotes that degree of population ageing in region i is high, while its surrounding regions has a low degree; and the fourth quadrant (LH) indicates that the degree of population ageing in region i is low, while its surrounding regions have a high degree. The elements in HH and LL present a positive autocorrelation, while the elements in HL and LH present a negative autocorrelation.

2. 3 Case Study

2.3.1 Data description

This chapter uses China as a case study and take its 31 provinces as the observed jurisdictions. The geographical locations of these provinces and the region division can be observed in Figure 2-2. Considering the differences in economic strength with respect to geographical location, the provinces are divided into three primary regions: eastern, central, and western. A ladder-like distribution of economic strength is exhibited in China following the high to low principle. China's regional total and aged population data are selected in order to evaluate population ageing (National Bureau of Statistics of China 1999-2015). The analysis is restricted to the period 1998–2014 (excluding 2001) based on data availability (see Table A-1).

Figure 2-2. Map of China.

2.3.2 Temporal differences in population ageing

2.3.2.1 *Basic profile of total and aged population*

The basic demography of total and elderly populations distributed in the three primary regions is presented in Figure 2-3. The stacked columns A and B for each year show the total and aged populations respectively. The upper-most sections of the columns depict population ageing in the western region, while the middle and lower segments represent the central and eastern regions.

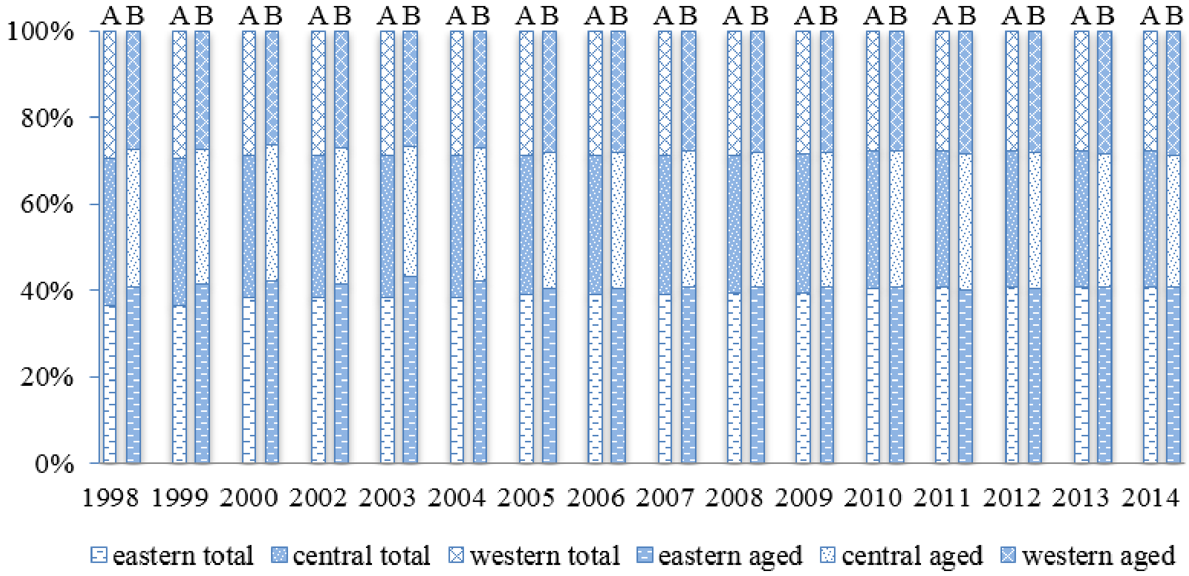

Figure 2-3. Basic demography of regional total and aged population.

Overall, it can be observed that the population in the eastern region accounts for the largest proportion (about 40%), followed by the central (about 32%) and western regions (about 28%) over the whole period, even though the western region has the greatest number of provinces. This indicates that the regions in China with higher levels of economic development tend to have larger populations. In fact, numerous studies have demonstrated that economic development plays a significant role in population growth (Ogilvy 1982, Cincotta and Engelman 1997, Firmino Costa da Silva et al. 2017). Compared with 1998, the percentage of the total population is observed to be increasing (by 11.1%) in the eastern region by the end of the studied period, while it is decreasing by 7.0% and 5.9% in the central and western regions respectively. In terms of aged population, there is a slight fluctuation during the observed period, and sorting based on percentage is congruent to that of the total population. The most notable difference is that the SDs of the total population percentage in the eastern and central regions (0.0130 and 0.0075 respectively) are larger than those of aged population percentage (0.0079 and 0.0042 respectively). Conversely, the variation of aged population percentage (0.0064) in the western region is slightly larger. In general, the proportional distribution of the total and aged populations remains relatively stable in each region during the observed period.

The average degree of population ageing is calculated for the entire country and the three primary regions annually, and their change trends over the period are plotted in Figure 2-4.

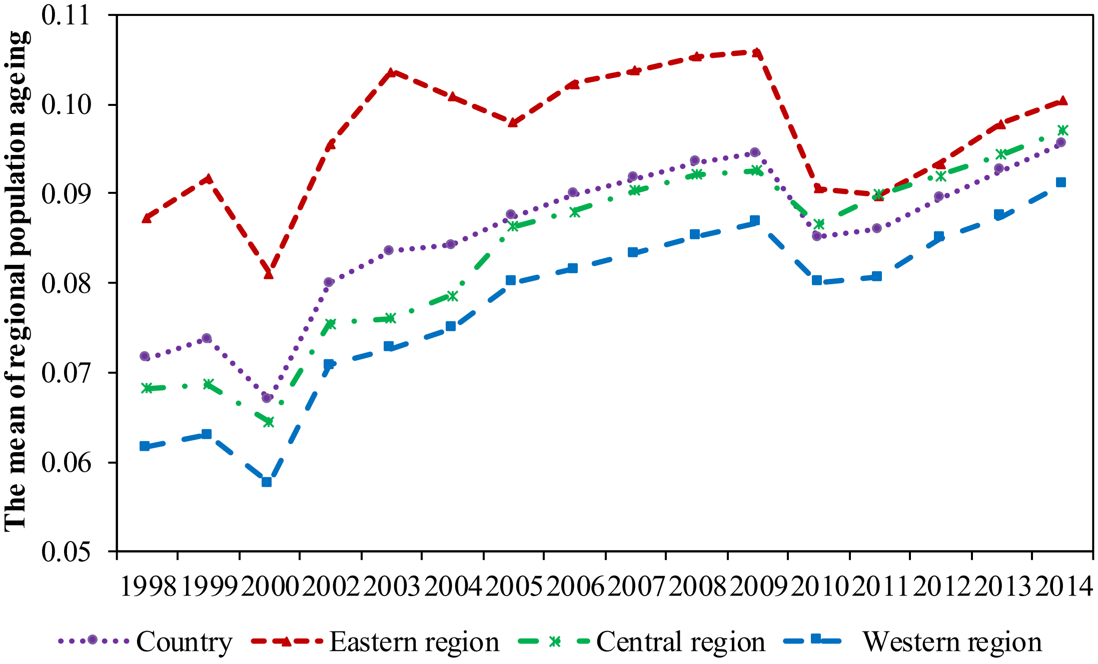

Figure 2-4. Trends in the average degree of regional population ageing.

In terms of the overall perspective, the average degree of population ageing gradually fluctuates with an increasing trend across the entire country and for each of the three primary regions during the 17-year period. This underscores the fact that population ageing in each region increases, while the maximum values do not exceed 11%. Moreover, the change trends of the four curves are similar, except that the eastern region experiences a higher fluctuation of population ageing during the period, and its differences before 2010, when compared with the other regions, are relatively clear. Also, the average degree of the eastern region typically exceeds the values of the other three regions, being followed by the entire country, then the central and western regions. To be specific, the fluctuations in population ageing for all regions are found to be small for the period of study before 2000, with the maximum in 1999 (0.092) and the minimum in 2000 (0.058). From 2000 to 2009, a surge in population ageing occurs in all regions in the first two years, while it transitions to more constant growth in the western and central regions and a large fluctuation in the eastern region over the period that follows. Moreover, regional population ageing sees a rapid decline in 2010 and then increases slightly over the remainder of the studied period.

2.3.2.2 *Concentration degree of population ageing*

For each year, the cumulative percentages of the elderly are calculated after first ranking the populations of the 31 provinces in ascending order, and the corresponding cumulative percentages of the total population are then obtained. Lorenz curves for population ageing in each year can be created based on the above principle. In the interest of clarity and simplicity given the large data set, Figure 2-5 presents four selected years to illustrate the concentration degree of population ageing by means of Lorenz curves.

All the Lorenz curves are under the diagonal, which indicates that the percentages of the aged in the various regions are not identical, that is, the concentration degree of the elderly varies regionally. However, the degree of deviation from the diagonal is not obvious and a small degree of fluctuation exists in regional population ageing over this period. This indicates that the distribution of population ageing is not concentrated among the provinces with the highest degrees of ageing. This result also verifies the finding represented in Figure 2-3—that is, that the sorting of aged populations based on the percentage among three primary regions is the same as that of the total population. To capture more clearly the concentration degree of population ageing in China during these years, Eq. (2-1) is used to obtain the values of GCs presented in Table 2-1.

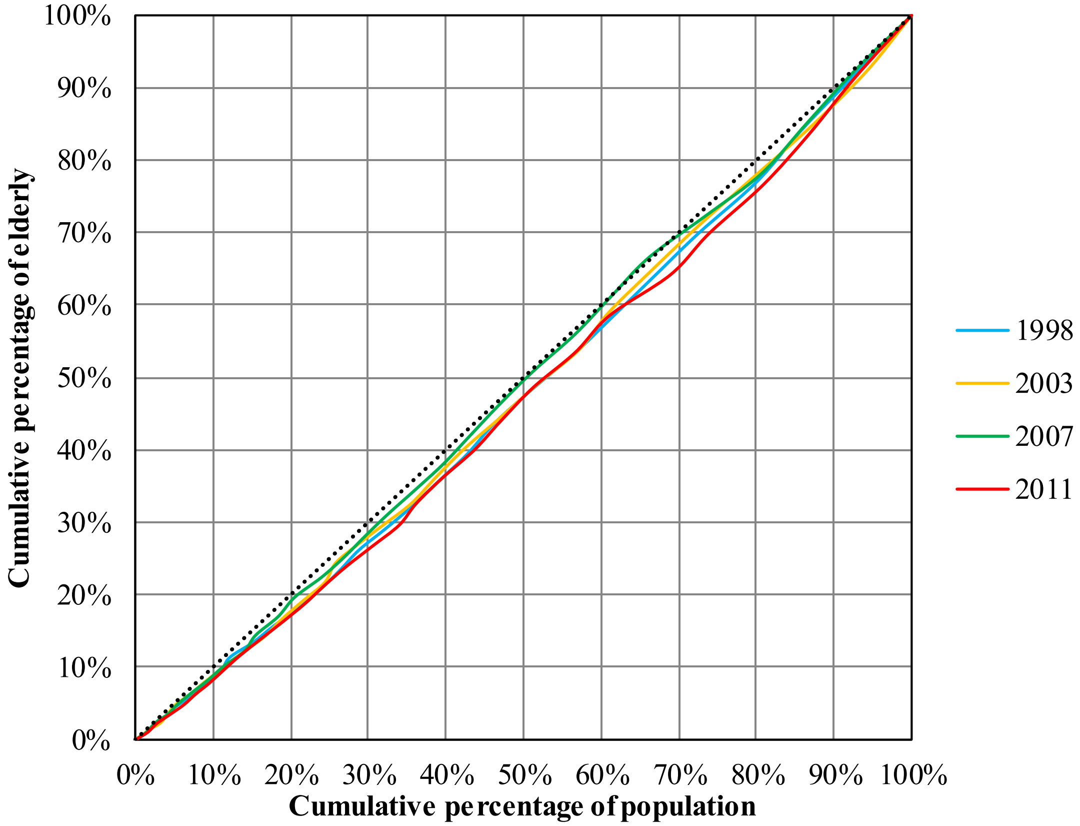

Figure 2-5. Lorenz curves of population ageing for four selected years.

Table 2-1. GCs of population ageing in China, 1998-2014.

	GC
1998	0.023
1999	0.022
2000	0.023
2002	0.014
2003	0.020
2004	0.013
2005	0.018
2006	0.016
2007	0.010
2008	0.011
2009	0.016
2010	0.019
2011	0.029
2012	0.022
2013	0.022
2014	0.025

Overall, the degree of fluctuation of population ageing GC is found to be relatively stable. The values of GC lie in the interval $(0,1)$, indicating a difference in distributions of the elderly among the provinces, and that the entire situation is not complete inequity. Moreover, the values are much closer to zero, meaning that the distribution of population ageing tends to be regionally uniform.

2.3.2.3 *Regional differences of population ageing*

The regional diversity underscores not only the imbalance in population across the country, but also the differences among the three primary regions and among the provinces within each region. According to Eq. (2-2), trends in the CV of population ageing in each region are measured and the mutual influences among them are analyzed.

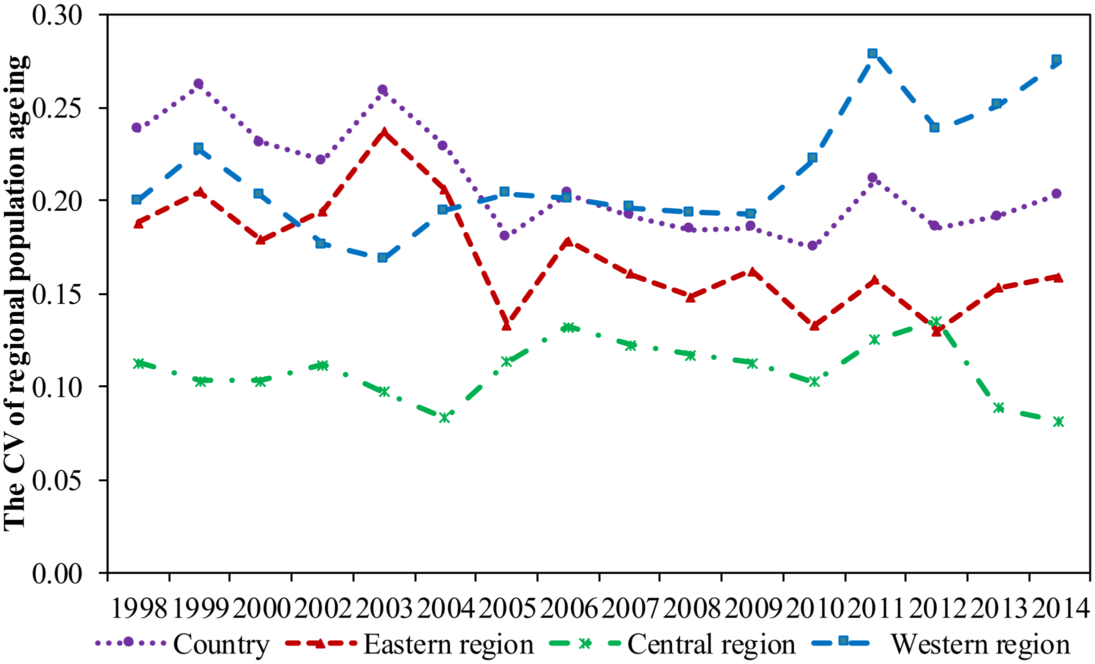

Figure 2-6. Trends in the CV of regional population ageing.

As can be observed in Figure 2-6, the CV of population ageing is decreasingly variable across the entire country during the 17-year period, which reflects the fact that the gaps in population ageing between regions are declining overall. This point also verifies the result that the concentration degree of population ageing is not obvious, which is reflected by the Lorenz curve trends and the GC values. In terms of trends and degree of fluctuation, the CV of population ageing for the entire country has a similar tendency as that of the eastern region, while the values are clearly larger (a mean = 0.210 for the whole country versus a mean = 0.170 in the eastern region). Conversely, the CVs of population ageing in both the central and western regions see an overall increase during this period. Population ageing has its greatest variation in the western region (mean = 0.214) during the observed period, while the central region has the lowest fluctuation (mean = 0.109) in the four curves. The change trends of CV in the three primary regions are consistent with the trend results over the period 1998–2011 using the Theil index (Chen and Hao 2014). Based on the mean CV for the entire country and the deviations among the three regions, it can be observed that the overall population ageing trend is primarily influenced by ageing fluctuations from the central and western regions.

A comparison of the CV in the four curves also reveals changes to the distribution of elderly people in each region. Before 2005, the CVs for the entire country are generally larger than those for any of the three primary regions, despite significant fluctuations among the three regions. By 2014, population ageing in the western region dominates the level of change with rapid growth. The CV of population ageing in the eastern region fluctuates continuously, while the CV in the central region exhibits an overall decreasing tendency. Although the level of economic development is lowest in the west, its comfortable living condition accounts for the marked change in the intra-region distribution of elderly people. Population health outcomes are shaped by complex interactions between individuals and the diverse physical, social and political conditions in which they live (Clarke and Nieuwenhuijsen 2009). Older adults tend to be more impacted by barriers in their surrounding social and physical environment due to declining health and functional status, financial strain, and social isolation (Wahl and Lang 2003, Oswald et al. 2007). This may become a factor to promote the migration of elderly people from other regions, indirectly resulting in variation of population ageing in the western region.

When comparing the results shown in Figure 2-4 and Figure 2-6, it can be seen that there is a large difference between the two figures. The former only describes the average degree of regional population ageing, while it cannot quantify the degree of dispersion of population ageing among all provinces in each region. Hence, the latter is better used to display imbalanced development of population ageing.

2.3.3 Spatial differences of population ageing

2.3.3.1 *Spatial clustering of population ageing*

To analyze further spatial differences in regional population ageing in China, based on the average ageing coefficients and spatial clustering theory, GeoDA095i software is employed to determine the three categories of population ageing. Detailed guidelines on the use of this software can be obtained from (Anselin 2004).

The first category (i.e., high degree of population ageing) includes the following 10 provinces: Sichuan, Chongqing, Hunan, Beijing, Tianjin, Liaoning, Shanghai, Jiangsu, Zhejiang and Shandong. The first three are in the central and western regions; most of the others are in the eastern region. This also verifies the result in Figure 2-4 that the average degree of population ageing in the east remains the largest among all regions during the studied period. The provinces in the eastern region enjoy a significant level of economic development due to industrial development and political/economic status (e.g., Beijing and Shanghai). These provinces provide active employment markets with more opportunities for young adults and their families (National Bureau of Statistics of China 1999-2015). As for the regions with relatively slow economic development, living conditions and lifestyle may figure as primary factors influencing elderly people in their decision about whether to reside in the area, since social and physical conditions strongly influence the health of seniors (Wahl and Lang 2003, Oswald et al. 2007, Clarke and Nieuwenhuijsen 2009).

The second category includes the following 11 provinces: Hebei, Fujian, Jilin, Anhui, Jiangxi, Henan, Hubei, Guangxi, Hainan, Guizhou and Shaanxi. These provinces are mainly located in the central and western regions, which suggests a strong market potential for population ageing in these provinces. The remaining 11 provinces form the third category comprising the group of low ageing degree. Nearly all these provinces are located in the western region. The components of the two categories also correspond to the results of the average degree of population ageing—that is, the western region tends to have the lowest degree of ageing. Based on the above findings, China's population ageing for all regions exhibits a ladder-like distribution different from the categorization based on regional economic strength. Moreover, the high degree of population ageing is not confined to a certain region; conversely, it spans all three regions despite their differing levels of economic development.

2.3.3.2 *Spatial autocorrelation of population ageing*

- *Global autocorrelation*

According to the annual ageing coefficient data, the statistical inference based on 999 permutations is referenced (Anselin 1996), and then GeoDA095i is used to calculate global Moran's I for the regional population ageing of China, as presented in Table 2-2. The expectation of global Moran's I during the period is −0.033, obtained using the equation: $E(I) = -1/(n-1)$, where n is the number of observed units.

Table 2-2. Global Moran's *I* of population ageing in China, 1998-2014.

	Moran's *I*	Z-value	P-value
1998	0.435	4.445	0.001
1999	0.441	4.435	0.001
2000	0.523	4.976	0.001
2002	0.465	4.523	0.001
2003	0.448	4.889	0.001
2004	0.389	4.208	0.001
2005	0.386	3.72	0.001
2006	0.312	3.067	0.002
2007	0.335	3.403	0.002
2008	0.288	2.729	0.010
2009	0.284	2.852	0.007
2010	0.302	3.008	0.002
2011	0.204	2.057	0.023
2012	0.226	2.223	0.027
2013	0.245	2.552	0.013
2014	0.163	1.764	0.039

As indicated in Table 2-2, the global Moran's *I*-values are all found to be greater than 0, and all values pass the significance test (under a 0.05 significance level). This shows that population ageing in the various provinces is not mutually independent, but clearly exhibits the feature of spatial agglomeration. To be specific, there is a polarization between the high level of population ageing (in most of the eastern region) and the low level of population ageing (in most of the western region). Furthermore, the global Moran's *I*-values are decreasing overall. This indicates that the conglomerated area of relatively high or low population ageing in the geographical space is decreasing, which could explain why the distribution of population ageing tends to be regionally uniform (refer to the GC results). It also reflects that there are adjacent effects among the regions, meaning that population ageing in a given region is influenced by the ageing situation in neighboring regions.

- *Local autocorrelation*

To determine the type of local autocorrelation pertaining to regional population ageing and its spatial distribution, the annual Moran scatterplots of the 31 provinces in China are exported based on the ageing coefficients. By gathering the quadrant change (i.e., the local autocorrelation change) of each province during the period, the evolutionary process of regional population ageing can be summarized as presented in Table A-2.

At the provincial level, local autocorrelation of population ageing in most of the provinces remains relatively stable during the 17 years. Fujian varies from HH to LH in 2000, to HL in 2006, and remains in LL for the last five years of data. The local autocorrelation between this province and neighboring provinces fluctuates continuously, while population ageing in this province is moderate. It can be observed that the ageing situation in Fujian is closely related to its neighboring ageing change. As for Jilin, its population ageing exhibits a low level before 2007, similar to its neighboring provinces. Then, from 2007 to 2010, Jilin falls within LH, then shifts positions among HH, HL, and LL over the course of the following four years. This result indicates that population ageing in Jilin is generally low and that the fluctuations in neighboring provinces are significant. In contrast to Jilin, in Shaanxi population ageing is representative of a trend of local autocorrelation. The key difference is that Shaanxi is in LH for the period of 2007–2010, which signifies a trend of increasing population ageing in neighboring provinces compared with the situation at the beginning of the period of study.

At the regional level, the provinces in the HH quadrant account for the largest percentage of all the provinces in the eastern region, followed by those in the LH and HL quadrants. Among these, Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang and Shandong exhibit a similar population ageing development trend. This not only demonstrates the existence of a cooperation mechanism in population ageing to some degree but also improves the level of population ageing for the whole region. The distributions of the central provinces in HH and LL tend to be relatively uniform, followed by LH with a small gap. This spatial pattern points to a moderate level of population ageing in the central region. In the western region, the provinces in LL reveal a clear dominance in population ageing, resulting in a low level of population ageing for the whole region. Furthermore, spatial autocorrelation of population ageing in these provinces and their neighbors, such as Hainan, Tibet, Qinghai, Xinjiang and Inner Mongolia, is relatively stable, indicating that, regardless of the province, the degree of population ageing is very low. The development of population ageing in Sichuan is also steady (HL), which confirms that this province belongs to the first clustering category of population ageing.

The number of provinces counted in each quadrant experiences a small fluctuation during this period. This situation can be regarded as a relatively stable spatial pattern. Of the quadrants, LL accounts for the largest percentage, followed by HH, LH and HL sequentially. Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang and Shandong fall within HH, which indicates that the high level of population ageing is mainly concentrated in the eastern region. Hainan, Yunnan, Tibet, Gansu, Qinghai, Ningxia, Xinjiang and Inner Mongolia are in LL, which indicates that the low level of population ageing is primarily concentrated in the western region. This verifies that China's population ageing exhibits bipolar agglomeration in the space. In the quadrants of negative autocorrelation (HL and LH), Liaoning is undergoing rapid economic development and features a high level of population ageing, but its neighboring provinces, including Jilin, Hebei and Inner Mongolia, have a low level of population ageing. The situation is similar in Sichuan and Guangxi for some portions of the period under study.

2.3.4 Suggestions and policy implications

Based on the above temporal and spatial analyses of regional differences in population ageing, some suggestions and policy implications are proposed:

1) Adjust starting age structures: either the entire country or the three primary regions have experienced an increase of ageing degree during the observed period. Compared with other regions, in the east population ageing is relatively pronounced, which is reflected in both the change trends of population ageing and provincial distribution in the three spatial clusters. The Chinese government introduced a two-child policy in 2016 in order to boost the country's birth rate and further mitigate population ageing in future. As such, the government needs to strengthen the promotion of this new policy in three primary regions, especially directing its efforts toward those provinces in the east with a higher degree of population ageing, such as Beijing, Tianjin, Liaoning, Shanghai, Jiangsu, Zhejiang and Shandong.
2) According to spatial clusters and local spatial autocorrelation, the degree of population ageing in each province has been presented. Accordingly, policy-makers could establish and optimize a pension service system, reinforce social and welfare services for the elderly, and implement measures to prevent a mismatch between the established service system and the degree of local population ageing, such as over- or under-service. In this regard, it should also be mentioned that it is preferable to implement these measures beginning with the provinces where the degree of population ageing is much higher.
3) Necessary resources, such as medicine and health care, should be judiciously and evenly allocated to guarantee that the basic needs of the elderly are met. As for the central and western regions, the level of economic development still lags behind, while the average

degree of population ageing in the two regions has an increasing trend. Meanwhile, differences in population ageing are found to exist within each of the two regions. Some provinces with low economic strength belong to the clusters with a higher degree of population ageing. As for these provinces, the government should consider providing more effort and focus on economic development and necessary resource allocation.

4) Although the concentration degree of population ageing is not obvious, differences in regional population ageing are diverse. The CVs of the country as a whole are found to be larger than those in the three primary regions for the period before 2006, while the CVs of the east represent the greatest contribution to the entire difference during the following period. Meanwhile, the degrees of fluctuation reflect diversity among these regions. Thus, an improvement plan for regional population ageing should consider differences within and among regions from temporal and spatial perspectives, and then provide the corresponding remedies to balance regional development.
5) Strengthen regional communication and collaboration: the ageing degree of the entire country is influenced by those of the three primary regions, indicated by ageing trends and CV. This regional effect also exists in global autocorrelation and local autocorrelation. In other words, change in a province (individual) will affect the neighboring provinces (groups) and, in turn, the whole country (system). As for the provinces with similar degrees of population ageing (such as provinces in the first clustering category or the provinces in the HH quadrant), regional communication and collaboration are beneficial for promoting mutual learning and problem solving.
6) Implement a new pension mode: "ageing in place", an emerging paradigm in ageing policy, aims to help older people to continue living at home, and fundamentally and positively

contributes to an increase in well-being, independence, social participation and healthy ageing (Sixsmith and Sixsmith 2008). It not only benefits the older person in terms of their quality of life but also presents a cost-effective solution to the problems caused by an expanding population of older adults (Tinker et al. 1999). Since the eastern region with better economic strength dominates the degree of population ageing, there is potential to deploy this new pension mode in some of the provinces in this region (e.g., Beijing, Shanghai, Jiangsu and Zhejiang) as a pilot project in order to implement this pension mode in other provinces if it performs well.

2. 4 Conclusions

This chapter proposes a systematic methodology for difference analysis of regional population ageing from temporal and spatial perspectives, and applies these methods to a case study of China over the period 1998–2014. As for the temporal analysis, regional population ageing trends, the concentration degree and regional differences are explored using stacked column graphs, a Lorenz curve, GC and CV. The results indicate that the average degree of population ageing fluctuates with an increasing trend in all the regions during the period, while the largest ageing degree does not exceed 11%. The change trends within the entire country and within the three primary regions are similar, but population ageing in the eastern region has a higher fluctuation, and is clearly different than in other regions in the period before 2010. The concentration degree of the elderly is low and varies regionally; there is a small degree of fluctuation in regional population ageing GC over the studied period; and the overall situation is not complete inequity due to the GCs located in the interval (0, 1). The CV of population ageing fluctuates with a decreasing tendency for the entire country during the period of study; this trend is similar to that in the eastern region, but opposite to those in the western region, with greatest variation, and the central region, with the lowest fluctuation; the CV trend for the whole country is mainly influenced by ageing fluctuation from the central and western regions.

As for the spatial analysis, spatial clusters, spatial autocorrelation and evolution of population ageing among regions are analyzed by means of spatial clustering, global Moran's *I* and Moran scatterplot. The results indicate that China's regional population ageing exhibits a ladder-like distribution different from the distributions pertaining to economic strength among the eastern, central and western regions; the highest degree of population ageing is not confined to a certain region, but has penetrated the three primary regions. Population ageing is not mutually independent among all the provinces but reveals a clear feature of spatial agglomeration; the spatial convergence effect is weakened overall during the period since the values of global Moran's *I* are found to be decreasing. There is also local spatial autocorrelation in China's population ageing, which forms a relatively stable spatial pattern. Specifically, the provinces in the HH quadrant account for the largest percentage of all the provinces in the eastern region; the number of provinces in each quadrant fluctuate constantly with slight variation.

Based on the achieved research results, some suggestions and policy implications are provided for population ageing involving several aspects: age structure adjustment, pension service system establishment, sound social and welfare services, reasonable resource distribution, diversity of regional management plan, regional communication and collaboration, and ageing in place. Simply put, the research methods proposed in this study can achieve theoretical innovation in the research area of regional population ageing from multiple dimensions, and can also be applied to other countries where regional differences in population ageing exist. Moreover, it can provide a reference point for policy making pertaining to regional ageing gap reduction and balanced development. However, this study only explores population ageing in terms of regional differences from a descriptive analysis perspective. Future studies are needed to analyze the influencing factors of population ageing and the formation mechanism of regional differences from a spatial perspective.

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Chapter 3: SPATIAL ANALYSIS FRAMEWORK FOR AGE-RESTRICTED COMMUNITIES INTEGRATING SPATIAL DISTRIBUTION AND ACCESSIBILITY EVALUATION[3]

3.1 Introduction

As of 2015, the population of people aged 60 years or over reached 901 million worldwide, an increase of 48% from 2000; this number is projected to grow to 1.4 billion by 2030 and to 2.1 billion by 2050 (United Nations 2015). With this change on the horizon, many countries are confronted with an unprecedented challenge. For instance, the shift in demographics is predicted to lead to changes in housing needs. In recent years, the percentage of 55+ households in Canada has grown and is currently at 38% (Statistics Canada 2017a). As a member of the organization for economic cooperation and development (OECD), Canada is recognized for having one of the strongest policies in terms of retirement income support for senior citizens (Martin and Whitehouse 2008). As a result, Canadian seniors are generally living above the poverty threshold and most retirees have high rates of replacement income (Department of Finance Canada 2014). It comes as no surprise that these socially-oriented policies allow the majority of Canadian retirees, most likely empty nesters, to have sufficient purchase power, allowing them to enjoy a high standard of living, including reasonable options for housing. Age-restricted communities have become a popular residential option for older adults (Ginzler 2009). Three types of age-restricted communities are common—independent, supportive, or combined living—depending on the health and mobility of the resident. The communities considered in this chapter are restricted to residents with a minimum age of 65, which is a commonly-used age threshold to define this demographic (WHO 2013). Recent studies indicate that seniors living in these kinds of communities enjoy many advantages, including being with individuals of a similar age and

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[3] A version of this chapter is under review for publication in *Journal of Urban Planning and Development.*

avoiding the cost of property ownership (Racca 2006, Oswald Beiler et al. 2016). Residents of age-restricted communities are shown to have better residential satisfaction due to high quality of life (Metlife and NAHB 2011). In addition, this form of housing provides seniors with a possible solution to reduce the risk of social isolation and economic deprivation (United Nations 2015).

Although age-restricted communities provide seniors an alternative mode of life, they can also be fully integrated within existing urban neighborhoods. As such, the design of these neighborhoods can have a significant impact on the health of those who live there and particularly on seniors, who tend to be sensitive to the features of the built environment. In this regard, the World Health Organization (WHO) (2007) published *Global Age-Friendly Cities: A Guide* in order to provide guidelines that could help planners design neighborhoods and cities that are socially inclusive. One element of the WHO guidelines (WHO 2007) that is frequently emphasized is accessibility in the general sense, which includes: (i) geographical accessibility to specific locations, such as for the purpose of government services or leisure (Handy and Niemeier 1997); and (ii) soft accessibility, such as accessibility to information (Culnan 1985). In this chapter, the focus is on geographical accessibility, which is largely understood as the ease with which people can reach destinations (Hansen 1959). Many guides for building age-friendly communities have been put forward, but it is difficult to judge, due to a lack of quantitative indicators, whether or not the accessibility of age-restricted communities in a neighborhood is appropriate (Public Health Agency of Canada 2015).

Geographical accessibility is paramount since it can be an incentive for physical activities such as walking, which is a widely recommended form of exercise. Survey data has demonstrated that the most common activity among older adults is walking or jogging (14%), followed by sports (9%), other physical activities (9%), and other outdoor activities (7%) (Szanton et al. 2015).

However, while young individuals can easily overcome minor physical barriers such as walking a long distance (e.g., up to a half-mile) to reach a bus stop or to complete an errand, older adults may find this challenging, especially if the weather conditions are inclement. As a result, the location of a given age-restricted community may pose a challenge for elderly residents wishing to access the built environment, natural surroundings, and biodiversity. This could be detrimental to their physical and mental health due to reduced social interaction and community involvement. With these elements in mind, this study considers a neighboring area to be age-friendly if it provides sufficient accessibility, making it a suitable geographical location for an age-restricted community. Furthermore, since in many North American cities infill development is currently increasing, this research aims to provide additional insight into the process of evaluating the suitability of existing neighborhoods for hosting age-restricted communities.

To address the research gaps and achieve the objectives proposed above, spatial analysis framework for age-restricted communities is conducted in this study using both regional and local perspectives. Regional analysis investigates the spatial distribution of age-restricted communities (or residential facilities) over a given region, i.e., a single city or an urban agglomeration, in order to gain better insight into the factors that can impact the location of these communities, e.g., neighborhood design, existence of other close-by age-friendly facilities, demographics (especially data that are relevant to aged population), etc. The local perspective focuses on developing metrics of quality of life that could be applied to evaluate individual age-friendly communities. One of these metrics is the comprehensive accessibility of age-restricted communities to various types of neighboring facilities and services that are the most important to seniors which can be developed on the basis of established distance thresholds documented in the scientific literature and as set forth in the Leadership in Energy and Environmental Design for

Neighborhood Development (LEED-ND). A sensitivity analysis of comprehensive accessibility evaluation is then conducted for age-restricted communities in consideration of various influencing factors (i.e., evaluation objects, weights, and different distance thresholds for these neighboring facilities). The primary contribution of the present research is to demonstrate how age-friendly accessibility can be used to develop regional and local neighborhood policies aiming to improve quality of life of older adults. In practice, it not only can provide a basis for urban planning strategies that will help alleviate some of the challenges encountered by an ageing population, thus making age-restricted communities in a neighborhood age-friendly, but also offers suggestions to developers on where to locate future communities that are able to help provide a resilient lifestyle for the older-adult resident.

3.2 Literature Review

3.2.1 Measuring accessibility

Accessibility is generally defined as potential opportunities for interaction (Hansen 1959), which can be measured as person-based or location-based (Miller 2005). Person-based accessibility measures the opportunities at the individual level and investigates individual factors (e.g., ability, budget, and other barriers) influencing the ease with which one can reach their desired destination, while location-based accessibility presents aggregated measures, quantifying the number of opportunities accessible from a location by means of a specific mode (Al-Sahili and Aboul-Ella 1992, Aultman-Hall et al. 1997, Handy and Niemeier 1997, Geurs and van Wee 2004). The latter is most commonly used by policy makers since this analytical approach provides a comprehensive measure of the land use and transportation system at the regional scale (Dodson et al. 2007). Hence, location-based accessibility is the focus of the present study due to its relevance to planning. In general, the measurement of accessibility primarily comprises two parts: attraction of an activity (or opportunities) and transportation impedance, which is calculated based on travel time or distance (Hansen 1959, Geurs and van Wee 2004, El-Geneidy et al. 2016). Currently, there are two widely-used methods for location-based measures in accessibility research. The first is the cumulative opportunity measure, which counts the number of potential activities (or opportunities) reachable within a specified transportation impedance when departing from a given location by means of a particular travel mode (Handy and Niemeier 1997, Geurs and van Wee 2004). This method is simple to use and understand, but it also has some shortcomings, including: (i) all destinations are treated equally; (ii) a threshold that is generally empirically chosen is used to differentiate travel distance or time in order to count the opportunities within the threshold; and (iii) this method ignores travelers' perceptions of time (Ben-Akiva and Lerman 1979). The second is the gravity-based measure first introduced by Hansen (1959), which discounts the attractiveness of the destinations with increasing distances (or, equivalently, time) from the origin. Cumulative opportunity measure yields accessibility in terms of the number of opportunities, while the gravity-based measure is expressed as opportunities over a distance(time)-decay function (Geurs and van Wee 2004). Hence, the cumulative opportunity measure is used in this study, since it is easy to generate and interpret and is better matched to the research objectives.

Relative accessibility is a measure of dissimilarities in access which compares the levels of accessibility across different groups (Niedzielski and Eric Boschmann 2014). It has been drawn upon in the accessibility measures of various topics, such as disability access (Church and Marston 2003), food deserts (Páez et al. 2010), and daycare facilities (Páez et al. 2012). This concept, which lays the foundation for comprehensive accessibility evaluation for all facilities and a comparison among various types of age-restricted communities, will be used in this study.

3.2.2 Age-restricted communities

Physical and social aspects of the neighborhood environment play a role in the health of older individuals and can predict health outcomes regarding individual deprivation and psychosocial characteristics (Kubzansky et al. 2005, Yen et al. 2009). Notably, when older adults are suffering from decreased mobility, the physical and social characteristics of a neighborhood can be significant contributors to their emotional well-being (Yen et al. 2009). Therefore, given the connection between neighborhood features and the quality of life of the elderly, it is important to further explore the foundations of age-friendly communities that will allow seniors of all physical and mental conditions to live safely and with dignity.

Oswald Beiler et al. (2016) mapped age-restricted communities in the geographic information system (GIS) and identified their locations, but no more detailed analysis was conducted related to the locations and neighboring environment. Furthermore, few studies have explored the relationship between the locations of age-restricted communities and the density of the senior population around them, integrating different community types (i.e., independent living, supportive living, and combined living). Locating age-restricted communities where there is currently a higher concentration of seniors may stimulate market demand and increase the opportunity for older adults to live in familiar environments. It is worth exploring whether there exists a tendency that age-restricted communities by type tend to be located in neighborhoods with more ageing population.

In addition, accessibility-focused research on older adults is a relatively new area of research. Most studies consider senior population from a regional perspective (e.g., using census/SAs)), but do not analyze seniors at the micro-level of communities while considering neighboring facilities (Engels and Liu 2011, WILMAPCO 2011, Ricciardi et al. 2015, Oswald Beiler et al.

2016). Chen et al. (2018) explored the regional accessibility of age-restricted communities to various facilities in all neighborhoods, including hospitals, recreation facilities, shopping centers, and parks, by means of the gravity-based measure. An exemplary study was conducted by WILMAPCO (2011), which provided a preliminary investigation by identifying the level of connection to transit and sidewalk accessibility for age-restricted communities. Oswald Beiler et al. (2016) also examined transit and pedestrian accessibility using an age-restricted community assessment method based on connectivity thresholds. Their study categorized age-restricted communities into four threshold levels (i.e., connection exists; short-term improvement; long-term improvement; unlikely/difficult) based on different distances from a transit line with or without a bus stop or transit hub. Similarly, they classified age-restricted communities into four similar threshold levels in regard to pedestrian routes. However, opportunities for transit stops were lacking of counting at each threshold level, since different numbers of stops within the threshold can influence choice and convenience for seniors. Furthermore, neighboring facilities are mainly limited to public transit and pedestrian routes, and are not extended to other possible facilities that are necessary to seniors, such as recreation facilities and parks. In this respect, this chapter focuses on measuring age-restricted community accessibility to several types of necessary neighboring services and amenities, quantitatively identifying age-friendly communities, and evaluating the comprehensive accessibility among various types of communities.

3.3 Methodology

3.3.1 The analytical framework

The proposed framework for spatial analysis of age-restricted communities is composed of two aspects: regional analysis and local analysis. An overview of the framework is provided in

Figure 3-1, where GIS is used as the primary tool to achieve the research objectives from the two aspects of spatial analysis (regional and local).

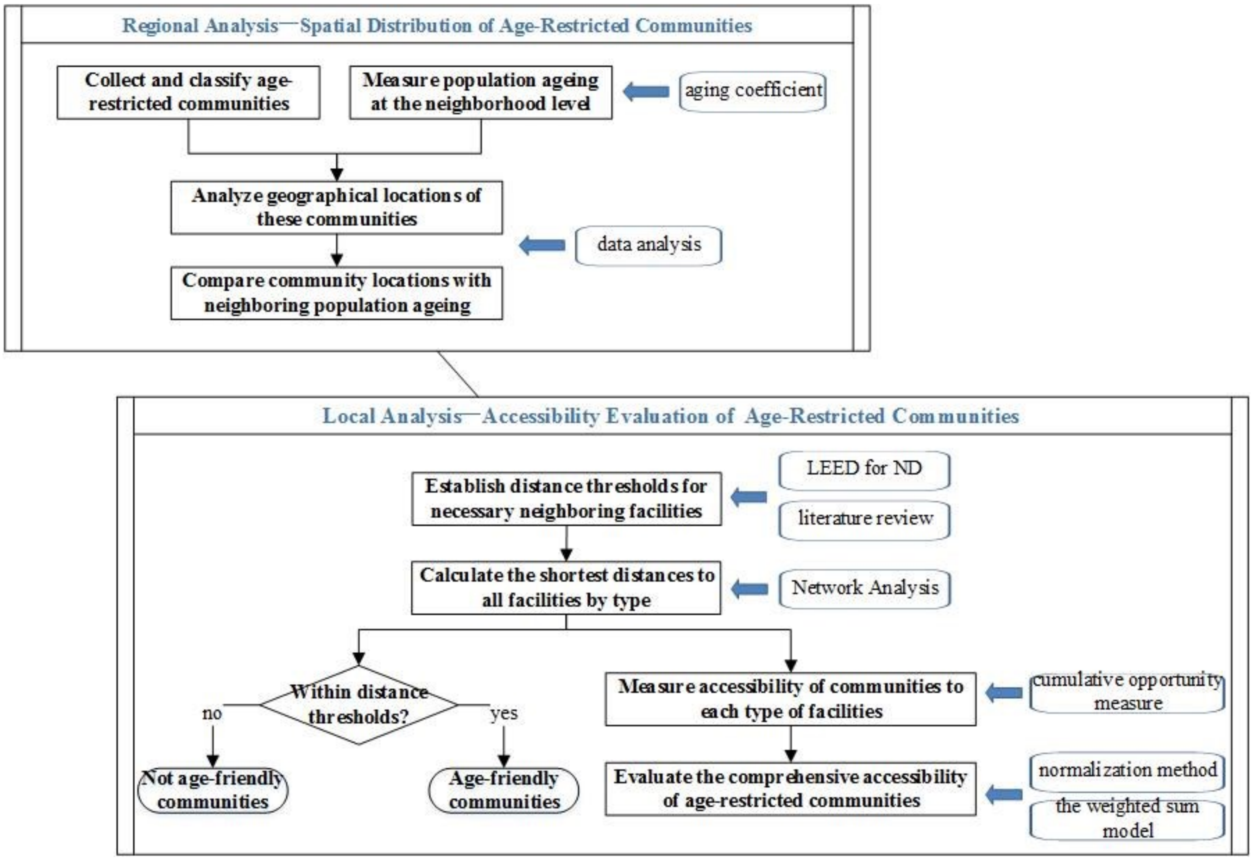


Figure 3-1. Analytical framework for age-restricted communities.

Regional analysis is employed to explore the spatial distribution of age-restricted communities. The data of these communities is collected and classified into three types (i.e., independent living, supportive living, and combined living). An ageing coefficient is used to measure the degree of population ageing among neighborhoods. Geographical locations of age-restricted communities by type are investigated, and their relationship with neighboring population ageing is analyzed. This helps to verify whether these communities tend to be developed in neighborhoods with a higher degree of population ageing, since these kinds of neighborhoods may stimulate market demand for age-restricted communities and allow seniors to continue living in a familiar built environment.

Local analysis focuses on the accessibility evaluation of age-restricted communities, which comprises age-friendly community identification, accessibility measure, and a comprehensive accessibility evaluation. First, neighboring facilities necessary to seniors are selected as destinations (or opportunities) in the accessibility model. The distance thresholds of age-restricted communities to each type of facilities are established based on literature review and LEED-ND, which lays a foundation for identifying age-friendly communities and accessibility measures. If at least one facility of each type is located within the corresponding distance threshold, the neighboring area of this age-restricted community is regarded as an age-friendly community. Network analysis is used to calculate the shortest distances from age-restricted communities to all facilities by type. This can help identify age-friendly communities accurately and assess the accessibility of communities to each type of facility by means of the cumulative opportunity measure. These accessibility values include only the counted opportunities (or number of facilities by type) within the distance thresholds, but they do not reveal the level of accessibility of each age-restricted community to all facilities. Comprehensive accessibility is evaluated using a normalization approach and the weighed sum model. The output can be used to compare and rank comprehensive accessibility to necessary neighboring facilities within and among the three types of age-restricted communities.

3.3.2 Population ageing measures

Population ageing considerably alters the age structure of a population by decreasing the proportion of children and increasing the proportion of elderly people in the total population (Dandekar 1996). For the present research, 65 years of age, a threshold commonly used in the literature, is used to define the elderly demographic (WHO 2013). The proportion of elderly persons directly reflects the absolute degree of ageing, which is the most frequently-used indicator of demographic ageing (Cowgill 1974, Chen et al. 2018c). Ricciardi et al. (2015) selected this index to measure the elderly population distribution in districts of Perth, Australia, investigating the horizontal equity of transit service across a total population and exploring the vertical equity of transit service provision to disadvantaged populations, including older adults. Chen et al. (2018b) used this index to quantify public transit demand from seniors in an analysis of relative spatial gaps in urban public transit. Based on this, our study presents the proportion of elderly people in terms of an ageing coefficient to help explore the relationship between spatial distribution of age-restricted communities and the degree of regional population ageing.

$$AC_i = SP_i / TP_i \tag{3-1}$$

where AC_i is the ageing coefficient in region i; SP_i is the senior population aged 65 and over in region i; and TP_i is the total population in region i.

3.3.3 Selection of necessary neighboring facilities

Age-friendly communities target physical and mental wellness by providing at least three elements: mobility, adequate open spaces, and adequate access to neighboring facilities. For the latter, the first step is to identify which facilities are necessary for seniors; this, in turn, can be used for age-friendly community identification and accessibility measures. Engels and Liu (2011) undertook a detailed land use audit, involving site visits, on-line data checking, and various directories, in order to identify services and facilities for seniors. Six types of services and facilities were identified: medical services, emergency services, municipal facilities, social and cultural facilities, retail, and entertainment. In the present study, these opportunities (or destinations) for accessibility measures correspond to facilities that are most important to the elderly with a focus on five urban elements: public transit, outdoor spaces, recreation, retail, and health services. It is important to note that the types of facilities that will represent the destinations for modeling accessibility are context-dependent and thus need to be tailored to the study at hand. Different geographical regions and cultural diversity may influence selection of facilities and services for seniors.

- *Public transit*

A fair distribution of public transportation resources provides transit users with various travel options to increase their access to opportunities (El-Geneidy et al. 2016). Socially disadvantaged individuals are commonly defined using social indicators, which identify underprivileged groups lacking access to goods and resources compared to the rest of society (Townsend et al. 1988). The elderly are among the socially disadvantaged, and are likely to be transit-dependent due to social and physical factors (Dodson et al. 2007). Older people generally are less likely to own and operate their own vehicle and thus use alternative modes of transportation more often than do younger people, especially if public transit services in their neighborhood are easily accessible (Cao et al. 2010). Moreover, walking and other pedestrian-supporting modes such as transit are positively associated with enhanced quality of life, specifically for ageing societies (Kim and Ulfarsson 2013, Oswald Beiler et al. 2016). Numerous studies assessed accessibility to transit, counting the number of transit stops within a specified walking distance (Olszewski and Wibowo 2005, Zielstra and Hochmair 2011, Moniruzzaman and Páez 2012). Although the above studies do not assess the quality of transit service to reach a desired destination, their measures provide an indicator of the present service in an area. Considering discrepancies of coverage area among various types of transit facilities and to ensure consistency in transit accessibility, bus stops are selected as the facilities to describe public transit in the present study.

- *Outdoor spaces*

Outdoor (or open) spaces are regarded as one of the cornerstones of age-friendly communities (WHO 2007). In fact, there is compelling evidence indicating that green spaces in urban areas are linked to many physical and mental health benefits such as improved longevity of the population, including senior citizens, regardless of their age, sex, marital status, baseline functional status, or socioeconomic status (Takano et al. 2002, Lee and Maheswaran 2011, WHO 2016). However, providing green spaces and parks can be beneficial to the population only if these spaces are well maintained and accessible, whether by walking or by means of the transit system (WHO 2007). Parks are selected as one of the top 10 services and facilities that are frequently visited by and important to seniors (Engels and Liu 2011).

- *Recreation*

Social interaction and participation in the community are positively connected to good health and well-being throughout life (WHO 2007). Whether for indoor or outdoor activities, recreation facilities allow older people to continue their involvement in the community through sharing experiences and knowledge while remaining physically active. These types of facilities tend to be deliberately dispersed across a city for easy and regular use (Engels and Liu 2011). In this respect, it is important to regard recreation facilities as necessities for the quality of life of older adults, which justifies their inclusion in the various opportunities for measuring the accessibility of a neighborhood.

- *Retail*

Grocery stores act as the medium to connect food producers and consumers. For seniors, shopping, including in grocery stores, is the second-most frequent activity in daily life, and the usage pattern does vary negatively by distance of stores from home (Engels and Liu 2011). Furthermore, good retail accessibility can help reduce auto dependence, particularly for older individuals. The concept of a “food desert”, referring to a region devoid of nutritious food options for residents, has been largely explored by geographers, public health academics, governments, and media institutions; the existence of a food desert can be the result of complex social and structural processes with real public health consequences (Farber et al. 2014). Therefore, spatial access to grocery stores is a prerequisite for the provision of retail service, which directly influences quality of life for seniors (and others).

- *Health services*

Having well-located, easily accessible health services is fundamentally important for older people to maintain health and independence in the community (WHO 2007). Generally, seniors are willing to travel longer distances to visit a doctor, pharmacist, or a hospital, despite the fact that they are frequently required to do so (Engels and Liu 2011). However, for emergency situations, response time is a vital element for seniors, especially those experiencing life-threatening events. Emergency medical services (EMS) engage in providing patients with effective care by providers at the proper time (AHS 2017). Statistics demonstrate that emergency departments are used more frequently by the elderly than by younger patients (Reeder et al. 2002, Ruger et al. 2004). Hence, understanding the accessibility of age-restricted communities to EMS stations is important and useful to seniors.

3.3.4 Accessibility measure and evaluation

Based on the literature review and research objectives, the cumulative opportunity measure is used to measure accessibility of age-restricted communities based on the five types of neighboring facilities identified above as the most important for seniors. The cumulative opportunity measure is derived from the generalized accessibility model (Hansen 1959, Geurs and van Wee 2004) as below.

$$A_i^k = \sum_{j=1}^{n} O_j^k f(C_{ij}^k) \tag{3-2}$$

where A_i^k is a measure of accessibility in zone i to all opportunities of type k, such as five types of neighboring facilities available in zone j; the constant O_j^k is to the attractiveness (or simply the number of opportunities of type k) in zone j; and $f(C_{ij}^k)$ is the cost function, also known as the impedance or resistance model, calculating travel time or distance from zone i to opportunities of type k in zone j.

Since mobility is dependent upon physical ability, general health and fitness level, financial constraints, and the environmental challenges facing the individual (Webber et al. 2010), these factors will influence the time seniors spend walking on a certain route (e.g., the shortest distance between two locations). In this case, travel distance is used as transportation impedance in this accessibility analysis. Based on this, by substituting a step function for the impedance model (El-Geneidy et al. 2016), the cumulative opportunity measure for age-restricted communities is defined satisfying Eq. (3-3).

$$A_i^k = \sum_{j=1}^{n} O_j^k f(d_{ij}^k) = \sum_{j=1}^{n} O_j^k \left[1 - H_{d_0^k}(d_{ij}^k)\right] \ where\ H_{d_0^k}(d_{ij}^k) = \begin{cases} 0 \ if \ d_{ij}^k \le d_0^k \\ 1 \ if \ d_{ij}^k > d_0^k \end{cases} \tag{3-3}$$

where A_i^k is the accessibility from age-restricted community i, to neighboring facilities of type k; $f(d_{ij}^k)$ is the distance-based cost function; $H_{d_0^k}(d_{ij}^k)$ is the step (or Heaviside) function; d_0^k is the distance threshold for facilities of type k; d_{ij}^k is the shortest distance from community i to facilities j of type k; and O_j^k is the number of reachable facilities of type k within d_0^k.

From Eq. (3-3), the number of opportunities is determined by counting the facilities belonging to each of the above identified types and falling within a distance $d_{ij}^{k} \leq d_{0}^{k}$ measured from age-restricted communities. Thus, the method of assigning values to these distance thresholds is a key issue to be resolved in the cumulative opportunity measure. Although many guides for building age-friendly communities have been put forward, few quantitative indicators are available to judge whether the accessibility between age-restricted communities and neighboring facilities is appropriate (WHO 2007, Public Health Agency of Canada 2015). LEED-ND provides detailed neighborhood development criteria and a set of rating systems for the design, construction, operation, and maintenance of green neighborhoods (U.S. Green Building Council 2016). This study uses LEED-ND standards and relevant research as the basic distance thresholds for five types of necessary neighboring facilities, thereby laying a foundation for age-friendly community identification and comprehensive accessibility evaluation for age-restricted communities. The detailed distance thresholds for different facilities are presented in Table 3-1.

Table 3-1. Distance thresholds of five types of neighboring facilities.

Type	Facilities	Distance threshold (m)
Public transit	Bus stops	400
Outdoor spaces	Green spaces/parks	400
Recreation	Recreation facilities	800
Retail	Grocery stores	400
Health services	EMS stations	6,250

LEED-ND outlines specific requirements for facilities related to public transit, green spaces/parks, and recreation facilities as shown in Table 3-1 (U.S. Green Building Council 2016). A walking distance of 400 m is commonly used for a distance threshold for a bus stop in the existing public transit design (Engels and Liu 2011, WILMAPCO 2011, Oswald Beiler et al. 2016). In terms of grocery retail, LEED-ND gives restrictions for farmers' markets within an

800-meter proximity. Handy and Niemeier (1997) defined commercial coverage as the percentage of area within a quarter mile (considered to be a comfortable walking distance) occupied by a supermarket, convenience store, or any commercial activity. Based on this, the distance threshold of grocery stores in this study is restricted to 400 m. Currently, EMS stations have no specific criteria to account for influences from multiple variables such as traffic conditions, labor cost, and vehicle availability. Hence, an indirect method is employed to measure the average distance ambulance cars travel in a given region, according to speed limit for EMS vehicles and average response time. Since Edmonton, Canada, is selected for the case study, the average response time for life-threatening events, approximately 7.5 mins, is used (AHS 2017). Considering waiting time for traffic lights and drivers' perceptions of time, it is assumed that the actual travel time is 6 mins. EMS vehicles in Alberta by law can travel 25% faster than the speed limit when responding to emergencies and transporting patients (AHS 2016). Fifty km/h is the maximum speed limit on a roadway that is located within an urban area (Alberta Transport 2017). It is assumed that the average distance to the required service is approximately 6.25 km (i.e., [(6mins/60mins/hr)×50km/hr×1.25]) based on the above principle. The distance threshold of EMS stations may vary based on actual situation and regulations of the given jurisdiction, and thus can be adjusted accordingly for different case studies.

Since the importance degree of each type of facility may vary among stakeholders, including urban planners, developers, and seniors, accessibility of each type of facility is aggregated by means of the weighted sum model. Considering that the values of accessibility to all facilities are the opportunities available within the specified thresholds (Table 3-1), a normalization method is used to map the opportunities as values between 0 and 1 with no specific dimensions, thereby allowing relative accessibility to specific facilities to be compared. It is helpful to clearly grasp which type of facility seniors in an age-restricted community have better access to and directly display how an age-restricted community can have access to a certain type of facility among communities.

$$A_i^{k'} = \frac{A_i^k - Min(A_i^k)}{Max(A_i^k) - Min(A_i^k)} \tag{3-4}$$

where $A_i^{k'}$ is the normalized accessibility from age-restricted community i to all facilities of type k; and $Max(A_i^k)$ and $Min(A_i^k)$ $(i = 1, 2, ..., m)$ are the maximum and the minimum of the accessibility to all facilities of type k among m communities, respectively.

The comprehensive accessibility of age-restricted communities is aggregated by the following equation.

$$A_i = \sum_{k=1}^{5} \omega_k A_i^{k'} \tag{3-5}$$

where A_i is the comprehensive accessibility; and ω_k is the weight or importance degree of all facilities of type k. The range of the comprehensive accessibility values is [0, 1].

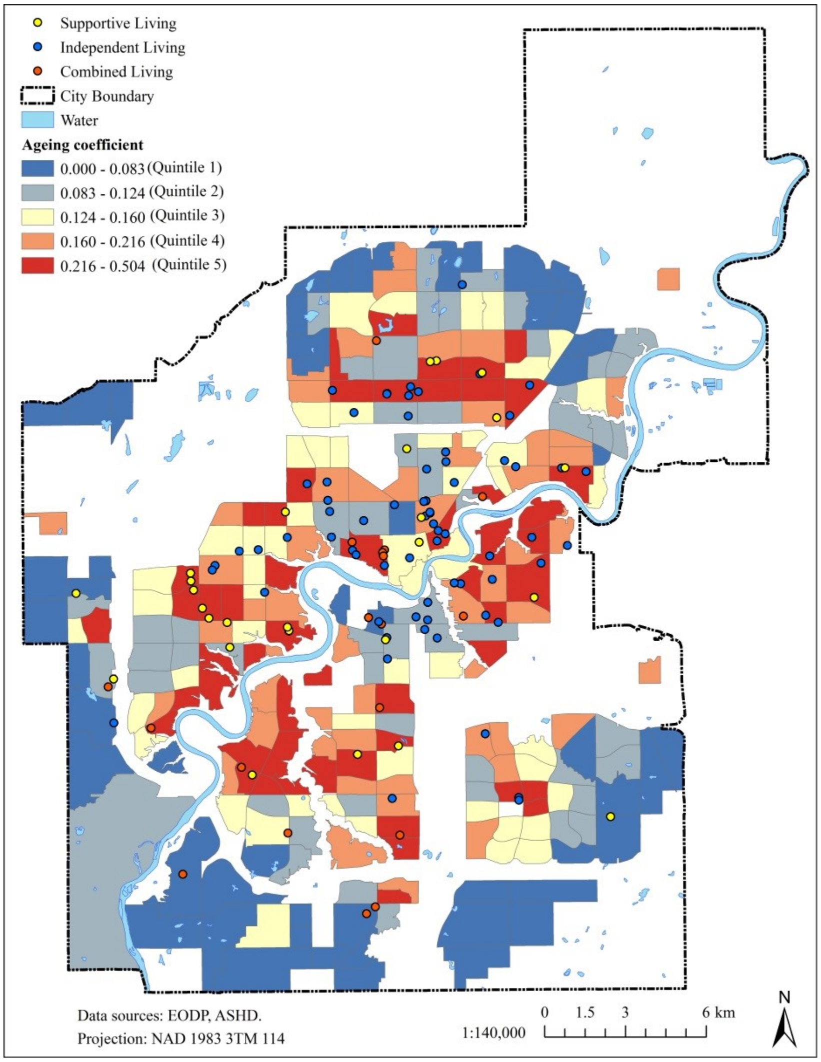
3.4 Case Study

3.4.1 Data sources

People aged 55 and over in Edmonton, Canada, accounted for approximately 21% of the population in 2006, and this number is projected to approach 32% by 2041 (City of Edmonton 2010). This change has the potential to increase the market share of age-restricted community development. Moreover, Edmonton formulated an action plan for an age-friendly Edmonton in 2011, aiming to build a city that values, respects, and actively supports the well-being of seniors and advances the goal of improving Edmonton's livability (Edmonton Seniors Coordinating Council 2011). This chapter uses Edmonton as a case study to analyze spatial distribution and accessibility evaluation of age-restricted communities using neighborhoods as the geographical unit of analysis. Multiple data sources are used in the analysis, namely, demographic neighborhood information by age, neighboring facility locations from the City of Edmonton's Open Data Portal (EODP 2017), the street network from the Government of Canada’s Open Data (GCOD 2015), locations of age-restricted communities with different lifestyles in Edmonton from the Alberta Senior Housing Directory (ASHD 2017), and locations of 18 EMS stations in Edmonton from Alberta Health Services (AHS 2017).

3.4.2 Spatial distribution of age-restricted communities

Regional population ageing is analyzed at the neighborhood level, with a total of 386 neighborhoods in Edmonton. However, neighborhoods that have industrial, natural, or transportation assets do not have demographic information. Moreover, age-restricted communities cannot be developed in an industrial or transportation-centric neighborhood even if these locations have some residential land use. Since the population in newly planned areas is not steady or mature, and no age-restricted communities have been developed in new suburbs, these neighborhoods are not considered in this research. Based on Eq. (3-1), the degree of population ageing in each neighborhood is evaluated. According to different lifestyles, a total of 116 age-restricted communities are divided into three types: independent living (n = 70), supportive living (n = 26), and combined living (n = 20). Figure 3-2 presents the results of Edmonton’s age-restricted communities in terms of spatial distribution.



Data sources: EODP, ASHD.
Projection: NAD 1983 3TM 114

Figure 3-2. Spatial distribution of age-restricted communities in Edmonton.

Population ageing is distributed in a radial pattern, with a higher degree concentrated in the center of the city, and the intensity decreasing farther away from the center. The highest degree of population ageing is slightly more than 50% in one neighborhood, while the average degree is approximately 15% with standard deviation valued at 8.5. Thus, there exists a large variation in population ageing among neighborhoods within Edmonton. As for age-restricted communities, most are located centrally in the city, while others are scattered throughout the surrounding areas. Furthermore, the communities for independent living have a more concentrated distribution than the other two types. However, not all age-restricted communities are located in the neighborhoods with higher degrees of population ageing. This is a reasonable finding since the location of age-restricted communities is influenced by multiple factors such as land availability, land price, and neighboring facilities.

In Figure 3-2 above, the degree of population ageing (i.e., the values of ageing coefficients) is divided into five quintiles, labelled from Quintile 1 to Quintile 5 in ascending order, with the lowest quintile corresponding to the lowest 20% of the ageing coefficient values. The total number of age-restricted communities in these quintiles increases as the degree of population ageing rises. The detailed distribution results of the various types of age-restricted communities gathered by quintile and by type can be observed in Figure 3-3 and Figure 3-4, respectively.

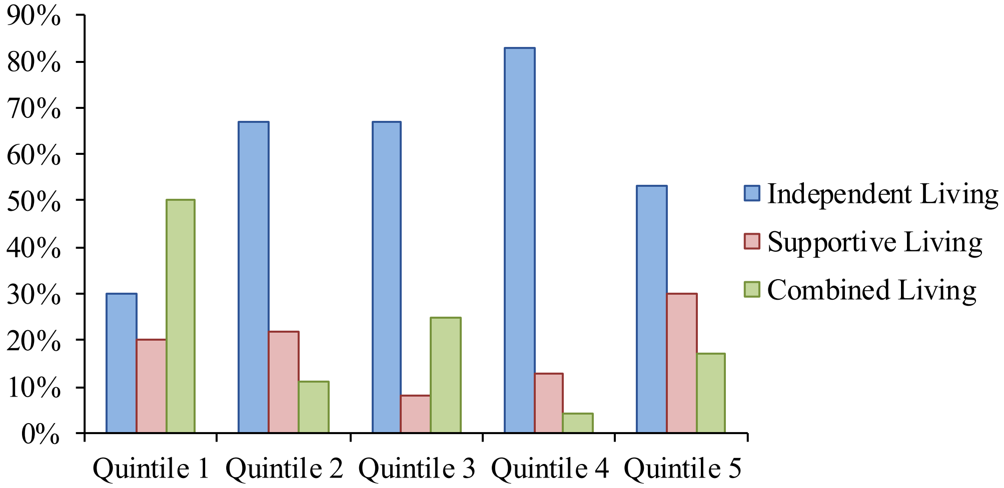


Figure 3-3. Distribution of age-restricted communities by quintile.

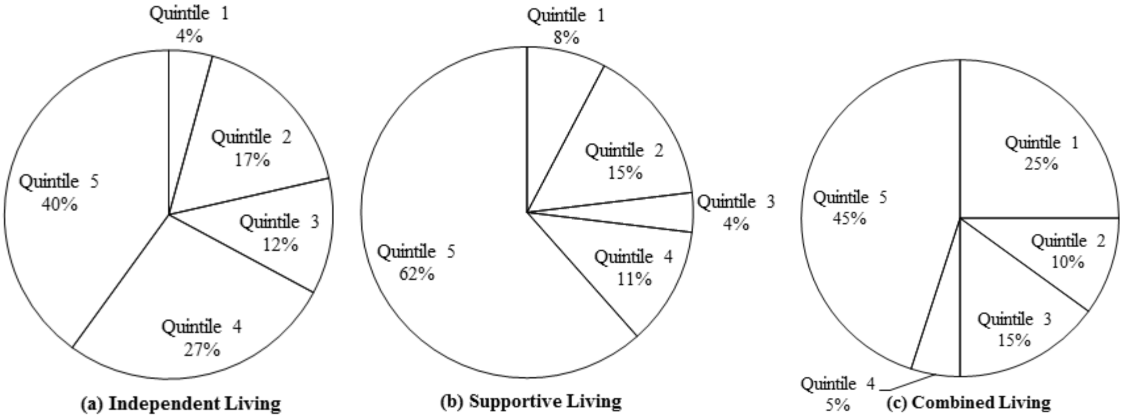


Figure 3-4. Distribution of age-restricted communities by type.

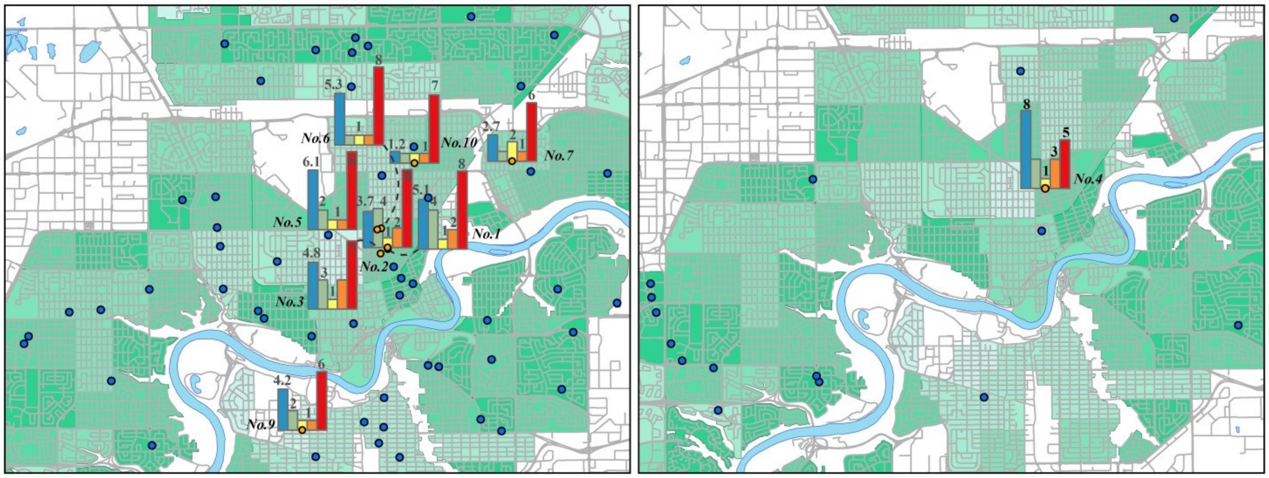
With the exception of Quintile 1 in Figure 3-3, the communities for independent living play a dominant role in each quintile—a function of the nature of market supply of these facilities. Specifically, this type of community accounts for 83% in Quintile 4, while occupying an equal percentage (67%) in Quintile 2 and Quintile 3. From distribution by type (Figure 3-4), these communities for independent living are primarily located in the neighborhoods with higher degrees of population ageing (Quintile 4 and Quintile 5). There are a larger number of communities for supportive living than those for combined living in Quintile 2, Quintile 4, and Quintile 5, but the percentages of the former are below 30%. Also, the neighborhoods with higher population ageing quintiles encompass the highest percentage of the communities for supportive living. The communities for combined living involve older adults in need of independent and supportive services. This type of community features the largest supply in the lowest population ageing quintile of all the types. Quintile 5, however, encompasses the largest percentage of the communities for combined living. The above analysis verifies that the degree of population ageing in a region is regarded as just one of the factors influencing the location of age-restricted communities.

3.4.3 Accessibility evaluation of age-restricted communities

Based on the methodology framework presented in Figure 3-1, accessibility evaluation of age-restricted communities is primarily composed of three parts: age-friendly community identification, accessibility measure for each type of facility, and comprehensive accessibility evaluation for all facilities. The first two parts involve a common step, that is, calculating the shortest distances to all facilities, thus parts one and two are merged together in the following section.

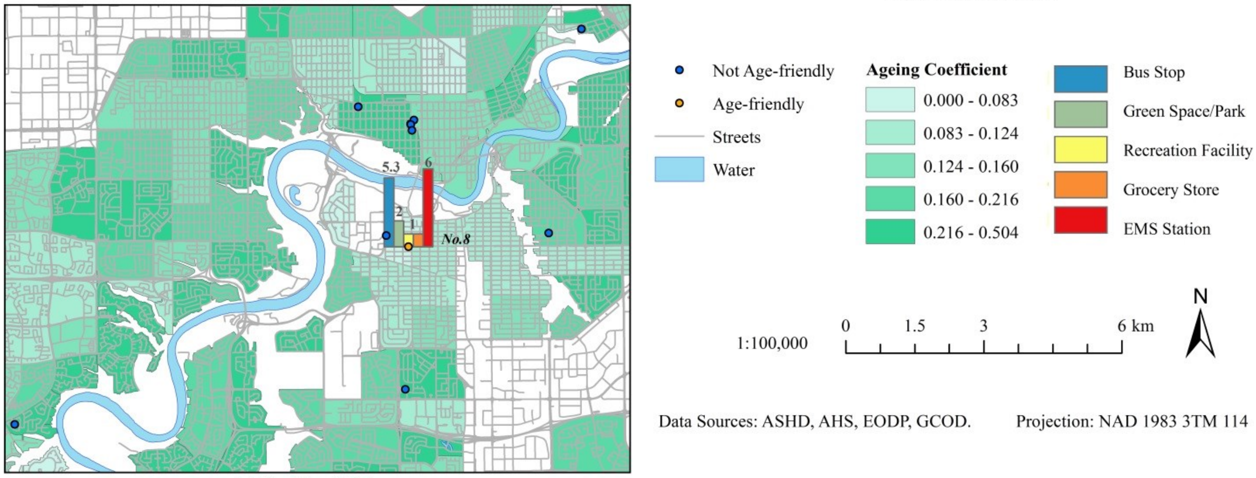
3.4.3.1 Accessibility measure

Public transit, outdoor spaces, recreation, retail, and health services are selected as five types of neighboring facilities that are important to seniors. Based on the distance thresholds of these facilities represented in Table 3-1, network analysis is used to calculate the shortest distances to all facilities by type, and the cumulative opportunity measure expressed in Eq. (3-3) is used to measure the accessibility of age-restricted communities to each type of facility. The results of accessibility of age-restricted communities are presented in Figure 3-5, focusing on the city center where age-friendly communities are concentrated. The “Age-friendly” symbol refers to age-restricted communities the neighboring area of which is friendly to seniors (i.e., an age-friendly community), meanwhile these communities are labeled by serial numbers from 1 to 10. The remaining age-restricted communities are labeled by a “Not Age-friendly” symbol. The histograms are used to display opportunities for different facilities in terms of a friendly age-restricted community. In order to better display discrepancies in opportunities, the values for bus stops are reduced in scale by ten times while the other facilities are counted by raw data. For instance, in Figure 3-5c (combined living), the value 5.3 refers to 53 bus stops surrounding this age-restricted community. The values of ageing coefficients in Figure 3-5 are calculated using Eq. (3-1), which is divided into five quintiles similar to those in Figure 3-2.



(a) Independent Living

(b) Supportive Living



(c) Combined Living

Figure 3-5. Accessibility of age-restricted communities to each type of facility.

It can be observed that the friendly age-restricted communities are primarily distributed north of the river and in the central part of the case study city, and the degree of population ageing in these neighborhoods is largely in the mid-range ageing coefficient quintile. These kinds of age-restricted communities are limited, as they only account for a small percentage of the overall age-restricted communities. Upon comparing the three types of age-friendly communities, it is evident that the majority are those designed for independent living. Seniors who reside in communities for independent living and some of those living in communities for combined living have relatively good mobility, thus they tend to have more choices available for neighboring facilities and options to enjoy a variety of outdoor activities. Elderly people in need of support, however, are not reliant on a diversity of neighboring facilities due to their physical conditions. Overall, physical health and mobility of seniors are important factors that may decrease the accessibility of communities to neighboring facilities. In addition, even for those communities that are friendly to seniors, the cumulative opportunities for facilities are not abundant enough, with the exception of nearby bus stops and EMS stations. For instance, two age-restricted communities (No. 6 and No. 10 in Figure 3-5) are only within the corresponding distance thresholds to one choice each for park, recreation facility, and grocery store. The opportunities for EMS stations in the age-restricted communities, such as those labelled from No. 6 to No. 9, account for 30% of the stations available citywide.

Figure 3-5 only displays the opportunities for various types of neighboring facilities in those communities that are friendly to seniors. In order to understand the opportunities and discrepancies for all facilities in other communities, Table 3-2 presents a basic profile for age-restricted communities not satisfying the relevant distance thresholds.

Table 3-2. The opportunities for other age-restricted communities unfriendly to seniors.

Type	Amount	Facilities				
		Bus stop	Green space/park	Recreation facility	Grocery store	EMS station
Independent living (62)	Max.	434	3	2	1	8
	Min.	2	0	0	0	1
	Null	0	19	51	59	0
	Average	35	1	0	0	5
Supportive living (25)	Max.	505	2	2	0	6
	Min.	0	0	0	0	1
	Null	3	13	18	25	0
	Average	38	1	0	0	3
Combined living (19)	Max.	92	3	2	1	8
	Min.	0	0	0	0	1
	Null	4	9	17	18	0
	Average	26	1	0	0	4

Note: null refers to age-restricted communities with no type of facility within the corresponding distance threshold.

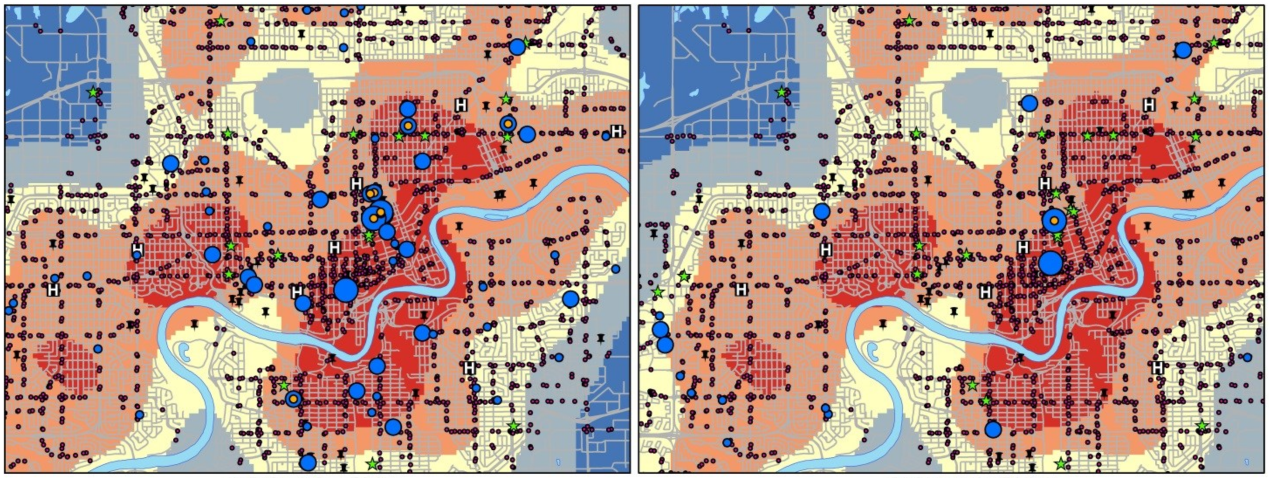
From the four indicators for opportunities available, it is clear that there exist significant differences by community type. Notably, the maximum values of bus stops in three types of communities are much larger than their corresponding averages, and exceed opportunities for bus stops in the communities friendly to seniors (see Figure 3-5). Abundant transportation resources can provide residents in these age-restricted communities with various options, and this increases their access to destinations and enhances communication within and among neighborhoods. Specifically, some communities for supportive living and combined living lack nearby bus stops, since the values of null are equal to three and four, respectively, in Table 3-2. Moreover, at least one EMS station is available for each of the communities within the distance threshold, and this underscores the importance of this facility type for older adults. In terms of the remaining types of facilities, most of the age-restricted communities studied do not have convenient access to recreation facilities or grocery stores. Nearly half of the communities for supportive living and combined living lack opportunities for green spaces/parks, although this percentage is smaller in independent living communities. Overall, even for facilities within the distance thresholds, seniors lack choices for each type of facility. This phenomenon is also reflected in age-restricted communities that are friendly to seniors. Hence, adding neighboring facilities such as green spaces/parks, recreation destinations, and grocery stores is important to provide seniors with basic choices to improve their quality of life and make the communities truly age-friendly.

3.4.3.2 Comprehensive accessibility evaluation

In order to meet different demand for multi-group assessment, intra-group evaluation is to assess all members in each group and extra-group evaluation is to conduct a comparison among all group members. Similarly, comprehensive accessibility evaluation of age-restricted communities is conducted for each type of community and also among the three types of communities.

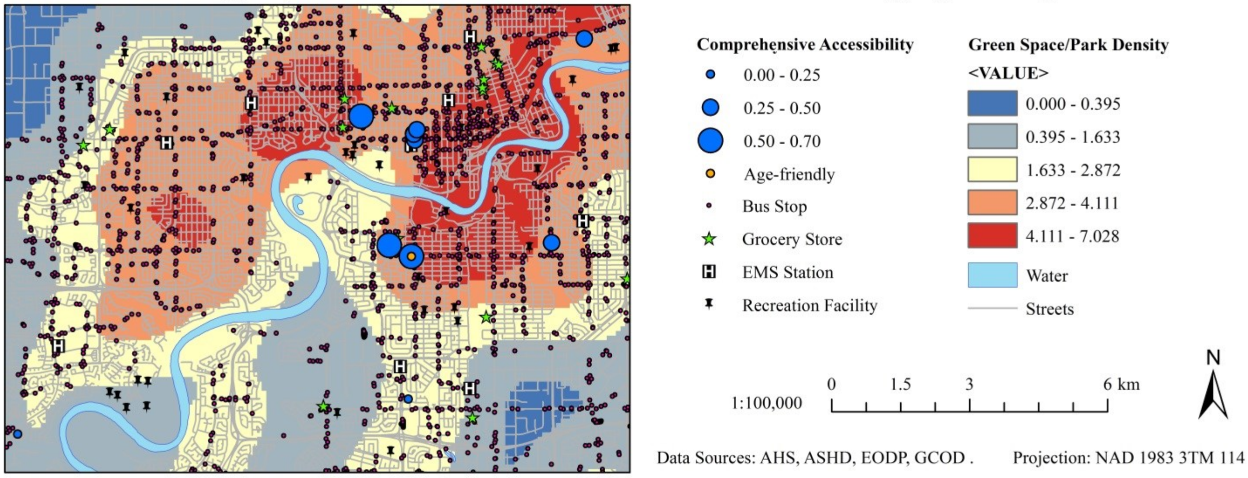
- *Intra-group evaluation*

Since the accessibility measured by Eq. (3-3) only reflects the absolute opportunities for each type of facility, it cannot be directly utilized in a comparison of age-restricted communities with respect to all facilities. Even for age-restricted communities not friendly to seniors, city planners or policy makers need to understand the accessibility rankings. Hence, the accessibility of each type of facility is normalized using Eq. (3-4), and the comprehensive accessibility is then evaluated for all age-restricted communities by type using Eq. (3-5). The results of the comprehensive accessibility evaluation within the three types of communities can be observed in Figure 3-6. Here, it is assumed that the weights of each type of facility are uniform at 0.2. A sensitivity analysis of weights for different facilities in the comprehensive accessibility evaluation will be discussed in the next section. The "Age-friendly" symbol represents the same meaning of that in Figure 3-5. With the exception of green spaces/parks displayed by the heat map, other facilities are directly reflected by their geographical locations.



(a) Independent Living

(b) Supportive Living



Data Sources: AHS, ASHD, EODP, GCOD . Projection: NAD 1983 3TM 114

(c) Combined Living

Figure 3-6. Comprehensive accessibility evaluation of age-restricted communities by type.

Age-restricted communities with greater comprehensive accessibility are primarily distributed in the city center. The degree of population ageing in these areas is illustrated Figure 3-2. It is evident that facilities by type are distributed intensively in the city center. However, for some facilities (e.g., recreation facilities and grocery stores), cumulative opportunities within the distance thresholds are generally small, thus resulting in the limited number of age-friendly communities and discrepancy in comprehensive accessibility evaluation. The densities of green spaces/parks, grocery stores, EMS stations, and recreation facilities tend to diminish proportionately with the distance from the city center, though some facilities such as green spaces/parks in other areas form concentrated centers with medium density.

Specifically, age-restricted communities that are friendly for supportive living and combined living have the greatest comprehensive accessibility to neighboring facilities. Within independent living communities, eight locations are age-friendly, while not all older adults within each location are equipped with more opportunities to different facilities, since the comprehensive accessibility of these communities is only ranked at the second level (i.e., values from 0.25 to 0.5). This can be attributed to two main causes. First, neighboring facilities of several types are located within the distance thresholds with more opportunities, from which it can be inferred that the normalized accessibility to these types of facilities is much higher in some non-friendly communities than in others. It further improves the comprehensive accessibility of these communities unfriendly to seniors, while relatively lowering the accessibility ranking of other age-friendly communities. Second, the importance degree of for all facilities is uniform, thus comprehensive accessibility is directly influenced by normalized accessibility to each type of facility. In this case, for comprehensive accessibility assessment of age-restricted communities, it is necessary to combine individual evaluation (satisfying distance thresholds) with comprehensive evaluation (opportunity aggregation for all types of facilities).

- *Extra-group evaluation*

Intra-group evaluation of comprehensive accessibility reveals how seniors in each type of community access neighboring facilities. The community for any lifestyle with superior comprehensive accessibility is, however, not representative for all age-restricted locations. Thus, communities for independent living, supportive living, and combined living are regarded as one group for this extra-group evaluation. Similar to the intra-group evaluation, Eq. (3-4) and Eq. (3-5) are used to evaluate the comprehensive accessibility for all the communities. The results indicate that all communities friendly to seniors are located in the top 16 range for comprehensive accessibility, accounting for 14% of all the age-restricted locations (see Table 3-3). Although some age-restricted communities less friendly to seniors have greater comprehensive accessibility, the rank of the top three communities is the same as that in the intra-group evaluation of communities for independent living, underscoring that older adults in the communities designed for independent living have better access to more opportunities for neighboring facilities.

Table 3-3. Comprehensive accessibility of top 16 age-restricted communities.

Rank	Comprehensive accessibility	Community type	Age-friendly community
1	0.6535	I	yes
2	0.6480	I	yes
3	0.6404	I	yes
4	0.5960	S	yes
5	0.5719	I	no
6	0.5429	S	no
7	0.4908	I	yes
8	0.4861	C	no
9	0.4753	I	no
10	0.4702	I	yes
11	0.4377	I	yes
12	0.4305	C	yes
13	0.4293	I	no
14	0.4262	I	no
15	0.4261	I	yes
16	0.3928	I	yes

Note: I = independent living; S = supportive living; C = combined living

3.5 Discussion

3.5.1 Various evaluation objects

In this study, age-restricted communities are divided into three types: independent living, supportive living, and combined living. Based on this disaggregation, comprehensive accessibility is evaluated for intra-groups and extra-groups. The common principle is that age-restricted communities friendly to seniors can be identified according to the criteria for satisfying distance thresholds. However, the results for comprehensive accessibility evaluation and the corresponding rank vary due to various evaluation objects, even though the type of community may be the same. For instance, Table 3-3 presents the top three communities for independent living. The ranks of these three communities are congruent with the intra-group evaluation and the comprehensive accessibility evaluation for communities friendly to seniors. The normalization method expressed as Eq. (3-4) is used to unify the dimensions of all facilities, and enables a comprehensive accessibility evaluation. This method is primarily dependent upon the object selected to be normalized, and it further influences the evaluation results. Moreover, five categories of neighboring facilities are selected in this study as necessary facilities in terms of accessibility for older adults. Other facilities such as coffee shops and shopping malls may also be added for different research purposes in the application of the proposed methodology. However, there may be a lack of scientific references or specific criteria to support the distance threshold seating for other added facilities. In order to overcome the problem of low data availability, an indirect method, such as a method for calculating the distance threshold to an EMS station or a survey of seniors, can be employed instead. Moreover, clearly grasping the evaluation objectives and selecting corresponding objects are crucial steps to be achieved before adopting the normalization method for comprehensive accessibility evaluation.

3.5.2 Various weights

In the case study presented above, the importance degree of each category of facility is $\omega = 0.2$. However, the weights may differ for various stakeholders such as older adults, policy makers, and developers, and this can have an impact on the comprehensive accessibility evaluation. In fact, there are many possible values for the five weights and comprehensive accessibility evaluation is dependent on object selection. Considering age-restricted communities friendly to seniors as evaluation objects, Table 3-4 illustrates three weight sets and compares the results for the comprehensive accessibility evaluation.

Table 3-4. Comprehensive accessibility rank of friendly age-restricted communities by various weights.

	Facilities				
	Bus stop	Green space/park	Recreation facility	Grocery store	EMS station
Weight Set 1	0.20	0.20	0.20	0.20	0.20
Weight Set 2	0.25	0.10	0.10	0.20	0.35
Weight Set 3	0.35	0.10	0.10	0.20	0.25

Community No.	Weight set 1		Weight set 2		Weight set 3	
	Comprehensive accessibility	Rank	Comprehensive accessibility	Rank	Comprehensive accessibility	Rank
1	0.615	1	0.693	1	0.651	1
2	0.574	2	0.642	2	0.579	4
3	0.573	3	0.632	3	0.619	2
4	0.533	4	0.517	5	0.617	3
5	0.411	5	0.563	4	0.536	5
6	0.321	6	0.501	6	0.461	6
7	0.311	7	0.272	8	0.261	9
8	0.254	8	0.301	7	0.328	7
9	0.222	9	0.260	9	0.271	8
10	0.133	10	0.233	10	0.167	10

Note: Community No. corresponds to the age-restricted communities by number in Figure 3-5.

Following the increase in the weights for bus stops and EMS stations and the decrease in the weights for green spaces/parks and recreation facilities, the comprehensive accessibility to neighboring facilities tends to improve, while for some communities the rankings differ among the three scenarios. An example of this is the ranking of No. 4 and No.7 under the three weight sets. The weights of neighboring facilities can be adjusted to realize different purposes and meet the demands of decision makers or evaluators. For instance, scenario 2 and scenario 3 consider public transit as more important; thus, decision makers may focus more on transit convenience in the development of age-friendly communities. Similarly, EMS stations play a key role in maintaining the health of older adults, and are regarded as the most important facilities to the communities in weight set 2.

3.5.3 Various distance thresholds

Table 3-1 presents the basic distance thresholds for five types of neighboring facilities, and lays a foundation for age-friendly community selection and comprehensive accessibility evaluation. These distance thresholds can become more rigorous if the communities are expected to be more age-friendly. For instance, if the shortest distance between recreation facilities and age-restricted communities is reduced to a reasonable walking distance (e.g., 400 m), there are no communities for supportive living and combined living that satisfy the distance threshold. Furthermore, the number of communities for independent living that are friendly to seniors is limited to three (i.e., No. 2, No. 6, and No. 10 in Figure 3-5). Although more conservative distance thresholds may result in a decrease in the number of age-friendly communities, the comprehensive accessibility of these communities does improve. Various distance thresholds can also be used for the various stages of evaluation, such as location selection, design, and post construction, and to improve existing age-restricted communities.

3.6 Conclusions

Population ageing has become a global challenge facing many countries. Age-restricted communities, as a new residential option, have gained popularity, offering clear advantages for older adults when housing (and living) requirements change. Appropriate housing and access to community and social services influence seniors' independence and quality of life. Age-friendly communities can be conceptualized in a way that promotes physical and mental wellness by ensuring at least three elements are considered: mobility, adequate open spaces, and good access to neighboring facilities and amenities. This chapter combines two research perspectives (regional and local) in order to explore the spatial distribution of age-restricted communities, and demonstrates the measurement and evaluation of their accessibility to neighboring facilities for seniors. The main contributions of this study include the following: (1) Determination of a set of quantitative indicators that can help evaluate whether the accessibility of age-restricted communities to necessary neighboring facility by type (not only limited to public transit) is appropriate to older adults and that can help with identifying in a quantitative manner whether or not a given community is age-friendly. The approach proposed in this study, based on the cumulative opportunity measure, allows practitioners and researchers to select distance thresholds for the different types of facilities that are most important to seniors. (2) Elaboration of a framework for the analysis of the comprehensive accessibility, such that the normalization method and the weighted sum model are developed to achieve accessibility comparison of age-restricted communities to all types of necessary facilities for various assessment purposes (e.g., within each type of community or among several types of communities). (3) Discussion of the proposed methodology with regards to its usefulness in (a) other urban contexts, i.e., infill versus greenfield (suburban) development of senior communities or residential facilities; (b) developing regional and local neighborhood policies for building age-friendly communities; and (c) providing a basis for urban development strategies involving multiple stakeholders or decision makers at different stages (e.g., for design, construction, or renewal) with the aim of helping to provide a resilient lifestyle for older adults.

The proposed spatial analysis framework is applied to three types of age-restricted communities in Edmonton, Canada. In terms of spatial distribution analysis, the proportion of elderly people is selected as the ageing coefficient in order to explore the relationship between spatial distribution of age-restricted communities by type and degree of regional population ageing. The results indicate that population ageing is distributed as a radial pattern with a large variation among neighborhoods in Edmonton. Most age-restricted communities are located in the central area of the city near the river valley, and the communities for independent living have a more concentrated distribution in comparison to the communities for supportive living and combined living. However, not all communities are located in neighborhoods with higher degrees of population ageing. This confirms that potential demand in a region is just one of the factors influencing the location of age-restricted communities. A set of methods is proposed for accessibility evaluation based on established distance thresholds to neighboring facilities. The results indicate that the communities friendly to older adults are primarily distributed north of the river and in the central part of the case study city (Edmonton), while the number of age-friendly communities is severely limited, as are the cumulative opportunities for facilities (with the exception of nearby bus stops and EMS stations). This implies that seniors in these communities lack choice for each type of facility, such as green spaces/parks, recreation, and grocery stores. Consequently, the ideal solution would be to develop these important facilities and improve their variety in the close vicinity of age-restricted communities. Of course, while this solution can be implemented by developers in the context of suburban greenfield development, it is subject to the availability of land in the context of infill development. However, in this context, policy makers can provide a short-term solution which consists of improving the local transit system so as to allow older adults in these areas to easily access the facilities that are lacking in their neighborhoods. The quantitative methodology developed in this work can help cities make long-term plans such as purchasing old homes or land available on the market in specific neighborhoods and developing various facilities that will bring additional value to the quality of life of local elderly residents.

The developed approach can assist in exploring quantitatively spatial distribution and accessibility evaluation of age-restricted communities. There are also some limitations in the present study. First, the accessibility measure for public transit surrounding age-restricted communities only counts the cumulative opportunities for bus stops within a distance threshold (i.e., 400 m), but does not take service quality of public transit into account. Hence, this approach is more applicable to denser urban areas. i.e., the case study, where the frequency and variety of public transit routes are similar in all areas of the city, but may not be applicable in the case of sprawling/exurban areas where the quality of public transit services can be variable. Second, the proposed methodology is restricted to measure opportunities for important neighboring facilities and evaluate the comprehensive accessibility in order to facilitate age-friendly communities. Before concluding this section, it is worth noting that the framework presented above for assessing the accessibility of age-restricted communities to (selected) neighboring facilities can be used by city planners to evaluate the level of equity in the services provided by the City of Edmonton (the case study city) to its older adult communities as a function of their location. Whether this aged population can afford accessing the public facilities and services provided by the City of Edmonton, was not considered in this work since it can constitute a full study on its own. Suffice it to mention that many programs aimed at helping the elderly to have better access to the city have been implemented by the City of Edmonton, including reduced senior fares for the transit system and all the public facilities. Future study will extend research dimensions of age-friendly communities by including other aspects such as environmental influences, service gaps in service prevision and demand from seniors, etc.

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Chapter 4: SPATIAL GAPS IN URBAN PUBLIC TRANSPORT SUPPLY AND DEMAND FROM THE PERSPECTIVE OF SUSTAINABILITY[4]

4.1 Introduction

Public transportation is a vital infrastructure with long-lasting influence on the dynamics and morphology of neighborhood expansion and, in turn, on sustainable and resilient urbanization. The provision of efficient transport systems can help to reduce energy consumption (Liu et al. 2017) and carbon footprints (Aggarwal and Jain 2016), as well as mitigate traffic congestion and accidents (Dirgahayani 2013). As a sustainable mode of urban mobility, public transport can improve quality of life (Silva Cruz and Katz-Gerro 2016), enhance social inclusion (Lucas 2006), and provide a more environmentally-friendly and healthier activity pattern (López-Iglesias et al. 2018). An imbalanced distribution of public transport services across a population may result in adverse effects for groups that often find themselves relegated to the fringes of society because of a lower socioeconomic status (Lucas and Jones 2012). Despite the efforts of municipalities to provide subsidies and other incentive mechanisms as means to improve accessibility of public transit, transport-related social exclusion still exists, primarily because disadvantaged social groups often reside in areas lacking transport supply or transport accessibility (Chiou et al. 2013). Social equity in urban public transportation has become one of the primary long-term objectives of municipalities seeking to become more inclusive and sustainable.

The meaning of equity differs based on the given research objectives and metrics (Manaugh et al. 2015). Two key types of social equity are typically considered in the context of transportation planning: horizontal equity and vertical equity (Litman 2002). Horizontal equity refers to the

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equal distribution of effects, including resources/benefits and costs among individuals. In the interest of fairness (Litman 2002), researchers investigating horizontal equity prescribe that transport policies should avoid favoring one individual or group over others. Studies in this paradigm mainly focus on spatial distribution and influences of transport services across a total population (Ricciardi et al. 2015). In contrast, vertical equity advocates for the equitable distribution of facilities and services for socially disadvantaged groups (SDGs) (Murray and Davis 2001), i.e., those who lack access to goods and resources in comparison with society at large (Townsend et al. 1988). Some scholars have explored vertical equity of transport supply to disadvantaged groups, such as those who are unemployed (Ricciardi et al. 2015), no-car households (Jaramillo et al. 2012), those with low-income (El-Geneidy et al. 2016), and children (Fransen et al. 2015). Elderly people also constitute a group of socially disadvantaged individuals due to their relative physical condition and limited mobility. In response to the growing issue of population ageing, the World Health Organization (WHO) published *Global Age-Friendly Cities: A Guide* (WHO 2007) in order to provide guidelines that could help planners design neighborhoods and cities that are socially inclusive and sustainable. By comparison, relatively little research in the area of vertical equity analysis has been devoted to seniors. Older adults are traditionally incorporated as one component of demand for public transport services, resulting in few quantitative studies that specifically analyze the efficiency of public transport services for seniors. In fact, older people generally drive less often and use alternative modes of transportation more frequently than do younger people, especially if public transport services in their neighborhood are easily accessible (Cao et al. 2010). They are the most likely segment of the population to be transport-dependent (Dodson et al. 2007). Within this context, it is essential to develop a quantitative methodology allowing municipal planners to assess public transport equity among seniors.

According to the literature, there are two main approaches to measuring social equity in transport supply. One approach is to measure SDGs' accessibility to goods and services (van Wee and Geurs 2011). For instance, Paez et al. (2009) identify that seniors living outside the city center have extremely low accessibility to health care services. Another method for measuring social equity is conducted by exploring the relationship between transport supply and demand (i.e., relative public transport gaps) from a spatial perspective (Jaramillo et al. 2012). Public transport gaps render a region susceptible to developing transport poverty and to transport service efficiency (Fransen et al. 2015). Ricciardi et al. (2015), having conducted a study in Perth, Australia, find that 70% of the elderly share only 25% of public transport. In the available research, the indicators of public transport supply tend to be one-dimensional, limiting the scope to a single perspective. To address the abovementioned shortcomings of existing studies, the objectives of the research presented in this chapter are to assess public transport supply and measure demand from seniors using a multi-dimensional approach, allowing transport gaps (between supply and demand) to be determined and examined from various perspectives. A systematic methodology supported by the geographic information system (GIS) is proposed for the purpose of identifying the relative spatial gaps in public transport considering sustainability at the statistical area (SA) level, such as gaps among census tracts (CTs), traffic analysis zones (TAZs), and neighborhoods. The application of this methodology can address the status quo for public transport services, promote greater equality of transport opportunities, enhance transport service efficiency for SDGs, and provide a reference for policy making pertaining to the sustainable planning and development of urban transportation.

The structure of the remainder of this chapter is as follows. First, a review of the literature relevant to public transport supply and demand is presented. Then, a methodology for assessing public transport supply, demand from seniors, and the relative spatial gaps is introduced. The methodology is used to analyze transport service distribution among seniors in a case study of Edmonton, Canada. The final section summarizes the conclusions of this research and proposes policy implications and suggestions for future work.

4.2 Literature Review

Given the variety of research objectives and perspectives proposed in the various studies in this area, approaches to measure supply services for the transport-disadvantaged are numerous. Currie and Wallis (1992) use the density of bus vehicle mileage during a certain period in the unit km/km2 to illustrate transport supply. Currie (2004) establishes a public transport network from an analysis of bus routes, stops, and timetables, and generates travel cost for different trip purposes in order to evaluate public transport supply quality across the network. These measurements are only suitable for an entire region such as a city and cannot indicate the level of public transport supply available at the SA level. To resolve this issue, Currie (2010) proposes a supply measure combining average service frequency (i.e., vehicle trips per week) with access distance to each stop/station. This approach accounts for the spatial coverage by walking catchments (or walking buffers) to public transport and reveals a relative service level. It is applied to compare transport supply between different ages, income levels, and vehicle ownership groups (Ricciardi et al. 2015). Jaramillo et al. (2012) introduce both an absolute index and a relative index for public transport supply. The absolute index refers to the total sum of bus stops for a district weighted by vehicle capacity and service average frequency over the district's total area, while the relative index is equal to the coefficient of the absolute index to the population in the district. Compared with the approach in Currie (2010), the two above indicators consider vehicle capacity described by the number of passengers that each stop is capable of absorbing, as well as the proportion of the population in relative terms. Fransen et al. (2015) measure cumulative accessibility for the TAZ centroid to various service types within specific time thresholds (i.e., from 0 min to 60 min with intervals every 10 min), average these values for various thresholds by different weights, and calculate an average accessibility index to represent the provision of the public transport network. Based on the literature outlined above, the present research aims to conduct a comprehensive index for public transport supply from the perspective of the transport network itself and to draw comparisons among various SAs.

In terms of transport demand, existing studies can be divided into two groups: demand from separated disadvantaged groups (e.g., seniors, children, or those with low-income) and demand from combined disadvantaged groups. Transport demand from combined disadvantaged groups is determined by aggregating normalized demand for serval separate groups using the weighted sum model. The values of weights can be derived from a travel survey (Currie and Wallis 1992), factor analysis (Kamruzzaman and Hine 2011), or principal component analysis (Jaramillo et al. 2012). To align with its research objectives, the present study only considers the separated disadvantaged group (i.e., older adults), and transport demand refers to the demand from the senior population at the SA level.

4.3 Methodology

This study aims to assess and compare public transport supply and demand from seniors considering sustainability at the SA level using GIS technology. The research methodology illustrated in Figure 4-1 consists of three main components: (1) measuring a comprehensive public transport supply index (PTSI) based on the established transport supply indicators with partial least squares (PLS) path modeling and the normalization method; (2) measuring public transport demand index (PTDI) for seniors; and (3) assessing global relative public transport gaps among seniors using Lorenz curves and the Gini coefficient (GC), and local relative public transport gaps using gap measurement. This section characterizes the relationship between the research methods and research objectives and facilitates deeper understanding of the potential application of the presented methodology to other jurisdictions for the purpose of assessing relative public transport gaps and transport equity among SDGs from the spatial and regional perspectives.

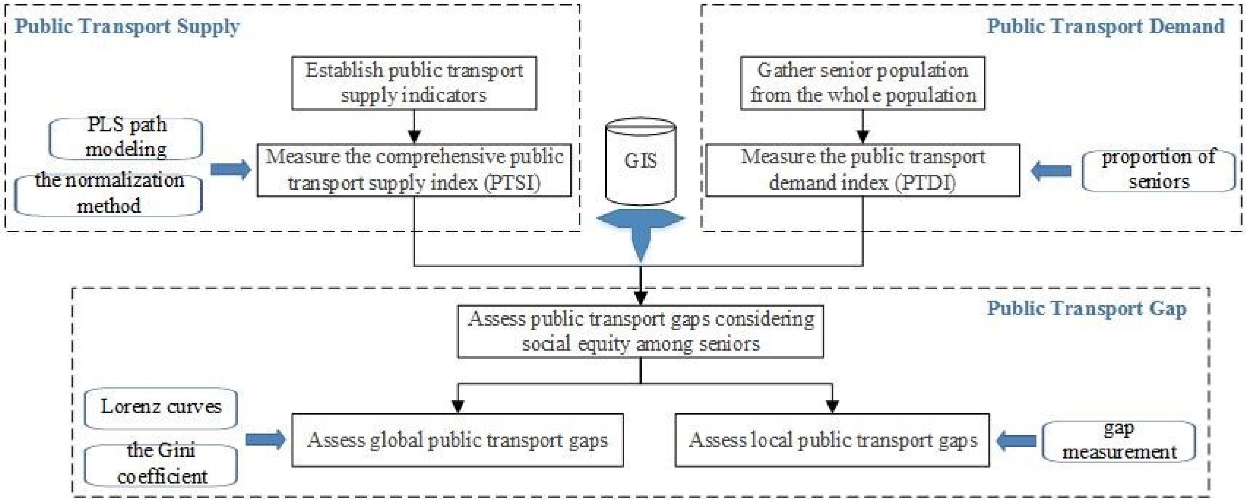


Figure 4-1. Research methodology.

4.3.1 PLS path modeling

The PLS path modeling, primarily developed by Wold (1985), has been employed to characterize the linear statistical relationships among multiple groups of variable sets. PLS path modeling involves two components: the measurement model for identifying system elements and the structural model for identifying cross-correlation within the system (Assemi et al. 2018). Suppose there exist J groups of variables in n observation samples, and each group contains k_j variables. Each group of variables can be represented by $X_j = \{x_{j1}, x_{j2}, ..., x_{jk_j}\} (j = 1, 2, ..., J)$, and the manifest variable, $x_{jh}(h=1,2,...,k_j)$, is centralized (i.e., the mean of the variables is equal to zero). The corresponding normalized latent variable is denoted by $\xi_j(j=1,2,...,J)$, where the mean is equal to zero and the variance is equal to one. The measurement model can be deployed to describe the relationship between the manifest variables and latent variables in each group as per Eq. (4-1):

$$x_{jh} = \lambda_{jh}\xi_j + \varepsilon_{jh} \tag{4-1}$$

where λ_{jh} is the regression coefficient, and ε_{jh} is the residual term. ε_{jh}, it should be noted, is not connected with the latent variable ξ_j, and the mean of ε_{jh} is equal to zero.

The structural model describing the relationship between the latent variables can be expressed as

$$\xi_j = \sum\nolimits_{i \neq j} \beta_{ji}\xi_i + \zeta_j \tag{4-2}$$

where β_{ji} is the regression coefficient, and ζ_j is a zero-mean random term that is not connected with the latent variable $\xi_i(i \neq j)$.

Regarding the above parameter estimation, PLS path modeling employs an iterative algorithm to estimate the values of the latent variables (Wold 1985a). The process is two-fold: external estimation and internal estimation. External estimation is used to assess the latent variable, ξ_j, with the linear combination of x_{jh}.

$$Y_j = \left(\hat{X}_j W_j \right)^* = \left(\sum_{h=1}^{k_j} w_{jh} x_{jh} \right)^* \tag{4-3}$$

where Y_j is the estimated value of ξ_j; $\hat{X}_j$ is the matrix whose column vector contains the observed manifest variables x_{jh}; W_j is the matrix whose column vector consists of the external weights w_{jh}; and * is used to normalize the linear combination of the variables in parentheses.

Internal estimation is used to assess the latent variable, ξ_j, associated with the estimated value, $Y_i(i \neq j)$, of the other related latent variables.

$$Z_j = \left(\sum_{i:\beta_{ji} \neq 0} e_{ji} Y_i \right)^* \; with\; e_{ji} = sign(r(Y_j, Y_i)) = \begin{cases} 1 & r(Y_j, Y_i) > 0 \\ -1 & r(Y_j, Y_i) < 0 \\ 0 & r(Y_j, Y_i) = 0 \end{cases} \tag{4-4}$$

where Z_j is the estimated value; β_{ji} is the regression coefficient from Eq. (4-2); e_{ji} is the internal weight calculated by the sign function; and $r(Y_j, Y_i)$ is the correlation coefficient between the external estimated values, Y_j and Y_i.

As for the external weights, w_{jh}, in the matrix W_j, Wold (1985) proposes a calculation method to obtain W_j using the correlation coefficient between the transposed variable, $\hat{X}_j^T$, and the variable, Z_j.

$$W_j = \frac{1}{n} \hat{X}_j^T Z_j \tag{4-5}$$

According to the above estimated latent variables, the measurement and structural models can be developed using the PLS algorithm (Mugion et al. 2018). Guinot et al. (2001) introduce a particular PLS path model called the multiple table analysis model. In their model, the left-hand side contains all the tables, and all manifest variables of the same data table are influenced by a single latent variable; the right-hand side consists of all the manifest variables (see Figure 4-2). The measurement model and the structural model in a multiple table analysis model can be derived from Eq. (4-1) and Eq. (4-2).

$$\begin{cases} x_{jh} = \lambda_{jh} \xi_j + \varepsilon_{jh} \\ \xi = \sum_{j=1}^{J} \beta_j \xi_j + \zeta \end{cases} \tag{4-6}$$

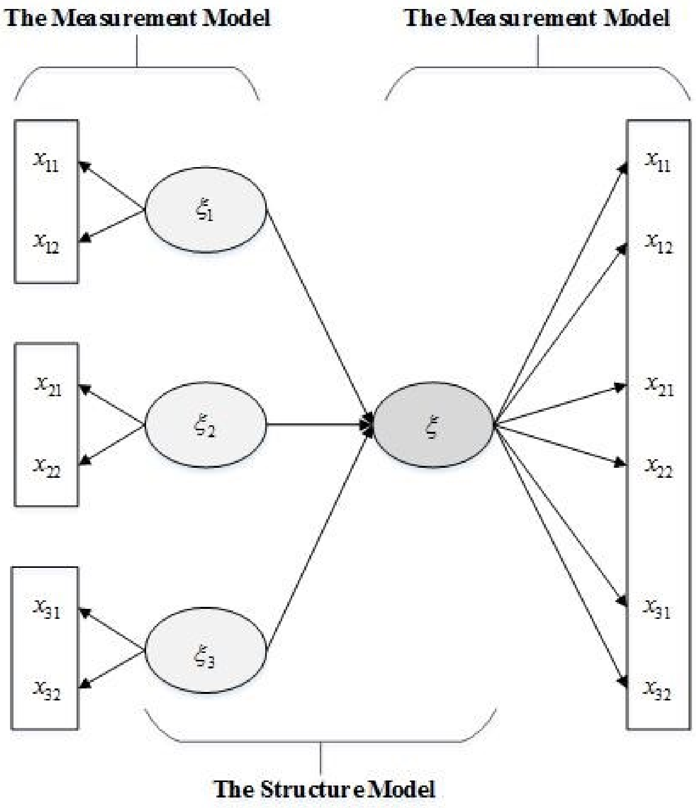


Figure 4-2. Example of path relationship in a multiple table analysis model.

The multiple table analysis model can objectively determine the weights for each manifest variable and each latent variable and yield a comprehensive evaluation of all manifest variables. It has been deployed in the domains of social science (Wang and Fu 2004), economics (Liu et al. 2014), and engineering (Liu et al. 2015). In the present research, we utilize a multiple table analysis model to yield a comprehensive transport supply index for analysis of relative public transport gaps.

4.3.2 Public transport supply index

Based on data availability and knowledge gained from a review of the relevant literature, the research presented in this chapter assembles public transport supply indicators at the SA level (see Table 4-1). It is important to mention that the selected transport supply indicators are restricted to measuring physical transport services.

Table 4-1. Public transport supply indicators.

Latent variables	Manifest variables	Interpretation
Service coverage (ξ_1)	Service area ratio (x_{11})	Sum of service area of each bus stop/station / Total area of each SA
	Service density (x_{12})	Total number of stops/stations / Sum of service area of each bus stop/station
Service level (ξ_2)	Service frequency (x_{21})	Total number of public transport (e.g., bus, tram, and train) arrivals for all stops/stations per week
	Route diversity (x_{22})	Number of different routes
Service accessibility (ξ_3)	Accessibility within a SA (x_{31})	Average number of stops/stations reachable from the origin within a time threshold per day
	Accessibility across SAs (x_{32})	Average number of destinations (other districts) from the origin (a district) within a time threshold per day

The first latent variable, service coverage (ξ_1), is one goal that decision makers will take into account for transportation planning (Walker 2008). It is primarily derived from two manifest variables: (1) service area ratio (x_{11}), which describes the proportion of service coverage areas available for public transport, and (2) service density (x_{12}), which represents the density of public transport that the users can access in the areas of service coverage. Previous research utilizes walking buffers to calculate the service area of each bus stop/station, which refers to the area surrounding a stop/station within a certain distance threshold accessible by walking (Currie 2010). For instance, use 400 m and 800 m as the walking access thresholds for bus stops and train stations. However, the walking buffer application is inaccurate, and does not take into account the actual distribution of the street network. The present study uses network analysis in GIS to measure service areas for all bus stops/stations based on the street network.

The second latent variable, service level (ξ_2), is defined from two manifest variables: service frequency (x_{21}) and route diversity (x_{22}). One week is used as the time interval for measuring service frequency (Ricciardi et al. 2015), as the use of this interval prevents the corruption of data due to variations in public transport arrivals between weekdays and weekends and the disparity of transport arrivals during a given day (i.e., peak time and non-peak time). Route diversity is indicative of the number of opportunities available to users to access services and amenities and how dynamic the transport system is in each SA.

The third latent variable, service accessibility (ξ_3), represents accessibility within and across SAs (i.e., x_{31} and x_{32}). Accessibility is generally defined as potential opportunities for interaction (Hansen 1959). Measuring accessibility by public transport is a critical step in evaluating the distribution of services in a region based on equity (Foth et al. 2013). The cumulative opportunity measure, a widely-used method for measuring accessibility, quantifies the number of opportunities reachable within a specified transportation impedance (e.g., distance, time, or cost) when departing from a given location by means of a particular travel mode (van Wee and Geurs 2011). In this method, all potential destinations within the impedance are weighted equally. As for accessibility within a given SA, this metric emphasizes the convenience of taking public transport: able to access more bus stops/stations within a transportation impedance in a SA, seniors have greater potential to make use of facilities and services near the alighting locations. In contrast, accessibility across SAs integrates the number of opportunities for relevant land uses for seniors with the transportation impedance. Chen et al. (2018a) list four types of desired destinations for seniors—hospitals, recreation facilities, parks, and shopping centers. Engels and Liu (2011) undertake a detailed land use audit to identify which types of facilities non-driving seniors in Melbourne, Australia, tend to use more frequently, finding shopping centers, hospitals, parks, and social clubs to be the facilities most frequently accessed. Based on this, in the present research the cumulative opportunity measure is utilized to determine accessibility of seniors within and across SAs by public transport.

$$A_{within}^{i}=\sum_{j=1}^{n}O_{j}f(T_{ij})\ \ with\ f(T_{ij})=\begin{cases}1\ if\ T_{ij}\le T_{within}\\0\ if\ T_{ij}>T_{within}\end{cases}\ \ and\ \ O_{j}=\begin{cases}1\ if\ f(T_{ij})=1\\0\ if\ f(T_{ij})=0\end{cases}\qquad(4\text{-}7)$$

where A_{within}^{i} is the accessibility within SA i; O_j is the opportunity for bus stop/station j $(j=1,2,...,n)$; $f(T_{ij})$ is an indicator function with T_{ij} being the time of travel from the centroid of SA i to bus stop/station j in SA i; and T_{within} is the travel time threshold within a given SA.

$$A_{across}^{i}=\sum_{k=1,k\neq i}^{m}O_{k}f(T_{ik})\ \ with\ f(T_{ik})=\begin{cases}1\ if\ T_{ik}\le T_{across}\\0\ if\ T_{ik}>T_{across}\end{cases}\qquad(4\text{-}8)$$

where A_{across}^{i} is the accessibility from SA i to other SAs; O_k is the number of facilities that are considered for seniors in SA k; $f(T_{ik})$ is an indicator function with T_{ik} being the time of travel from the centroid of SA i to the centroid of SA k; and T_{across} is the travel time threshold across SAs.

El-Geneidy et al. (2016) select 45 min and 60 min as the travel time thresholds for accessibility measure in Montréal, Canada. Fransen et al. (2015) set 60 min as the cut-off travel time for measuring public transport supply in Flanders, Belgium, in order to reduce computation time. The travel time thresholds T_{within} and T_{across} are set to 60 minutes for Eq. (4-7) and Eq. (4-8) in the present study. Since the frequency of public transport varies during the operation period of a given day, a time interval such as 15 min is used to collect the opportunities for bus stops/stations or SAs. The accessibility within and across SAs can be obtained by averaging these opportunities among all time intervals.

Given the established transport supply indicators, PLS path modeling based on multiple table analysis is utilized to calculate the comprehensive PTSI, that is, ξ, by means of Eq. (4-6) and the PLS algorithm. The path relationships among all variables are illustrated in Figure 4-2. Given that PLS path modeling requires that the manifest variable x_{jh} is centralized, a normalization method is employed to convert the values of x_{jh} into new data where the mean of the variables by type is equal to zero.

$$x_{jh}^{k'} = \frac{x_{jh}^{k} - \overline{x_{jh}}}{\delta_{jh}} \tag{4-9}$$

where $x_{jh}^{k'}(j=1,2,3;h=1,2)$ is the normalized manifest variable in SA i; $\overline{x_{jh}}$ is the mean of all manifest variables, x_{jh}, among all SAs, namely $\overline{x_{jh}} = \frac{1}{m}\sum_{k=1}^{m} x_{jh}$; and δ_{jh} is the standard deviation (SD) of all manifest variables, x_{jh}, among all SAs, namely $\delta_{jh} = \sqrt{\frac{1}{m}\sum_{k=1}^{m}(x_{jh}^{k} - \overline{x_{jh}})}$.

Since the values of the latent variable ξ in SA i have a mean equal to zero and a variance equal to one, it is not suitable for an analysis of the global relative public transport gaps. The following equation is utilized to standardize the values of ξ, ensuring that the values of PTSI in SA i fall within the range [0,1].

$$PTSI_i = \frac{\xi_i - \xi_{\min}}{\xi_{\max} - \xi_{\min}} \tag{4-10}$$

where $\xi_{\max}$ and $\xi_{\min}$ are the maximum value and minimal value of PTSI among all SAs; $PTSI_i = 0$ and $PTSI_i = 1$ refer to the lowest and highest levels of comprehensive public transport supply in SA i.

4.3.3 Public transport demand index

The present research in its public transport demand analysis focuses only on seniors—those aged 65 or over, since 65 years is commonly used as the age threshold to define this segment of the population (Ricciardi et al. 2015). Currently, transport demand is quantified by a population measure relative to the number of people in a defined target population (Currie 2004). For instance, the total number of seniors in a given SA is used as an indicator to capture the potential of transport demand from seniors at the SA level (Jaramillo et al. 2012). This approach is simple to use and easy to interpret, but the measured transport demand comprises both actual demand (i.e., the number of seniors taking public transport) and latent demand. The latter refers to the desired demand for activities and travel that is not realized due to a variety of constraints, such as lack of money or unavailable service (Clifton and Moura 2017). In consideration of data availability, this absolute indicator can be regarded as an approximate method, but it fails to describe the potential demand from seniors in comparison to demand from the total population. To address this shortcoming, the present research uses a relative indicator to describe PTDI.

$$PTDI_i = SP_i / TP_i \tag{4-11}$$

where $PTDI_i$ refers to public transport demand in SA i; SP_i indicates the senior population aged 65 or over in SA i; and TP_i refers to the total population in SA i.

4.3.4 Relative spatial gaps in public transport

- *Global relative public transport gaps*

Global relative public transport gaps measure relative discrepancies between supply and demand by aggregating all SAs using a combination method that integrates Lorenz curves and the GC. Lorenz curves were initially developed in the field of economics to graphically represent the cumulative distribution functions of wealth across a population (Lorenz 1905). In the present research, Lorenz curves are employed to quantify inequalities in public transport distribution across demand from seniors by sorting statistical-level observations of transport supply in ascending order. The cumulative percentage of public transport demand is represented as the horizontal axis, while the cumulative percentage of public transport supply is represented as the vertical axis. If transport services are treated equally for all seniors, the Lorenz curves are plotted as diagonal lines representing an equal distribution; otherwise, Lorenz curves are under the diagonal. A curve farther from the diagonal indicates a higher degree of inequality in transport services.

The Gini coefficient is a relative index based on Lorenz curves used to mathematically describe the overall degree of inequality. It is equal to the ratio of area A (i.e., between the diagonal line and the Lorenz curve) to area B (i.e., the total area under the diagonal line) (Gini 1912); (for an illustrated example the reader may refer to Figure 4-5). An approximate mathematical calculation of the GC can be expressed through the following equation (Delbosc and Currie 2011).

$$G = 1 - \sum_{i=1}^{n} (x_k - x_{k-1})(y_k + y_{k-1}) \tag{4-12}$$

where x_k is the cumulative proportion of the public transport demand variable with $x_0 = 0$ and $x_n = 1$, and y_k is the cumulative proportion of the public transport supply variable with $y_0 = 0$ and $y_n = 1$. If $G = 0$, the distribution of transport services is regionally equal; if $G = 1$, the distribution of transport services is completely inequitable; if $0 < G < 1$ and closer to 1, this indicates relatively large differences in transport service supply among regions; If $0 < G < 1$ but closer to 0, transport service supply tends to be uniform.

- *Local relative public transport gaps*

The local relative public transport gaps are used to individually identify relative discrepancies between transport supply and demand from seniors in each SA and compare the degree of relative deviation among all SAs.

$$GAP_i = PTSI_i - PTDI_i \tag{4-13}$$

where GAP_i is the local relative public transport gap in SA i; $PTSI_i$ is the PTSI in SA i; and $PTDI_i$ is the PTDI for seniors in SA i. If $GAP_i > 0$, the estimated public transport supply is relatively larger than the expected transport demand in this region (i.e., over-service); if $GAP_i < 0$, the estimated public transport supply is relatively smaller than the expected transport demand in this region (i.e., under-service); if $GAP_i = 0$, public transport supply and demand from seniors are considered to be balanced. The larger the absolute value of GAP_i ($GAP_i > 0$ or $GAP_i < 0$), it should be noted, the higher will be the degree of relative deviation between transport supply and demand in SA i.

It should be noted that the estimated values of $PTSI_i$ range between 0 and 1, while the values of $PTDI_i$ (larger than 0) calculated using Eq. (4-11) indicate the percentage of seniors in SA i. $PTDI_i$ must first be standardized by means of Eq. (10), in order to identify the relative transport gap in each SA with the same magnitude. In other words, $PTDI_i = 0$ and $PTDI_i = 1$ refer to the public transport demand from seniors in SA i at its lowest and highest.

4.4 Case Study

4.4.1 Study area and data source

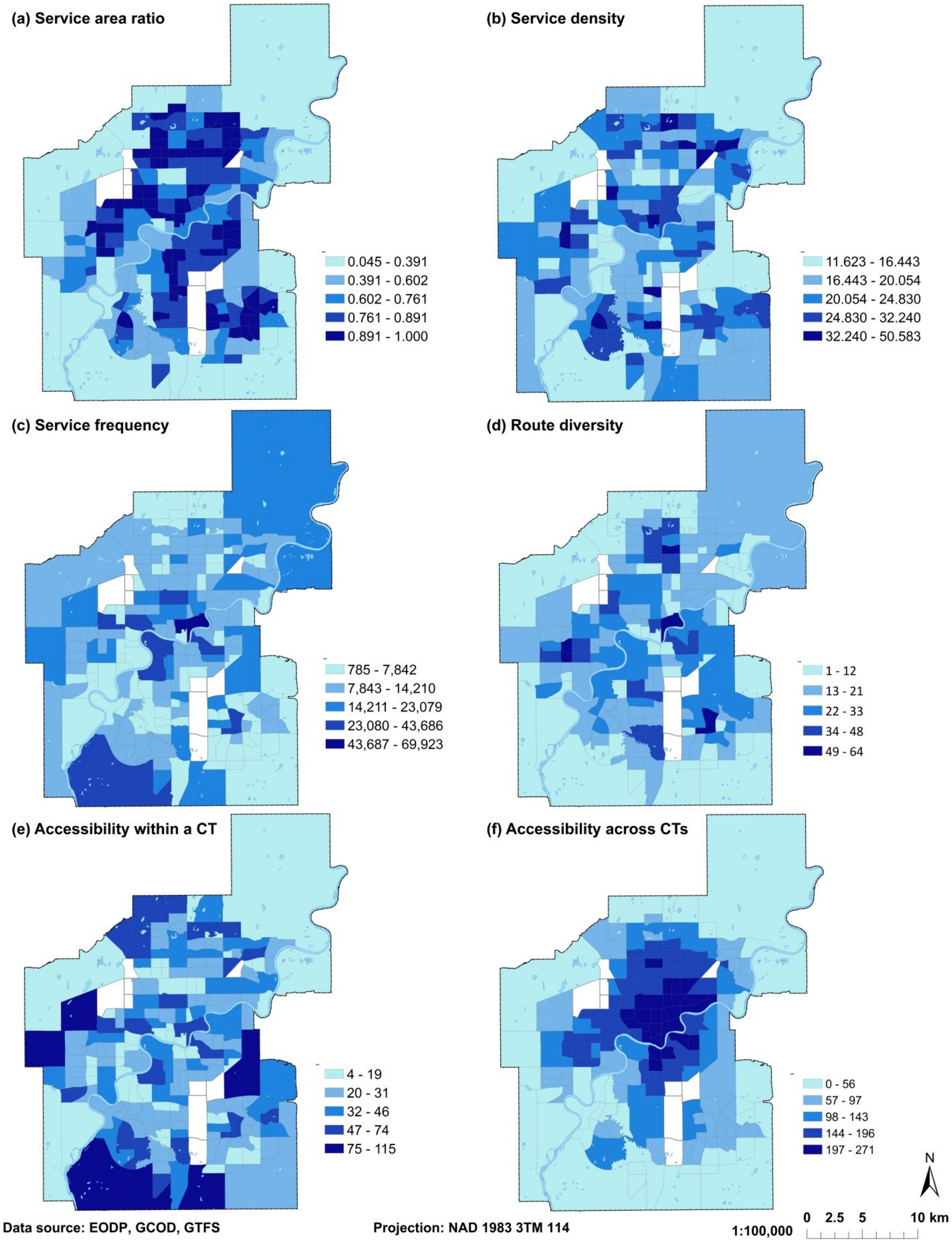
The selected study area for the case study is Edmonton, Canada, a city which consists of 200 CTs (see Figure B-1). The city has a population of approximately 932,500 inhabitants in an area of 700 km^2, making it Canada's fifth-most-populous municipality (Statistics Canada 2017b). Currently, the public transport system in this city consists of buses and two lines for light rail transit (LRT). The analysis in the case study is conducted at the CT level (i.e., 191 CTs). All CTs either with a total population of fewer than 20 people or with no senior population are excluded, since data in these areas can introduce significant bias into the research results. The distributions of the senior population and of the urban facilities that are under consideration in terms of accessibility to seniors—hospitals, parks, shopping centers, recreation facilities, and museums—are shown in Figure B-2. There are three data sources used in this study: demographic CT information by age, locations of bus stops/stations, and locations of urban facilities from City of Edmonton's Open Data Portal (EODP 2017); the street network from the Government of Canada's Open Data (GCOD 2015); and September–November 2017 General Transit Feed Specification (GTFS) data for the Edmonton Transit System from Transit Feeds (2017). Based on GTFS data, the transport schedule and service frequency for each CT are collected. In the present case study a routable network is created applying the Add GTFS to the Network Dataset tool developed by (Morang 2018a).

4.4.2 Public transport supply assessment

4.4.2.1 Public transport supply indicators

Six manifest variables for public transport supply indicators, presented in Table 4-1, need to be calculated based on the data sources. The data pertaining to service area ratio and service density is collected based on bus stop distribution and street network by means of GIS. Service frequency and route diversity are derived from the transport schedule based on GTFS data. According to the daily public transport schedule, service accessibility within and across CTs is measured using Eq. (4-7) and Eq. (4-8). A time interval (15 min) is used to collect the opportunities for bus stops/stations and the opportunities for CTs. The basic data profile of public transport supply indicators can be observed in Figure 4-3.

For most CTs, the active service area accounts more than 50% of the total area, whereas cases where the active service area ratio exceeds 90% represent only approximately 30% of CTs. The CTs with better service coverage are primarily located in the central region of Edmonton. By comparison, the distribution of service density reflects diversity among CTs and does not have a clear relationship with service area ratio. Most CTs are found to have a low service frequency during a given week, while only 11 CTs have the higher service frequency in the first two categories. There also exists distinctiveness in the above three features of transport supply (service area ratio, density, and frequency). For example, the CT located in the top-right corner of the city has a poor service area ratio and service density, but the total number of public transport arrivals per week is found to be in the medium category. The distribution of route diversity is similar to that of service density, revealing a degree of spatial dispersion. Accessibility within the CTs has an imbalanced distribution among all categories. Overall, the choices for bus stops/stations within 60 min are abundant in each CT, since the mean of accessibility within CTs is approximately 30 bus stops/stations. By contrast, greater accessibility across CTs is concentrated in the center of the city while, for other CTs, these opportunities for urban facilities generally decrease with distance from the city center.



(a) Service area ratio

(b) Service density

(c) Service frequency

(d) Route diversity

(e) Accessibility within a CT

(f) Accessibility across CTs

Data source: EODP, GCOD, GTFS

Projection: NAD 1983 3TM 114

Figure 4-3. Distribution of public transport supply indicators in Edmonton.

4.4.2.2 Estimation of the PLS path modeling

Based on Table 4-1, six indicators for transport supply are normalized using Eq. (4-9) and the values of PTSI for all CTs are determined following the theory of PLS path modeling. The results for the path coefficients in the multiple table analysis model are presented in Figure 4-4, which demonstrates that both the three latent variables (ξ_1 - ξ_3) and the PTSI (ξ) effectively summarize the information from the three groups. The path coefficient vector is denoted by $\beta = (0.413, 0.525, 0.277)$. The value of R^2 (0.99) indicates an excellent degree of fitness for this model, and that the calculated coefficients are reliable. From the values of the T statistic in parentheses, each path coefficient is observed to be significant at the 1% confidence level.

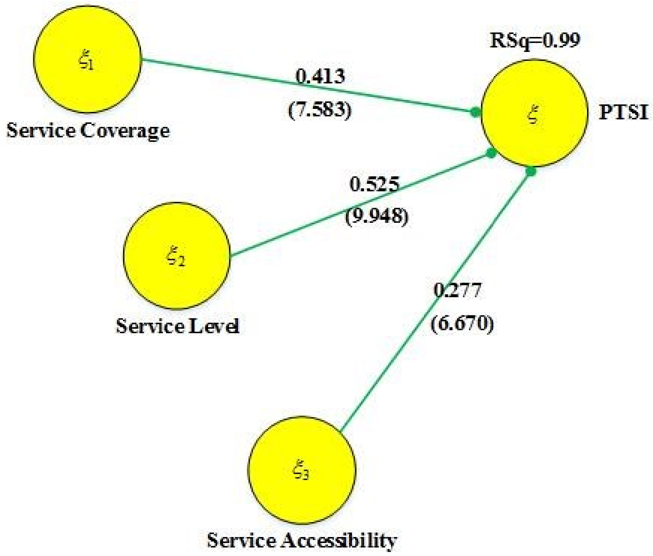


Figure 4-4. Path coefficients between the latent variables and PTSI.

Table 4-2. Estimated values for λ_{jh} and w_{jh}.

Variables		λ_{jh}	w_{jh}	Variables		λ_{jh}	w_{jh}
Service coverage (ξ_1)	x_{11}	0.743	0.492	PTSI	x_{11}	0.507	0.203
	x_{12}	0.887	0.715	(ξ)	x_{12}	0.738	0.295

Service level (ξ_2)	x_{21}	0.880	0.605	x_{21}	0.793	0.317
	x_{22}	0.852	0.549	x_{22}	0.720	0.288
Service accessibility (ξ_3)	x_{31}	0.662	0.761	x_{31}	0.526	0.211
	x_{32}	0.657	0.756	x_{32}	0.523	0.209

The detailed estimates of regression coefficients, λ_{jh}, in Eq. (4-1) and the external weights, w_{jh}, in Eq. (4-3) can be found in Table 4-2. The correlation between the manifest variables by group and the corresponding latent variables are observed to be quite high. In addition, the PTSI correlates strongly with various transport supply indicators, including service density, service frequency, and route diversity. All the correlation coefficients, λ_{jh}, of the above indicators are found to exceed 0.7. The PTSI correlates significantly with service area ratio, the accessibility within and across CTs, with the correlation coefficients exceeding 0.5.

4.4.3 Global relative public transport gap analysis

After standardizing the values of PTSI by Eq. (4-10), Lorenz curves and the GC are utilized to measure the global relative public transport gaps among all CTs. The results are shown in Figure 4-5.

All the Lorenz curves are observed to be under the diagonal, which indicates that the demand from seniors in various CTs is not identical to public transport supply, that is, the degree of concentration of public transport varies regionally. The degree of deviation from the diagonal is not significant, since the values of GCs (in parentheses in Figure 4-5) are less than 0.5. Specifically, in regard to service area ratio and service density, there tends to be a uniform distribution for the senior population in these CTs. The distribution differences increase in accessibility across CTs and route diversity, and the senior population has greater inequity in service frequency and accessibility within a CT. The GC of the PTSI against the PTDI is 0.17, which indicates uniform overall transport service provision.

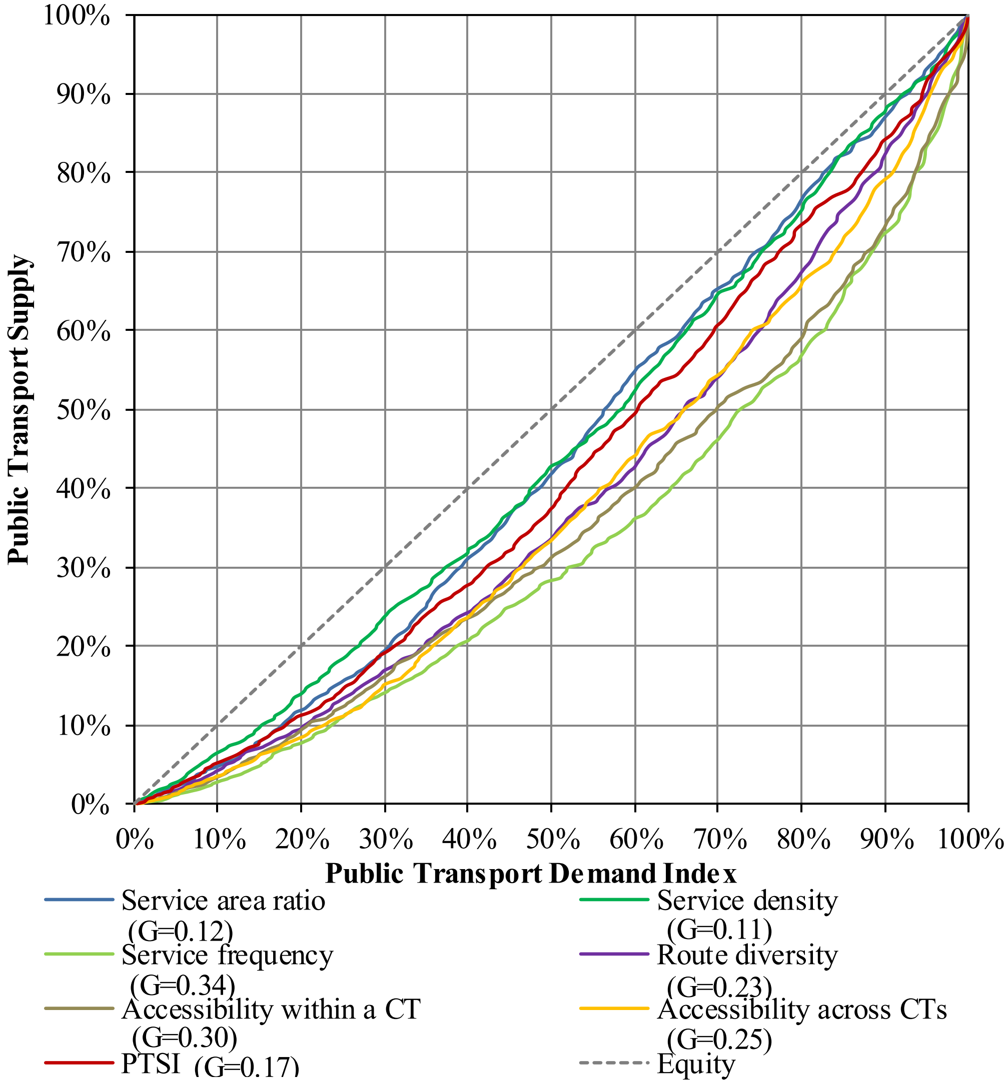
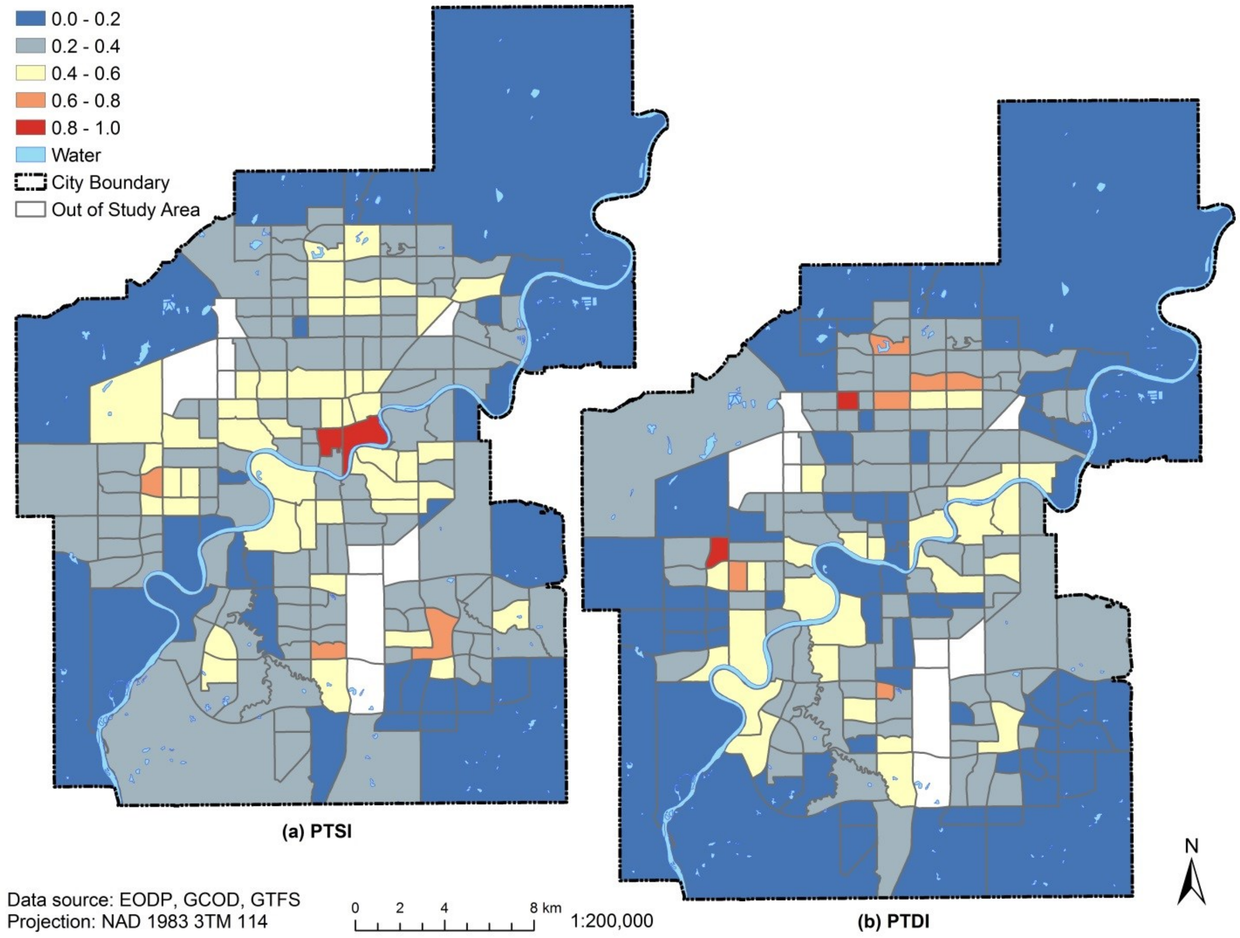


Figure 4-5. Global relative public transport gaps in Edmonton.

4.4.4 Local relative public transport gap analysis

Based on the standardized PTSI estimated from the PLS path modeling and the standardized PTDI derived from Eq. (4-10), Figure 4-6 presents the results for public transport supply and demand from seniors, divided into five categories.



(a) PTSI

(b) PTDI

Figure 4-6. Edmonton public transport supply and demand from seniors.

Both the PTSI and the PTDI in the lowest category (i.e., the values smaller than 0.2) are primarily located in the periphery of the city, whereas the CTs belonging to the two categories (i.e., the values between 0.2 and 0.6) are mainly concentrated in the central part of this city. There exist both similarity and diversity between a CT and its neighbors in terms of either transport supply or demand. As for the remaining CTs in other categories, their transport supply or demand values are higher, but are sparsely scattered in throughout the city. The case city is divided into two parts by a large river (i.e., the north part and the south part). This geographical division introduces some unique features in transport service distribution among seniors. As for the PTSI in the north part of the city, the total number of its CTs in all categories is larger than that in the south part, resulting in the total value of its PTSI and PSDI that are approximately 50% larger. The north part of this city has higher transport supply and demand. Previous studies have found a significant association between built environment and travel behavior, but the association is insufficient to establish causality; travel behavior is also influenced by self-selection, which refers to the choice tendency of people based on travel abilities, needs, and preferences (Cao et al. 2009). For instance, suburban residents tend to depend more on automobile, which could explain why public transport supply in these regions is not sufficient in Figure 4-6. If a bus-oriented environment is built in a CT, it will attract more bus-oriented seniors, especially in the form of latent demand.

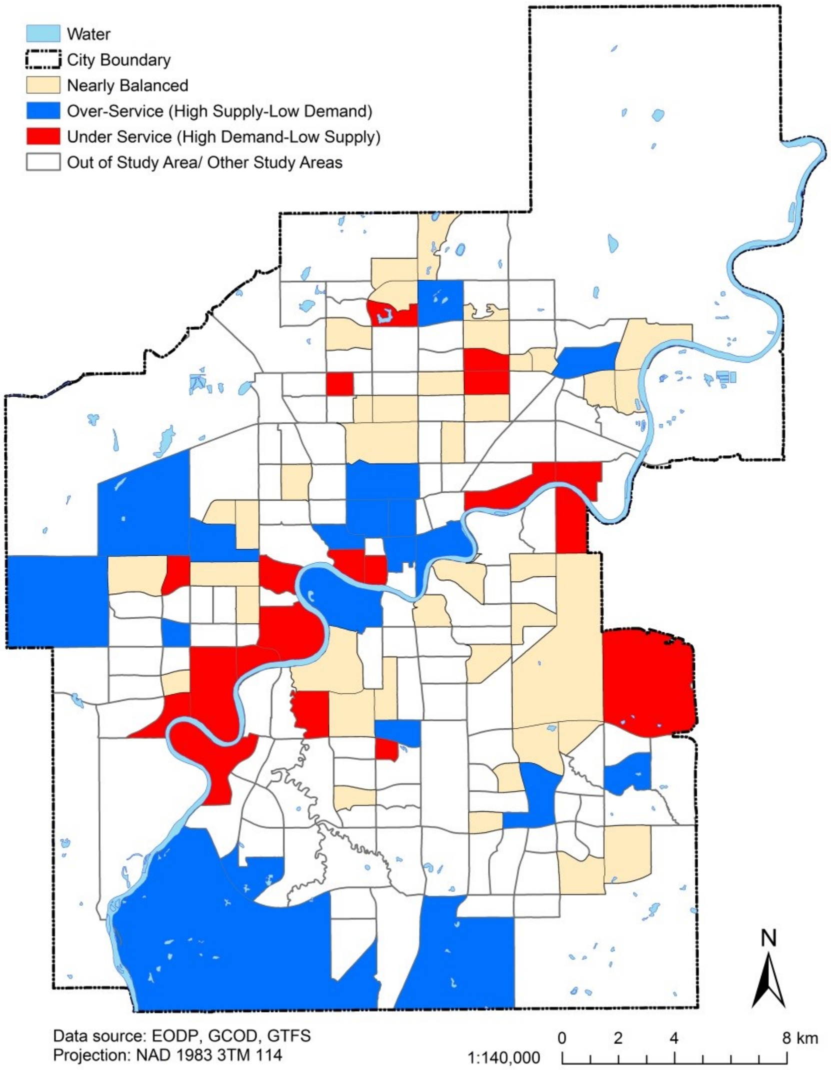
Table 4-3. Detailed data for public transport supply and demand categories.

PTDI		PTSI					
		0.0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1.0	Total
0.0–0.2	No. CTs	14	39	11	0	1	65
	Senior population	6,215	18,935	4,795	0	435	30,380
	%	5.53%	16.84%	4.27%	0.00%	0.39%	27.02%
0.2–0.4	No. CTs	13	58	21	0	0	92
	Senior population	6,160	31,600	13,270	0	0	51,030
	%	5.48%	28.11%	11.80%	0.00%	0.00%	45.39%
0.4–0.6	No. CTs	3	13	6	3	1	26
	Senior population	2,215	12,140	5,195	3,130	1,395	24,075
	%	1.97%	10.80%	4.62%	2.78%	1.24%	21.41%
0.6–0.8	No. CTs	0	1	5	0	0	6
	Senior population	0	450	4,690	0	0	5,140
	%	0.00%	0.40%	4.17%	0.00%	0.00%	4.57%
0.8–1.0	No. CTs	0	1	1	0	0	2
	Senior population	0	895	905	0	0	1,800
	%	0.00%	0.80%	0.80%	0.00%	0.00%	1.60%
Total	No. CTs	30	112	44	3	2	191
	Senior population	14,590	64,020	28,855	3,130	1,830	112,425
	%	12.98%	56.94%	25.67%	2.78%	1.63%	100%

Note: % refers to the percentage of senior population in each category of the total senior population.

Table 4-3 shows the distribution of transport supply and demand from seniors in each category for Edmonton. As seen in the table, category "0.2–0.4" dominates the total numbers of CTs by category for the PTSI; the percentage of the senior population in this category is much larger than those in other categories. Similarly, in the case of PTDI, there exists a large gap between the category "smaller than 0.4", which contains 157 CTs (accounting for 72.41% of the senior populations), and the other three categories (i.e., "0.4–0.6", "0.6–0.8" and "0.8–1.0"). As for the lower transport supply and demand categories (i.e., those lower than the middle category), these 124 CTs account for 55.96% of the senior population. In contrast, no CTs are located in the higher transport supply and demand categories (i.e., those higher than the middle category). In addition, 142 CTs, accounting for 69.92% of the senior population, live in the areas with the lower transport supply scores. Of these, 18 CTs score higher for transport demand, where 2,215 seniors live in areas with very low transport supply and 13,485 with low transport supply. These CTs are typically under-serviced. The higher scores of transport supply are distributed across 5 CTs representing 4,960 senior residents, and all of them are over-serviced.

Eq. (4-13) is applied in order to clearly grasp the relative public transport gaps among all CTs. The mean relative transport gap is 0.051, with a minimum value of −0.594 and a maximum value of 0.867. The geographical distribution of CTs with some typical features highlighted is displayed in Figure 4-7. Some under-serviced and over-serviced CTs are selected in the highest and the lowest deciles with gap values; the nearly balanced areas are displayed with a margin of error of 5%, that is, the range of possible values of the gaps is [−0.05, 0.05]. Since the focus in this study, as shown in the figure, is on revealing the above three features of the relative difference between transport supply and demand from seniors in each CT, spatial association of relative transport gaps between a CT and its neighboring CTs is not considered. However, such a metric could be measured by means of LISA (Anselin 1995). The figure shows a more scattered pattern for relative transport gaps, with stronger concentrations near the river. Under-serviced is primarily observed in the southwestern and the eastern surrounding areas. The over-serviced CTs tend to be adjacent to areas of under-service or balance. Most of the nearly-balanced CTs are distant from the city center, scattering in all directions.



Data source: EODP, GCOD, GTFS
Projection: NAD 1983 3TM 114

Figure 4-7. Relative public transport gap distribution in Edmonton.

4.5 Conclusions

Increasing public transportation ridership has the potential to reduce energy consumption (Yin et al. 2018) and carbon footprints (Ercan et al. 2016), while the premise of achieving the above goal is that regional public transport supply is commensurate with demand from users in order to increase transport service efficiency. Sustainability in public transport infrastructure not only requires equilibrium between environmental care and economic development, but also social equity in transport services especially for SDGs. Within this context, this chapter proposes a systematic methodology integrating the PLS path modeling, Lorenz curves, the GC, and gap measurement by which to perform an analysis of relative spatial gaps in public transport supply and demand from seniors at the SA level. The main contributions of this study include the following: (1) A systematic index system is built for quantifying public transport supply from multiple dimensions (i.e., service coverage, service level, and service accessibility). Practitioners and researchers can directly use or modify the ones more appropriate to their specific characteristics. For example, if people with low income are selected as the SDG under study, different land uses will be used in the accessibility calculations expressed by Eq. (4-8). (2) The PLS path modeling is used to objectively determine the weights of different supply indicators and yield a comprehensive PTSI; this eliminates the need for the use of subjective methods for weighting, such as the analytic hierarchy process method or the Delphi method. (3) To perform the analysis of relative transport gaps, the corresponding methods are developed from both the global and local perspectives. (4) The proposed methodology may be useful for other jurisdictions, enhancing social equity in transport services, improving service efficiency for various populations, and helping to reduce carbon footprints.

The proposed methods are implemented in a case study (Edmonton, Canada) in order to demonstrate their novelty and practical value in the analysis of relative public transport gaps. The results indicate that public transport services for seniors are not identical among all CTs. The degree of inequality is not clear, as the values of the GCs do not exceed 0.5. Older adults in all CTs tend to have uniform distributions for service area ratio, service density and PTSI, while the distribution differences increase in accessibility across CTs and route diversity. Greater inequity among seniors is noticed when comparing demand with other transport supply indicators (i.e., accessibility within CTs and service frequency). The CTs with PTSI and the PTDI values lower than 0.2 are primarily located in the periphery of this city, while the values of transport supply and demand reflect diversity in the remainder of the CTs. Some distinct features in transport service distribution among seniors are revealed in the two geographical segments divided by the river. Areas both of over-service and under-service exist in the case city, and the nearly balanced CTs are mainly scattered in areas far from the city center.

Based on the above results, some policy implications are proposed to improve public transport systems. It is recommended that substantive policy measures be taken for areas characterized by a mismatch between PTSI and PTDI in order to enhance transport service efficiency. For instance, the level of transport supply can be reduced in over-serviced areas. As for under-serviced areas, specific actions can be taken in terms of six transport supply indicators, where various areas should be compared after adjusting one or more indicators to verify the effectiveness of each action. As for service area ratio, service density, and route diversity, increasing the number of bus stops/stations and routes in CTs with a large percentage of seniors can reduce the degree of inequity among seniors. By contrast, social equity of the remaining transport supply indicators can be improved by taking measures to optimize the public transport system, such as adjusting transport schedules and route distributions within and among CTs.

The developed approach can assist in identifying relative spatial gaps in public transport supply among SDGs in a clear and quantitative manner. It is also worth noting that there are potential improvements to be explored in future research. First, for the purpose of the present study, service frequency is defined in such a manner as to determine the total number of public transport arrivals per week. In fact, as previous researchers have noted, transport disadvantage varies over time, so not all groups are disadvantages all the time (Kamruzzaman and Hine 2011). In future study, a more detailed analysis of this indicator will be conducted according to different periods such as peak time and non-peak time, which would be tantamount to a temporal study of the PTSI. Second, the street network derived from the road centerline is used to measure service area, and this may amplify the actual value for a given population group within a pre-setting threshold (e.g., 400 m for bus stops). Moura et al. (2017) conduct an assessment of walkability for district pedestrian groups from seven key dimensions: connectivity, convenience, comfort, conviviality, conspicuousness, coexistence, and commitment. The results show that nearly half of the pedestrian network in two observed districts of Lisbon is assessed by “adult” study participants to be “good”, while “senior” study participants assess the walkability of more than 60% of the identical network as only “fair” or “bad”. Depending on the street network, properly adjusting the distance threshold for measurement of service area is necessary with regard to different population groups and actual network quality. The transport demand in each SA is measured by an approximate indicator, which does not distinguish between demand from transport-dependent riders and latent demand. In fact, latent demand is an important factor influencing transport demand forecasting and policy making for transportation system expansion.

Future research will examine and classify latent demand from seniors based on the framework proposed by Clifton and Moura (2017), and will explore how to attract this kind of demand by improving public transport services.

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Chapter 5: ASSESSING ACCESSIBILITY-BASED SERVICE EFFECTIVENESS (ABSEV) AND SOCIAL EQUITY FOR URBAN BUS TRANSIT: A SUSTAINABILITY PERSPECTIVE[5]

5.1 Introduction

Transit systems are incorporated as one of the most important components in urban infrastructure, which have profound effects on the dynamics and morphology of neighborhood expansion and, in turn, on sustainable and resilient urbanization. Hence, the topic related to transit performance has become a widespread concern in academic circles. According to various research objectives, the literature on bus transit performance can be divided into two main categories: bus routes and transit systems. As for the former, scholars primarily focus on route spatial distribution, performance evaluation, and route planning optimization from a local perspective (Barnum et al. 2008, Güner and Coşkun 2016, Sun et al. 2016, Hahn et al. 2017). As for the latter, bus transit is regarded as an entire system in order to measure its performance and provide potential improvements (Fielding et al. 1985, Odeck 2008, Chiu et al. 2011, Ayadi and Hammami 2015). Regardless of category, transit performance measurement aims to systematically assess the level to which transit services are being delivered to a community, which is represented by the measurements of efficiency and effectiveness (Hatry 1980, Fielding et al. 1985, Daraio et al. 2016). Efficiency, or in other words, "do things right", is measured by the ratio of produced outputs (i.e., transit supply) to required inputs (e.g., labor, vehicle, and capital), that is, production efficiency (PE), while effectiveness, or, "do the right things", describes the impacts and quality of a service, whether goals are being met, and how to response to community needs

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(Hatry 1980, Fielding et al. 1985). In terms of bus transit, the effectiveness can be further divided into Service effectiveness (SEV) (i.e., the ratio of consumed outputs to produced outputs) and operational effectiveness (OEV) (i.e., the combination of PE and SEV) (Yu and Fan 2009, Yu et al. 2016). By comparison, PE is used to measure efficiency from the perspective of service providers, such as transit agencies; SEV primarily explores service utilization, service quality, revenue generation, and accessibility of service (Fielding et al. 1985), which can involve multiple stakeholders, such as transit riders, and directly reveal attractiveness and development potential of transit services on a societal level.

5.1.1 Performance measurement method

Due to the lack of standard criteria, it is difficult to assess the performance of a bus transit system or bus route using a single evaluation indicator (Sun et al. 2016). To aggregate multiple inputs and outputs, stochastic frontier analysis (SFA) and data envelopment analysis (DEA) are the primary methods applied in performance measurement of bus transit (Daraio et al. 2016). SFA is a parametric function existing between the inputs and outputs (Battese and Coelli 1995), while DEA is a non-parametric approach for comparing the inputs and outputs of a set of homogenous decision making units (DMUs) by evaluating their relative efficiency (Charnes et al. 1978). Since SFA requires assumptions for a pre-designed functional form of the production frontier and assumptions for specific statistical distribution of error terms, DEA is more widely-used in bus transit performance measurement (Daraio et al. 2016). In the context of the present research, the conventional DEA models proposed by Charnes et al. (1978) and Banker et al. (1984) provide the basis for studies of bus transit performance (Barnum et al. 2008, Odeck 2008, Sun et al. 2010, Ayadi and Hammami 2015, Güner and Coşkun 2016). With the further development of the efficiency evaluation approach, some advanced DEA models have emerged to satisfy different research purposes in the analysis of bus transit performance such as a network DEA model that involves two entities (i.e., operator and passenger), using operator-oriented outputs as inputs for the passenger entity in order to measure the efficiency of bus firms (Hahn et al. 2013); a modified value-chains DEA model that incorporates undesirable intermediates, intermediate input, uncontrollable input, and undesirable output in order to assess transit and economic efficiencies (Chiu et al. 2011); and a parallel slack-based measure DEA model for evaluating the overall efficiency of the land transportation sector and individual efficiencies of its subsectors (Liu et al. 2017). In summary, current research on bus transit services primarily focuses on assessing PE or OEV (with most of these studies considering holistic OEV, although several divide OEV into PE and SEV). Meanwhile, the inputs and outputs selected for the DEA model are diverse in PE and OEV measurement due to the wide range of evaluation objects, such as transportation terminals (Sun et al. 2010), bus routes (Barnum et al. 2008, Güner and Coşkun 2016, Sun et al. 2016), and transit firms (Odeck 2008, Hahn et al. 2013, Ayadi and Hammami 2015, Yu et al. 2016). Hence, these studies typically approach performance analysis primarily from a micro perspective, while not considering transit performance within or across regions. Moreover, few studies explore SEV assessment for bus transit by means of DEA, the result being that they lack a reference point for selecting the inputs and outputs as well as the type of the DEA model when establishing the effectiveness measurement model. Furthermore, there is no firm consensus as to the process for selecting inputs and outputs when assessing the performance of bus transit (Odeck 2008).

5.1.2 SEV from the accessibility perspective

As for SEV, the meaning of effectiveness varies widely; available goal and objective statements are a major source for deriving measures of effectiveness (Hatry 1980). To date, strengthening the competitiveness of public transit remains the primary and urgent task of urban transportation development, especially in cases where transit services are compared with privately owned vehicles (El-Geneidy et al. 2009, Sun et al. 2016). Statistics demonstrate that in Canada, 80% of all employees aged 15 years and over commute by automobile, while only 12% prefer public transit (Statistics Canada 2011). In fact, a potential savings of 30% in carbon dioxide emissions of a household can be achieved by eliminating the daily use of one car and replacing it with public transit (Science Applications International Corporation 2007). Hence, revitalizing the role of public transit systems has the potential benefit of creating sustainable urban mobility, given that it can lower energy consumption and carbon emission as well as ease traffic congestion, injuries and noise (Kwan and Hashim 2016, Addanki and Venkataraman 2017, Liu et al. 2017, Sun et al. 2018), further providing a more environmentally-focused and healthier activity pattern for society. In terms of such challenges, transit agencies need to offer competitive services, while the basic premise of achieving this goal is that the distribution of transit supply can attract more transit riders due to the level of convenience when choosing this mode of travel. Accessibility, which is generally understood as the ease with which people can reach desired destinations (Hansen 1959), can be properly used to measure the effectiveness of transit services under the existing transit supply. Furthermore, accessibility is proven to be a relevant indicator of sustainable urban transportation (Addanki and Venkataraman 2017) and social inclusion (Lucas 2012, Castanho et al. 2017). Enhancing accessibility by means of public transit involves the potential to improve transit services and satisfy more individual needs of citizens while mitigating their dependence on automobiles and enhancing transit ridership (Handy 2002, Manout and Bouzouina 2018), which will create a win-win situation for both transit agencies and transit riders. Accessibility by public transit has been investigated in numerous studies (Geurs and van Wee 2004, Foth et al. 2013, Fransen et al. 2015, El-Geneidy et al. 2016, Manout and Bouzouina 2018), but few of these have measured the SEV of bus transit from the accessibility perspective, let alone addressing the selection of inputs and outputs for the DEA model.

5.1.3 Social equity in sustainable development

Sustainability in public transit infrastructure needs to balance environmental protection, economic development, and social benefits, a task which involves accommodating various stakeholders with different priorities and values (Karatas and El-Rayes 2015, Nadafianshahamabadi et al. 2017, Naganathan and Chong 2017). Compared with the first two aspects (i.e., environment and economy), social sustainability, especially in relation to social equity, has garnered relatively little attention in academia and has proven difficult to incorporate into practice (Lizarralde et al. 2015, Trudeau 2018). Social equity advocates for the equal distribution of resources, benefits, and services among individuals or socially disadvantaged groups (SDGs). Here, SDGs refer to those who are lack of access to resources and services compared with the remaining of society at large (Townsend et al. 1988), such as the elderly, children, the unemployed, and people with low incomes. Furthermore, social equity has been incorporated as a long-term objective into urban transportation plans in order to ensure that all residents benefit from similar levels of accessibility, reduce adverse effects of uneven distribution of public transit on SDGs, and enhance their social inclusion (Jones and Lucas 2012, Lucas 2012). Accessibility as a critical indicator can be used to quantitatively evaluate service distribution in a region based on social equity (Foth et al. 2013). However, how SDGs benefit from SEV of bus transit and the comparison of SDGs to other population groups are matters that have rarely been explored in the literature.

5.1.4 Research objective

To address the abovementioned research gaps, the objective of this chapter is to propose a systematic methodology for measuring the SEV of urban bus transit from the accessibility perspective and analyzing social equity in SEV among various population groups including SDGs from a sustainability perspective. Specifically, accessibility-based service effectiveness (ABSEV) is proposed as a means by which to investigate the ratio of accessibility available to transit riders to the existing bus transit supply. The proposed indicator is capable of integrating two stakeholders—service providers and transit riders. Performance benchmarks are then formed based on the ABSEV assessment among regions in order to help maintain and improve the SEV of bus transit. The benefits that various population groups in regions receive from the SEV are analyzed and compared in consideration of social equity. The proposed methodology provides helpful tools for researchers and practitioners to differentiate between the ABSEV of bus transit for various regions and balance its attractiveness and convenience for various population groups, providing a reference for future policy-making pertaining to urban transportation sustainable planning and development.

The structure of the remainder of this chapter is as follows. Section 5.2 introduces a methodology for the ABSEV assessment of bus transit and social equity analysis. The methods mentioned above are used to analyze the ABSEV and its distribution among the total and senior populations in a case study of Edmonton, Canada in Section 5.3. The final section presents a discussion and conclusion based on the findings of the research.

5.2 Methodology

This study aims to assess the ABSEV of urban bus transit and compare SEV distribution in consideration of social equity at the Census tract (CT) level. The research methodology illustrated in Figure 5-1 consists of three key parts: (1) establishing input and output indicators for urban bus transit services; (2) assessing and visualizing ABSEV among CTs using the cumulative opportunity measure and DEA in support of the geographic information system (GIS); and (3) investigating distribution of SEV among various population groups including SDGs with Lorenz curves and Gini coefficients (GCs). This methodology can be applied to other countries for exploring the ABSEV of bus transit and social equity in transit services from the spatial and regional perspectives.

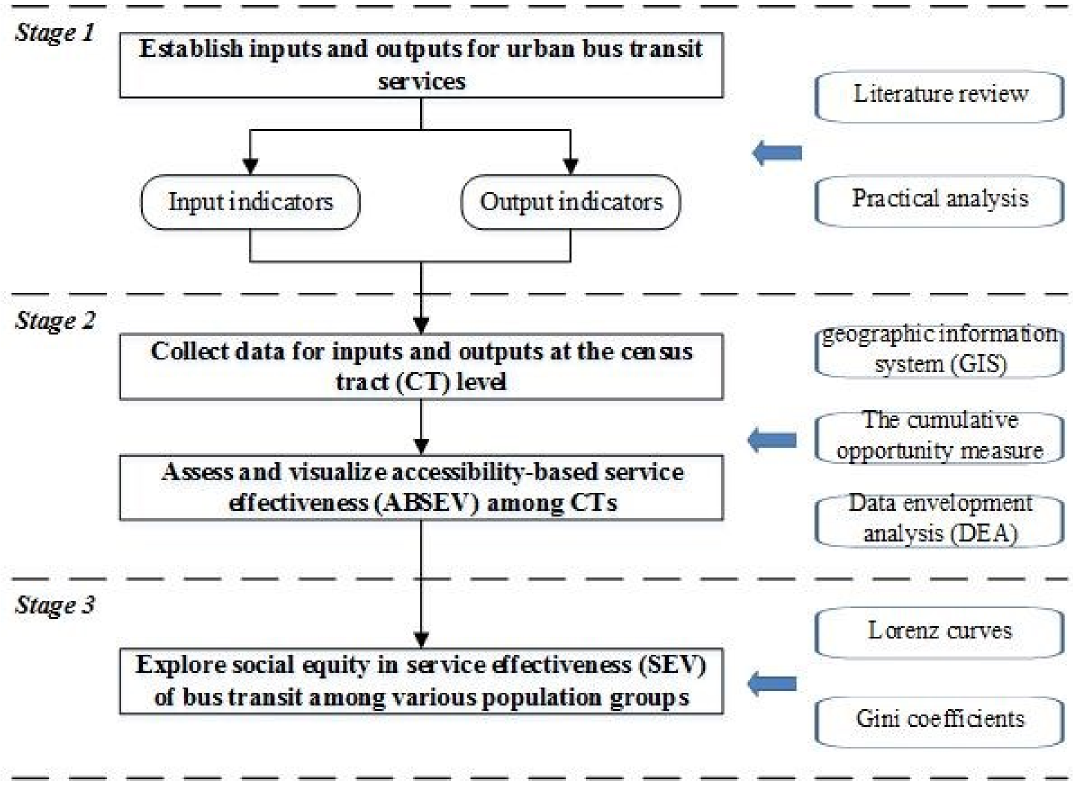


Figure 5-1. Methodological framework.

5.2.1 Design of inputs and outputs

As previously defined, the ABSEV of bus transit in the present study refers to the ratio of accessibility that transit riders have to the existing bus transit supply. Hence, the input indicators are bus transit supply while the output indicators are service accessibility. The description and calculation of all relevant indicators are introduced in detail as follows.

5.2.1.1 Input indicators

Current studies for assessing transit supply are relatively limited, and the indicators used vary due to differing research objectives and perspectives. Currie (2004) developed a public transit network model to evaluate transit supply across the network using generalized costs. The modeling process includes trip purpose definition; the building of a transit model involving routes, access and egress times, frequencies, travel times, and fares; and the generation of a travel cost matrix for various trip purposes. Currie (2010) adopted a supply index representing a relative service level, which combines service frequency, service area and total area. This approach has been employed by several researchers to investigate transit supply among various population groups distinguished by age, income, and vehicle ownership (Delbosc and Currie 2011, Ricciardi et al. 2015). Jaramillo et al. (2012) proposed two indices for public transit supply: the absolute index indicates the ratio of the total sum of stops by available transit modes for a district weighted by vehicle capacity and service frequency to the total area of the district; the relative index is expressed as the absolute index divided by the population in the district. The above established supply indicators serve as aggregated indicators integrating two or more aspects (i.e., the variables) in order to describe transit services. It should be noted that the majority of these variables under consideration refer to the physical attributes of public transit. In the present study, the four input indicators are selected to individually describe the overall status of bus transit supply from the physical perspective, that is, service area ratio, service density, service frequency, and route diversity. Of these, service area ratio and service density describe the service coverage of bus transit, while service frequency and route diversity depict the service level of bus transit.

- *Service area ratio*

Bus transit service area is a basic and important index to measure spatial coverage of transit services (or system availability) in a given region (Currie 2010, Delbosc and Currie 2011, Ricciardi et al. 2015). The greater the service coverage is over the total area of a given region, the more potential riders the bus transit can serve. Hence, service area ratio as an input indicator is expressed as

$$SAR_i = SA_i / TA_i \tag{5-1}$$

where SAR_i represents the service area ratio of CT i; SA_i represents the service area of CT i; and TA_i is the total area of CT i.

As for bus transit systems, the service area of each bus stop refers to the area surrounding the stop within a distance threshold. Previous studies have applied walk buffers to generate this amount of service area, with 400 m used as the walking access threshold for bus stops (Currie 2010, Delbosc and Currie 2011, Ricciardi et al. 2015, Habibian and Hosseinzadeh 2018), but the accuracy of this method is compromised since it fails to consider the actual street network distribution. To address this shortcoming, network analysis in GIS is used to measure service areas for all bus stops (i.e., SA_i) based on the street network. Since walking access by distance is used as the metric to measure service area for bus stops based on the geographical distribution of the street network, to some extent this approach could ignore the influence of the street hierarchy that divides streets in a city into different levels based on function and traffic capacity. It should be noted that overlaps in service area, such as for two nearby bus stops, are only counted once. An illustration of service area calculation is provided in Figure 5-2.

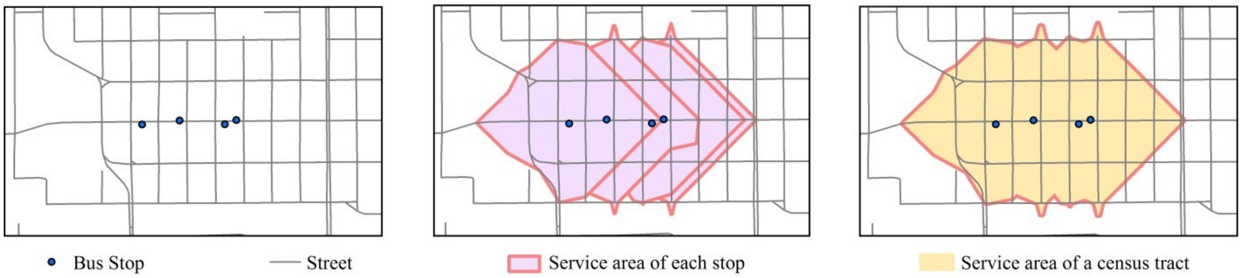


Figure 5-2. An illustration of service area calculation.

- *Service density*

Eq. (5-1) only describes the proportion of service area available for bus transit, but it cannot distinguish bus stop density of CTs, especially when the service area ratio of two CTs is identical. A higher density of bus stops tends to increase transit accessibility to riders (El-Geneidy et al. 2006). Hence, service density as another input indicator is selected to represent the choice diversity available to transit riders within a given area of service coverage.

$$SD_i = \frac{\sum_{j=1}^{n} BS_{ij}}{SA_i} \tag{5-2}$$

where SD_i represents the service density of CT i; BS_{ij} refers to bus stop j in CT i; and SA_i is as defined in Eq. (5-1).

- *Service frequency*

In addition to service coverage, service frequency is another indicator accounting for the importance of public transit stops within the overall transit network and capturing its influence on social quality of life (Fransen et al. 2015, Karatas and El-Rayes 2015). This indicator has been considered as a component of transit supply in many studies (Currie 2010, Delbosc and Currie 2011, Jaramillo et al. 2012, Ricciardi et al. 2015). Hence, service frequency of bus transit is selected as an input indicator in the present research, expressed as

$$SF_i = \sum_{d=1}^{7} \sum_{j=1}^{n} BA_{ijd} \tag{5-3}$$

where SF_i represents the service frequency of CT i; BA_{ijd} represents the number of bus arrivals for bus stop j in CT i on day d; and $d = 1,2,...,7$ (i.e., one week) is selected as the time interval.

- *Route diversity*

Stops are geographically-independent in the bus transit system, while transit routes are the medium from which stops draw connectivity. If there are more routes spanning the full breadth of a given region, there will be more access opportunities available to transit riders and a more dynamic and robust bus transit system. Hence, route diversity of bus transit is selected as an input indicator in the present research, expressed as

$$RD_i = \sum_{k=1}^{m} R_{ik} \tag{5-4}$$

where RD_i represents the route diversity of CT i; and R_{ik} represents route k in CT i.

5.2.1.2 Output indicators

Accessibility is generally defined as potential opportunities for interaction (Hansen 1959). If public transportation resources are distributed equitably within a region, transit riders can have various travel options and more opportunities to access desirable destinations (El-Geneidy et al. 2016). For accessibility measurement, the cumulative opportunity measure and the gravity-based measure are two widely-used methods. The former considers accessibility primarily from the transportation perspective, while the latter focuses more on land use (Geurs and van Wee 2004). Hence, the cumulative opportunity measure is used as the approach for measuring accessibility in the present study. Basically, the function of this measure is to quantify the number of opportunities reachable within a specified transportation impedance from a given origin by means of a particular travel mode (Handy and Niemeier 1997, Geurs and van Wee 2004). As such, all potential destinations within the transportation impedance are treated equally. A general form for the cumulative opportunity measure is expressed as

$$A_i = \sum_{j=1}^{n} O_j f(C_{ij}) \tag{5-5}$$

where A_i is a measure of accessibility in zone i to all opportunities in other zones $(j = 1, 2, ..., n)$; O_j is the number of opportunities in zone j ; C_{ij} is the transportation impedance by time, distance, or cost from zone i to zone j ; and $f(C_{ij})$ is the impedance function. If C_{ij} is within a specified transportation impedance that is selected empirically as a threshold, $f(C_{ij})$ is equal to 1; otherwise, $f(C_{ij})$ is equal to 0.

In addition to the significant role of accessibility in public transportation as described in the introduction, accessibility also serves as an indicator of the ability of a given public transit network to effectively transport individuals from the boarding location to the alighting location within a reasonable travel time, and further encompasses the operational functionality of a transit system for regional travel (Murray et al. 1998). Improving accessibility for the existing infrastructure in underperforming CTs can thus provide cohesion and support in order to achieve a better-balanced jurisdiction on a regional scale (Castanho et al. 2017). In the present study, service accessibility as the primary output of bus transit is ascertained by measuring accessibility within and across the CTs of a city. Here, accessibility within a CT refers to access to bus stops within a specified travel time threshold, where greater accessibility refers to greater potential for riders to reach destinations near the alighting locations. By contrast, accessibility across CTs emphasizes the convenience of regional communication and interaction within a city. In other words, this metric demonstrates the diversity of a CT accessing opportunities for other CTs within a specified travel time threshold. The cumulative opportunity measure has been used to investigate accessibility to jobs or various service types by transit across different SAs—including CTs—where the centroids of these SAs are selected as points of origin (or destination) (Foth et al. 2013, Fransen et al. 2015, El-Geneidy et al. 2016). Based on the above, the cumulative opportunity measure is utilized in the present research to quantify the two output indicators (i.e., accessibility within and across CTs) for the purpose of assessing the ABSEV of bus transit.

- *Accessibility within CTs*

$$A_1^i = \sum_{j=1}^{n} f(T_{ij}) \text{ with } f(T_{ij}) = \begin{cases} 1 & \text{if } T_{ij} \le T_1^* \\ 0 & \text{if } T_{ij} > T_1^* \end{cases} \tag{5-6}$$

where A_1^i represents the accessibility within CT i; $f(T_{ij})$ represents the impedance function with T_{ij} being the time of travel from the centroid of CT i to bus stop j within this CT; and T_1^* indicates the travel time threshold within a CT.

- *Accessibility across CTs*

$$A_2^i = \sum_{l=1, l \ne i}^{N} f(T_{il}) \text{ with } f(T_{il}) = \begin{cases} 1 & \text{if } T_{il} \le T_2^* \\ 0 & \text{if } T_{il} > T_2^* \end{cases} \tag{5-7}$$

where A_2^i represents the accessibility from CT i to other CTs; $f(T_{il})$ represents an impedance function with T_{il} being the time of travel from the centroid of CT i to the centroid of CT l; and T_2^* refers to the travel time threshold across CTs.

5.2.2 DEA model

DEA as a non-parametric approach does not require the rigid assumptions associated with SFA, and it offers the following advantages: (1) it is flexible to select inputs/outputs for efficiency measures and can easily interpret corresponding scores (Banker and Morey 1986); (2) it provides a comprehensive measure of DMU efficiency, which is the ratio of the aggregated, weighted outputs to the aggregated, weighted inputs (Barnum et al. 2008); (3) it is uniquely equipped to achieve the goal for generating an overall, objective, and summary performance indicator (Chu et al. 1992); and (4) it is more useful for stakeholders and policy makers who require quantitative data about the relative performance of the DMUs (Suzuki et al. 2010), as this method can identify all DMUs of efficiency and inefficiency necessary to create a benchmarking standard for performance improvement. However, DEA also has shortcomings since it traditionally treats DMUs as black boxes with consumed inputs and produced outputs, which hinders the identification of sources of inefficiency in the DMUs (Avkiran 2009). Notwithstanding these shortcomings, DEA as a dimensionless and comparative evaluation method has been widely used for bus transit performance measurement and benchmarking in transportation (Barnum et al. 2008, Odeck 2008, Sun et al. 2010, Ayadi and Hammami 2015, Daraio et al. 2016, Güner and Coşkun 2016). Therefore, the conventional DEA model is selected as the basis model by which to assess the ABSEV of urban bus transit, given that it is a widely-used model in bus transit performance evaluation and is well-aligned with the research objectives of the present research.

The two most frequently-used conventional DEA models are the CCR model (Charnes et al. 1978) and the BCC model (Banker et al. 1984). The CCR model corresponds to the hypothesis of constant returns to scale (CRS) for efficient frontier, while the BCC model assumes the variable returns to scale (VRS). In other words, the BCC model eliminates the influences of scale factors and represents operation and management levels of the assessed DMUs more accurately. Further, the BCC model divides technical efficiency (TE) into pure technical efficiency (PTE) and scale efficiency (SE), that is, PTE = TE/SE. Assuming there are n DMUs, and each DMU has m inputs and s outputs, the efficiency value of each specific DMU can be calclulated by the BCC model, as shown in Eq. (5-8). In this study, the DMUs in the BCC model refer to various CTs in a given city. Furthermore, m and s are equal to 4 and 2, respectively, according to the inputs and outputs selected for assessing the ABSEV of bus transit.

$$\begin{aligned} & Min\ \theta \\ & s.t.\ \sum_{i=1}^{n} X_i\lambda_i + s^- = \theta X_0 \\ & \sum_{i=1}^{n} Y_i\lambda_i - s^+ = Y_0 \\ & \sum_{i=1}^{n} \lambda_i = 1, \lambda_i \geq 0 \\ & s^+ \geq 0, s^- \geq 0 \end{aligned} \tag{5-8}$$

where $X_i = (x_{i1}, x_{i2}, ..., x_{im})^T$ represents the input vector of DMU i ; $Y_i = (y_{i1}, y_{i2}, ..., y_{is})^T$ represents the output vector of DMU i ; λ_i represents the weight of DMU i ; s^- and s^+ repesent slacks regarding the inputs and outputs, respectively; and θ represents the PTE, and its value belongs to [0, 1]. If the value of θ is closer to 1, the higher the PTE will be; $\theta = 1$ indicates this DMU is efficient; otherwise, this DMU is inefficient.

In addition, the input-oriented model and the output-oriented model are available for estimating the efficiency frontier with the DEA model, where the former focuses on the minimum amount of inputs under the assumption that the outputs are constant, and the latter aims to maximize outputs from a given level of inputs. The input-oriented model is more suitable for the efficiency analysis when the inputs of DMUs can be adjusted (Lovell 1993). As for bus transit systems, the outputs (i.e., accessibility within and across CTs) can be improved by adjusting and controlling the inputs (i.e., service area ratio, service density, service frequency, and route diversity). Therefore, the input-oriented BCC model is selected to measure the ABSEV of bus transit at the CT level after collecting data for the inputs and outputs of transit services. Thus, if the value of PTE is equal to 1, the ABSEV of this CT is identified to be effective, which indicates its performance relative to other CTs cannot be improved; otherwise, ineffective CTs have ABSEV values of less than 1.

5.2.3 Social equity analysis

Social equity advocates for the equal distribution of resources, benefits, and services among individuals within a total population or among SDGs such as the elderly. This concept is aligned with the principle of Lorenz curves. Lorenz curves, having been extensively applied to economics, graphically display the cumulative distribution functions of wealth across a population (Lorenz 1905). To date, some scholars have used this method to assess equity in public transit among various social groups in terms of transit supply (Delbosc and Currie 2011, Ricciardi et al. 2015). Based on this, the present study employs Lorenz curves to quantify inequality in ABSEV of bus transit across various population groups. First, all regions are sorted in ascending order, according to the values of ABSEV. Then, the cumulative percentage of population is represented as the horizontal axis, while the cumulative percentage of ABSEV is represented as the vertical axis; (for an illustrated example the reader may refer to Figure 5-3). If the ABSEV of bus transit is distributed equally among individuals in a population group, Lorenz curves are plotted as diagonal lines; otherwise, Lorenz curves are under the diagonal, which indicates the distribution is inequity in a population group. Furthermore, the distribution of

ABSEV of bus transit has a higher degree of inequality among this population group if the Lorenz curve is farther from the diagonal.

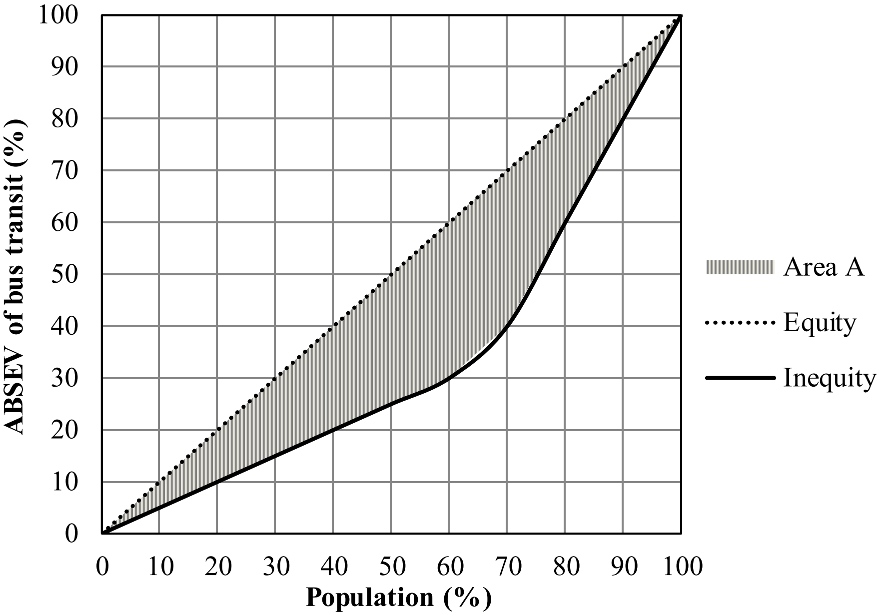


Figure 5-3. Example Lorenz curve.

Compared with Lorenz curves, the GC is a relative indicator to mathematically depict the degree of inequality. Assuming area A is the area between the diagonal line and the Lorenz curve (see Figure 5-3), and area B is the total area under the diagonal line (i.e., the area value is 0.5), the GC is expressed as the proportion of area A to area B (Gini 1912).

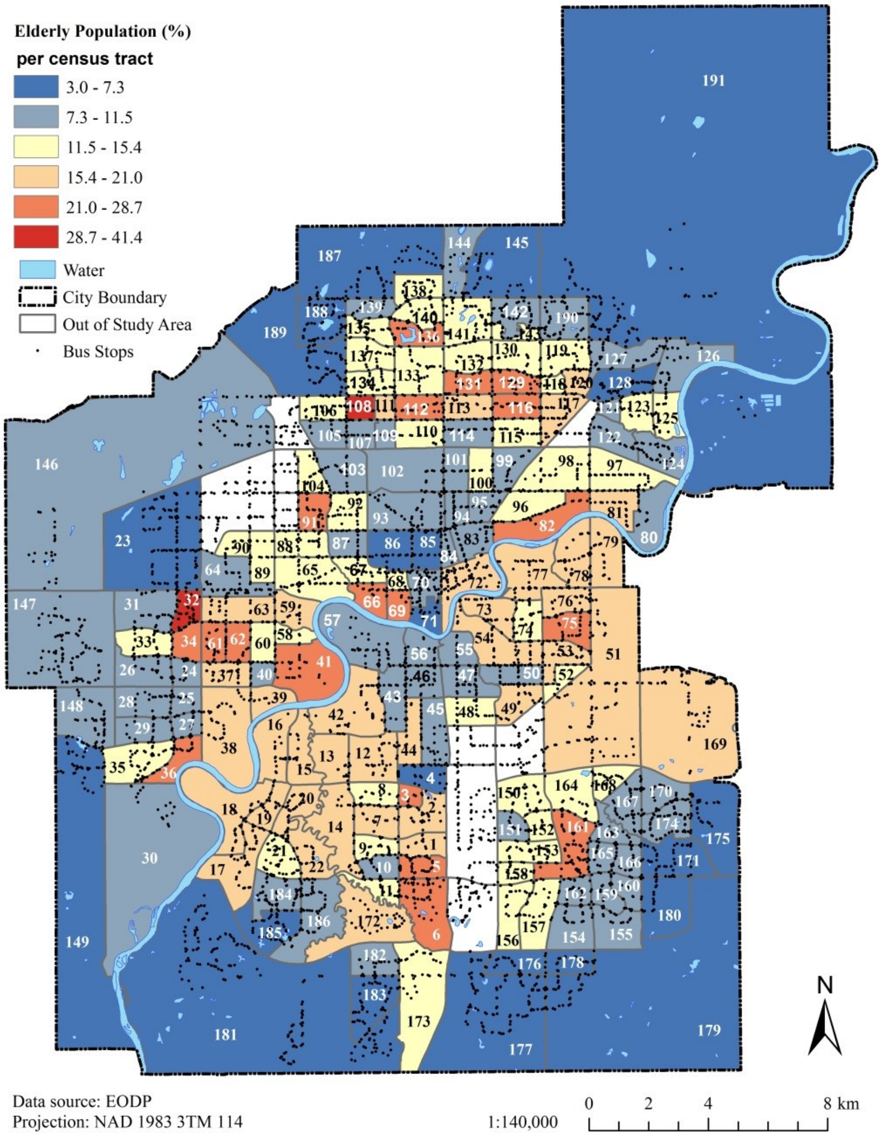
$$G = S_A / S_B \tag{5-9}$$

where S_A and S_B represent area A and area B, respectively. The GC varies between 0 and 1: (a) if $G = 0$, the distribution of ABSEV is equal among the population group; (b) if $G = 1$, the distribution of ABSEV is perfect inequity; (c) if $0 < G < 1$ and closer to 0, then the ABSEV distribution tends to be uniform; and (d) if $0 < G < 1$ and closer to 1, this denotes greater differences in the ABSEV distribution.

5.3 Case Study

5.3.1 Study area

Edmonton, Canada's fifth-most-populous city, is selected as the study area, with a large population of approximately 932,500 inhabitants in an area of 700 km^2 (Statistics Canada 2017b). The bus transit system in this city is operated by a public agency, and the regional distribution of bus stops in the transit system is presented in Figure 5-4. Population ageing is emerging as an unprecedented demographic challenge in many countries, a phenomenon now exerting a significant influence on age structure and resource distribution (Chen et al. 2018c). In this context, it is incumbent upon government-centered institutions and agencies in these countries to take proactive measures to offset the negative effects of population ageing and enhance social resilience (Peng et al. 2017). Within this context, Prof. Bernard Isaacs has offered a useful maxim for urban development: "Design for the young and you exclude the old. Design for the old and you include everyone". In this spirit, in the present study bus transit is regarded as an urban public service that is important to seniors, since this transportation mode is positively associated with enhanced quality of life, particularly for ageing societies (Kim and Ulfarsson 2013). Although all population groups can make use of existing transit resources, seniors tend to prefer this public transportation mode and use it more often than do younger people (Cao et al. 2010). Unfortunately, in countries with ageing populations at present, typically the availability of public transit resources is insufficient to meet the needs of the senior population (Gaber and Gaber 2002). Furthermore, compared with other SDGs, relatively few investigations have focused on seniors in assessing the social equity of bus transit services (Currie 2004, 2010, Fransen et al. 2015, Ricciardi et al. 2015). As a result, in the present study the senior is selected as an example for the SDG in the social equity analysis of ABSEV of Edmonton's bus transit system. Practitioners and researchers could select other SDGs (e.g., the unemployed, people with low incomes) based on the given study objectives and data availability.



Data source: EODP
Projection: NAD 1983 3TM 114

Figure 5-4. Bus transit system and elderly population distribution in Edmonton.

5.3.2 Data description

Three main data sources are used in the present research at the CT level: (1) demographic CT information by ages and locations of bus stops from the City of Edmonton’s Open Data Portal (EODP 2017). The city is composed of 200 CTs; however, only 191 CTs are selected as the region units in this analysis given that the population of each of the remaining CTs is less than 20 people or the presence of seniors in these CTs is statistically marginal. If using the relevant data of the excluded CTs, it can cause significant bias in the research results. Figure 5-4 also displays the serial numbers of all selected CTs and the percentages of seniors in the total population for each CT. Here, seniors are defined as the segment of the population aged 65 or over; and the percentage values of the senior population in all observed CTs are divided into six classes by means of the natural breaks classification method after analyzing the data's statistical distribution. (2) the street network from the Government of Canada's Open Data (GCOD 2015); and (3) September–November 2017 General Transit Feed Specification (GTFS) data for the Edmonton transit system from Transit Feeds (2017). In Edmonton, residents tend to participate actively in outdoor activities during the summer (i.e., June−August) but are less eager to do so in the other seasons due to the cold weather. As a result, the city's transit agency is particularly attentive to bus transit performance during the non-summer months. Edmonton's fall season (i.e., September–November) is thus selected as the observed period since its average snowfall volume is minimal in comparison with the winter and spring, while the bus transit schedule has by this time reverted to its regular service hours with summer coming to a close and a new school year beginning.

According to the three data sources, the data is collected for four input indicators and two output indicators in support of GIS, which lays a foundation for assessing the ABSEV of bus transit. Data of the service area, total area, and total number of bus stops in each CT can be gathered using street network analysis, the geometry calculation function, and the spatial join function in GIS based on bus stop distribution in all observed CTs. Using Eq. (5-1) and Eq. (5-2), two inputs—the service area ratio and service density in each region can then be determined. In terms of the other two inputs, service frequency and route diversity, the data can be derived from the bus transit schedule based on GTFS data using Eq. (5-3) and Eq. (5-4), respectively. In the process, two tools are installed in GIS—Display GIFS in ArcGIS and BetterBusBuffers, developed by (Morang 2018b, 2018c). As for accessibility within and across CTs, a routable network is first created in GIS using tools developed by (Morang 2018a) (i.e., add GTFS to a network dataset). Based on this created network, network analysis in GIS is used to measure the travel time from the centroid of a CT to each stop within this CT and measure the travel time from the centroid of a CT to the centroids of the other CTs severally. Sixty minutes is selected as the travel time threshold for T_1^* and T_2^* in Eq. (5-6) and Eq. (5-7), respectively (Fransen et al. 2015, El-Geneidy et al. 2016), in order to quantify the opportunities for bus stops within a CT and the opportunities for other CTs. Considering that the frequency of bus transit is diverse during the operation period of a given day, a time interval (i.e., 10 min) is used to obtain the above two types of opportunities. As such, the means of these opportunities by type among all time intervals describe the accessibility within and across CTs.

5.3.3 Statistical analysis of inputs and outputs

In order to clearly grasp the data underlying these indicators for assessing the ABSEV of bus transit, Table 5-1 provides the basic statistical features of inputs and outputs from all observed CTs.

Table 5-1. Descriptive statistics.

Variable	Max.	Min.	Mean	Standard Deviation (SD)	Coefficient of variation (CV)
Inputs					
Service area ratio	1.000	0.045	0.739	0.224	0.303

Service density	50.583	11.623	22.205	6.271	0.282
Service frequency	69,923	785	11,411.257	8,751.923	0.767
Route diversity	64	1	20.675	11.975	0.579
Outputs					
Accessibility within CTs	115	4	30.812	17.581	0.571
Accessibility among CTs	31	0	17.031	7.231	0.430

Note: CV is the ratio of SD to the mean as for each variable.

From the above table, the results indicate that there are differences in indicators of bus transit services among CTs in this city, but the values of CV reveal diversity. Of them, a significant imbalance exists in the service frequency of all CTs, while regional gaps of service area ratio and service density are relatively minor. Specifically, nearly 74% of this city is supplied with available bus service areas, and eight CTs have a service area ratio equal to one, which are located in the center of the city and north of the river intersecting the city. Service areas in the CTs located in the surrounding areas of this city (i.e., No. 30, No. 179, and No. 191) are relatively insufficient and represent the lowest 3 values of service areas. CTs No. 70 and No. 72 occupy the largest service density and service frequency, respectively. Route diversity in CTs No. 24 and No. 161 is the most plentiful, while the surrounding CT, No. 176, only has one bus route. Within the selected time threshold, CT No. 113 can access the maximum number of other CTs, which accounts for 16% of the observed CTs. By contrast, CT No. 191 reveals a lack of access to other CTs during the limited time threshold, while the accessibility to bus stops in this CT is typical.

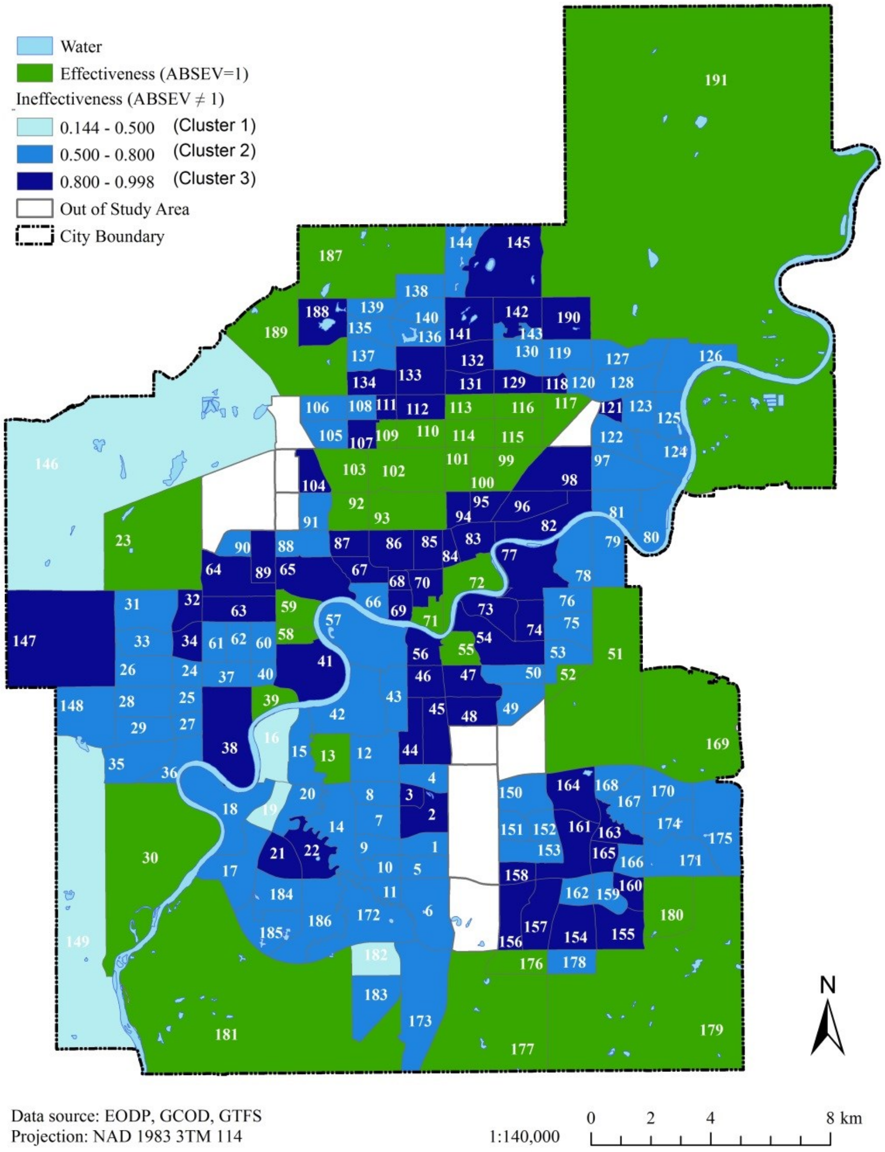
5.3.4 ABSEV assessment of bus transit

Since CT No. 191 has the minimal value of accessibility across CTs (i.e., “0” in Table 1), it violates the positivity requirement of the conventional DEA model, which is that the entries in the input vector X_i and in the output vector Y_i should be positive. Bowlin (1998) advised the substitution of a positive number smaller in magnitude than the other numbers in the dataset for any negative or zero value if the variable is an output. Thus, the value (0.01) is used to replace the original value (zero) for this DMU. Furthermore, the Pearson correlation test is conducted to analyze correlation between all inputs and outputs, respectively. No high correlations in the two indicator groups are found to be significant at the 0.01 level, since the maximum correlation coefficient is no more than 0.5. Based on this, all values of the variables in Eq. (5-8) can then be calculated according to the theory of the BCC DEA model. Table 5-2 lists the detailed results for ABSEV of bus transit in each CT, that is, θ, and Figure 5-5 illustrates the regional ABSEV results spatially.

Table 5-2. Comparison of regional ABSEV of bus transit.

No.	ABSEV	No.	ABSEV	No.	ABSEV	No.	ABSEV	No.	ABSEV	No.	ABSEV
1	0.768	33	0.687	65	0.982	97	0.658	129	0.938	161	0.941
2	0.868	34	0.87	66	0.733	98	0.987	130	0.754	162	0.743
3	0.828	35	0.667	67	0.864	99	1.000	131	0.960	163	0.804
4	0.749	36	0.652	68	0.877	100	1.000	132	0.969	164	0.899
5	0.693	37	0.721	69	0.878	101	1.000	133	0.992	165	0.823
6	0.647	38	0.918	70	0.986	102	1.000	134	0.826	166	0.728
7	0.703	39	1.000	71	1.000	103	1.000	135	0.674	167	0.703
8	0.703	40	0.721	72	1.000	104	0.867	136	0.601	168	0.640
9	0.783	41	0.852	73	0.887	105	0.668	137	0.791	169	1.000

10	0.644	42	0.546	74	0.956	106	0.670	138	0.575	170	0.622
11	0.567	43	0.767	75	0.574	107	0.919	139	0.650	171	0.755
12	0.773	44	0.924	76	0.558	108	0.784	140	0.691	172	0.620
13	1.000	45	0.923	77	0.826	109	1.000	141	0.830	173	0.676
14	0.741	46	0.848	78	0.633	110	1.000	142	0.816	174	0.691
15	0.581	47	0.814	79	0.539	111	0.871	143	0.686	175	0.770
16	0.356	48	0.895	80	0.755	112	0.928	144	0.506	176	1.000
17	0.540	49	0.707	81	0.574	113	1.000	145	0.918	177	1.000
18	0.672	50	0.712	82	0.998	114	1.000	146	0.437	178	0.622
19	0.485	51	1.000	83	0.970	115	1.000	147	0.937	179	1.000
20	0.569	52	1.000	84	0.888	116	1.000	148	0.548	180	1.000
21	0.811	53	0.748	85	0.927	117	1.000	149	0.144	181	1.000
22	0.872	54	0.852	86	0.985	118	0.938	150	0.777	182	0.452
23	1.000	55	1.000	87	0.951	119	0.784	151	0.744	183	0.564
24	0.683	56	0.949	88	0.786	120	0.743	152	0.733	184	0.630
25	0.675	57	0.744	89	0.885	121	0.826	153	0.799	185	0.620
26	0.625	58	1.000	90	0.705	122	0.796	154	0.811	186	0.613
27	0.679	59	1.000	91	0.771	123	0.756	155	0.910	187	1.000
28	0.609	60	0.680	92	1.000	124	0.755	156	0.983	188	0.951
29	0.525	61	0.767	93	1.000	125	0.588	157	0.860	189	1.000
30	1.000	62	0.750	94	0.895	126	0.532	158	0.885	190	0.886
31	0.620	63	0.821	95	0.860	127	0.722	159	0.710	191	1.000
32	0.846	64	0.872	96	0.983	128	0.752	160	0.859	Mean	0.800



Data source: EODP, GCOD, GTFS
Projection: NAD 1983 3TM 114

Figure 5-5. Spatial distribution of ABSEV of bus transit in Edmonton.

As illustrated in Figure 5-5, 34 CTs perform effectively in the ABSEV assessment of bus transit, which accounts for approximately 18% of the total CTs. Of the 34, 13 CTs are distributed in the surrounding areas of this city, forming an irregular circle around the city's perimeter. Notably, the geographical locations of some of the effective CTs are adjacent to one another; and the remaining CTs that perform effectively are concentrated in the city center, most of which are located north of the river. A common feature in these effective CTs is that the percentages of elderly people generally belong to the lowest class (see Figure 5-4), with the exception of the

CTs No. 51, No. 52, and No. 169. As for the CTs with ineffective ABSEV, three clusters are generated by setting break values (0.5 and 0.8), where 0.8 is the mean of ABSEV among all CTs. Only five CTs belongs to Cluster 1, scattering in the western region of this city, while the percentages of the elderly reveal diversity. Cluster 2 indicates the ABSEV is ineffective and under the average level of the whole city, but is greater than 0.5. This cluster includes nearly 47% of all CTs and the mean of these CTs is equal to 0.68. Their geographical distribution is primarily along the river and the coverage areas extend away from the river. The CTs in Cluster 3 perform ineffectively, accounting for 33% of the total CTs, but better than the remaining other ineffective CTs. Most of the CTs in Cluster 3 are adjacent to the neighboring CTs in Cluster 2 or the CTs with effective ABSEV, and the higher density for the CTs in Cluster 3 appears in the central area of the city.

5.3.5 Social equity in ABSEV of bus transit

Figure 5-5 only depicts ABSEV results among all CTs and their geographical distribution. It is difficult to clearly identify the relationship between the ABSEV of bus transit and the senior population and further make a comparison with ABSEV distribution among the total population in this city. Thus, Lorenz curves and GCs are used to achieve the above purposes, and the results of social equity are displayed in Figure 5-6.

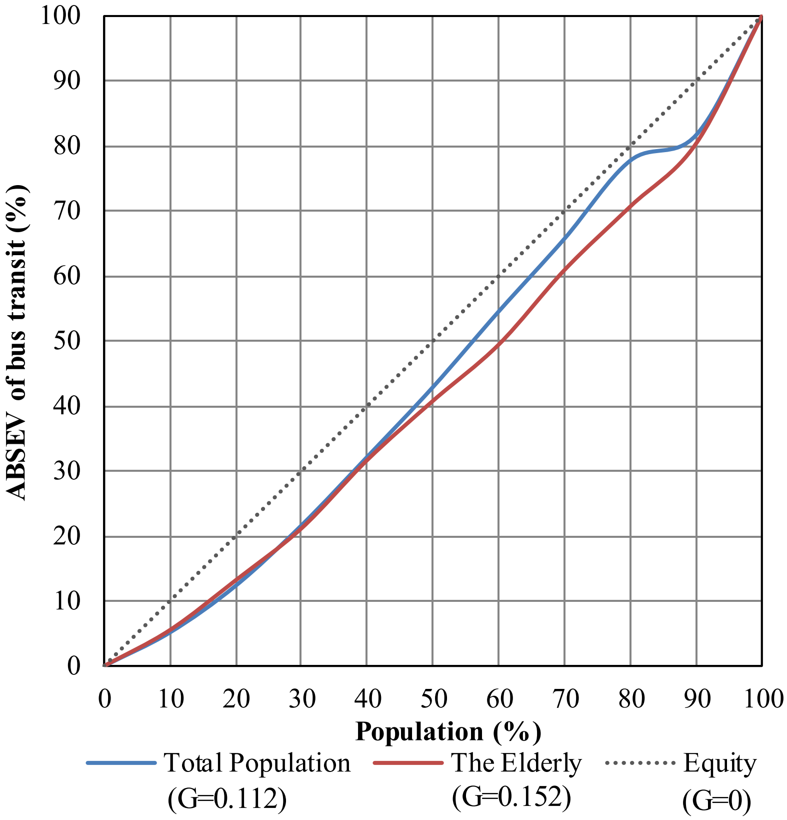


Figure 5-6. Social equity in ABSEV of bus transit.

It can be observed that both Lorenz curves for senior population and total population are under the diagonal, which indicates that the ABSEV of bus transit in various CTs is not identical among the two population groups. Although the degree of deviation from the diagonal is not significant, the GC (i.e., the value in the parentheses in Figure 5-6) of the elderly is slightly larger than that of the total population. Specifically, when the cumulative percentage of the population is smaller than 40% or the value is larger than 90%, the gaps between the two Lorenz curves are relatively small. This point reveals that the ABSEV of bus transit has similar distribution, which concentrates on the CTs with smaller or larger population for the two groups. The largest difference occurs when the cumulative percentage of population is near 80%. At this point, ABSEV of bus transit tends to be equitable to total population, while senior population has greater inequity in bus transit services.

5.4 Discussion and Conclusion

Public transit systems should not only satisfy the basic needs of sustainability in consideration of human and ecosystem health, energy consumption, and environmnetal pollution, but should also meet the criteria of accessibility, social equity, efficiency, and effectiveness (de Almeida Guimarães and Leal Junior 2017, Rao et al. 2018). Within this context, this chapter proposes a systematic methodology for assessing the ABSEV of urban bus transit and analyzing the SEV distribution among various population groups in consideration of social equity. The main contributions of this study include: (1) Determination of a set of quantitative input and output indicators that can help with evaluating the SEV of bus transit. The input indicators are derived from service coverage and service level, while the output indicators integrate accessibility measures within and across CTs during a time threshold, which helps planners to compare the accessibility of all CTs in a city from multiple perspectives. These indicators are practice-ready, providing a reference for practitioners and researchers to establish the SEV measurement model appropriate to their specific characteristics. (2) The BCC DEA model is used to assess the ABSEV of bus transit, which strengthens the theoretical basis of SEV assessment by means of DEA and extends accessibility studies from traditional measures to effectiveness analysis. The suggested method is simple and replicable and, furthermore, forms performance benchmarks for the ABSEV among the observed areas. (3) GIS technologies are incorporated in data collection and visualization for the ABSEV, which is beneficial for presenting spatial characteristics and regional differences. (4) The SEV distribution of bus transit is investigated among various population groups using Lorenz curves and GCs, which provides a helpful tool by which to explore social equity in ABSEV distribution, augment the benefits of bus transit to SDGs, and enhance sustainable development of urban bus transit systems.

The proposed methods are implemented in an empirical study of Edmonton's 191 CTs, which reveals diversity in all inputs and outputs of bus transit services. Nearly 74% of the CTs in the studied city are supplied with available bus service areas, and the regional gaps of service area ratio are relatively small. If the walkable distance threshold for bus stops is decreased, the service area will be reduced accordingly, which in turn will affect the population receiving transit services (Murray et al. 1998). By contrast, the distribution of service frequency among all CTs is significantly imbalanced. Some CTs feature limited bus routes or only possess several opportunities to other CTs during the specific time threshold. In terms of the ABSEV, 34 CTs perform effectively via bus transit, in which the percentages of seniors tend to be in the lowest class. Furthermore, most of these CTs are concentrated in the city center. The ineffective CTs with ABSEV values under 0.5 are scattered in the western region of this city, while the percentages of the elderly are diverse in these CTs. 47% of CTs distributed primarily along the river perform ineffectively, and their ABSEV measures from 0.5 to 0.8 (i.e., the average level). The remaining ineffective CTs, of which ABSEV exceeds the mean, account for 33% of the total CTs. The ABSEV of bus transit is not equally distributed among both senior population and total population, but the degree of inequality is not clear as the values of GCs do not exceed 0.5. By comparison, the elderly experience greater inequity in transit services than the total population, an observation which is in line with the findings of public transit equity analyses among various population groups as described by Ricciardi et al. (2015).

Based on the research results presented in this chapter, policy recommendations are provided for efficient services and sustainable development of urban bus transit systems. First, according to the established benchmarking for ABSEV, the SEV of bus transit in the ineffective CTs can be improved by reducing the inputs (i.e., four transit service supply indicators). The remedy for ineffective CTs is always against the minimization of capital and operating expenses. Hence, different scenarios need to be evaluated and compared in order to select the most proper one. Second, the improvement of ABSEV should also integrate the population distribution by type among regions in order to reduce the gap in transit equity for SDGs and total population. For instance, Alsnih and Hensher (2003) suggest that transit systems should focus more closely on understanding mobility and accessibility needs of seniors and ensure their specific requirements are not ignored.

There are also some limitations of the present study. First, the research object is restricted to urban bus transit, while other public transportation modes available, such as the subway system, is not considered. Hence, this approach is more applicable to urban areas where there is no subway system or where the subway system has a limited service area benefiting only a small segment of the population (e.g., Edmonton). By contrast, bus transit services within this context could spread to nearly all the divided regions such as CTs or neighborhoods, so the interference from other transportation modes could be ignored when using the proposed methods. Furthermore, there exists some vulnerability in the subway system to be considered including: (a) Physical vulnerability. The train is generally composed of a variety of subsystems (e.g., door system, body system, braking system, and bogie system), the failure of which may result in serious accident in daily operation (Deng et al. 2015). (b) Topology vulnerability. The subway network is of robustness against random attacks but fragile for malicious attacks, and the severest damage to the network is derived from the highest betweenness node-based attacks (Zhang et al. 2011). In future study, the proposed methodology could be extended in order to apply it to urban public transit systems in larger cities integrating bus and subway. For instance, for service area ratio calculated using Eq. (5-1), 400 m and 800 m can be used as the walking access thresholds for tram stops and train stations, respectively (Currie 2010, Delbosc and Currie 2011), and then the service area of this CT is yielded according to the principle in Figure 5-2. Second, accessibility measure across CTs using Eq. (5-7) selects the geometric centroid of each CT as the origin (or destination) with the special characteristics. To more accurately reflect accessibility between two CTs, future study can consider measuring all travel times from each bus stop in one CT to each stop in another CT, thereby yielding the average opportunities for stops in each CT within the time threshold. Third, the present study investigates the ABSEV of urban bus transit and its social equity from a descriptive analysis. Further studies are needed to generate a coordination mechanism for balancing regional ABSEV of bus transit, considering a tradeoff between the operation profit of transit services and its social benefits among various population groups.

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Chapter 6: A BI-LEVEL DECISION SUPPORT MODEL (BLDSM) FOR BUS ROUTE OPTIMIZATION AND ACCESSIBILITY IMPROVEMENT FOR SENIORS[6]

6.1 Introduction

Today, bus transit is considered a pivotal backbone of sustainable and resilient urbanization, thereby receiving considerable attention from both academia and industry (Chen et al. 2018b). As an economical transportation mode, bus transit in cities is also widely recognized as a potential means of energy conservation and carbon emission reduction, traffic congestion and accident mitigation, and social inclusion improvement (Chen et al. 2019). However, the actual performance of bus transit is not as operationally efficient or as user friendly as expected, leading to a mode shift towards private vehicles, which in turn decreases the daily usage of bus transit and triggers a negative effect on the city environment. Therefore, reinforcing the competitiveness and market share of bus transit continues to be the principal and critical task of urban transportation development (El-Geneidy et al. 2009, Sun et al. 2016). Basically, the efficiency of bus transit systems is derived from two primary parameters: route network and service frequency (Agrawal and Mathew 2004, Kepaptsoglou and Karlaftis 2009). Of them, route network determines the geographical distribution and service coverage of bus transit. In other words, more efficient distribution can facilitate better accessibility and greater convenience to transit users. Traditional route network planning primarily depends on the experience of designers and lacks consistency and reliability (Agrawal and Mathew 2004), which means it can at best only serve a certain percentage of city residents. To make up for this shortcoming, various approaches (broadly classified as analytical, heuristic, and nonconventional), have been proposed to plan and design bus route networks (Suh and Kim 1992, Chakroborty 2003, Agrawal and Mathew 2004,

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[6] A version of this chapter is under review for publication in *Journal of Computing in Civil Engineering*.

Fan and Machemehl 2006, Zhao and Zeng 2006, Kepaptsoglou and Karlaftis 2009, Blum and Mathew 2011, Almasi et al. 2015). However, the majority of these studies take the perspective of just one decision maker (i.e., transit agencies) in the decision-making environment and fail to sufficiently consider conflicting interests from various stakeholders (e.g., transit agencies and users).

Accessibility is generally defined as the ease with which people can arrive at a given destination by means of a given mode of transportation (Hansen 1959), and this is an important consideration in sustainable urban transportation and influences SEV of urban bus transit among transit users (Chen et al. 2019). To improve transit accessibility, routing spacing, operating headway, and stop spacing have been treated as decision variables in studies employing an analytic approach to minimize the total cost from suppliers and users for bus route optimization (Chien and Schonfeld 1997, Kuah and Perl 1998). Chien and Qin (2004) developed a mathematical model to optimize the number and locations of bus stops along a known segment route in order to minimize the total cost from suppliers and users. In their study, these two types of cost are calculated separately through a proposed iterative algorithm in order to obtain the minimal total cost. Some studies have also adopted the use of a genetic algorithm (GA) and an exhaustive search algorithm to optimize the location of a bus route, where the minimal objective is composed of supplier and user costs under the constraints of geography, capacity, and budget (Chien and Yang 2000, Chien et al. 2002). Various methods have been utilized in route optimization with the goal of improving transit accessibility. Although the identified problems in previous studies are diverse, transit suppliers (or transit agencies) and users are the two primary stakeholders to be taken into account. However, these past studies have tended to maximize aggregate benefits for these two stakeholders while typically paying little attention to or ignoring entirely the conflicting interests between them, which have not been directly and fully embodied in the mathematical modeling for route optimization. Furthermore, most of these studies have served general users for transit accessibility improvement, while not specifically considering socially disadvantaged groups. It should be noted in this regard that transit-related social exclusion is still presented in contemporary society, primarily resulting from insufficient transit supply or poor transit accessibility (Preston and Rajé 2007, Chen et al. 2018b).

Recently, an unprecedented challenge is being confronted by many countries related to the increase in the population of seniors, who are incorporated as one segment of socially disadvantaged groups (SDGs) (Chen et al. 2018c). For example, this phenomenon has triggered significant changes in urban facilities and service provision in the built environment. After all, their distribution initially aims to satisfy most general users and is not necessarily tailored to accommodate the needs of an increasing senior population in the near future. Bus transit as one type of urban public service is important to seniors, since the accessibility of this transportation mode is positively correlated with enhanced quality of life, livability, and welfare of cities, especially for ageing societies (Currie and Stanley 2008, Kim and Ulfarsson 2013, Nassir et al. 2016). As we know, bus stops are important components of a transit route. Previous studies primarily consider influencing factors such as population density, regional environment, and traffic conditions on the location selection of bus stops (Wang et al. 2014), while irregular service regions or a dispersed distribution of bus stops can limit accessibility of seniors to nearby stops. Generally, a walking distance of 400 m is used as a walkable distance threshold for bus stops in current public transit design practice (Engels and Liu 2011, WILMAPCO 2011, Oswald Beiler et al. 2016). Hence, the basic premise of achieving equitable distribution of transit services among seniors is that the accessibility of nearby bus stops to their housing maintains an acceptable walking distance in order to satisfy the needs of seniors. From this perspective, this chapter develops a bi-level decision support model (BLDSM) to facilitate redesign of the existing bus route surrounding the location of senior housing that combines the interests of both seniors and transit agencies. The proposed methodology can provide a helpful tool for researchers and practitioners to optimize the bus route, improve bus transit efficiency, and enhance social equity in urban transportation development. As for SDGs, this study also gives an example for strengthening the accessibility of bus stops to group members in order to reduce adverse effects of uneven distribution of bus transit and enhance social inclusion of population in these groups.

The subsequent sections of this chapter are organized as follows. We first present a literature review encompassing bi-level programming and its application in route optimization. Then, the research problem is defined, and its relevant assumptions are summarized for this study. Next, two BLDSMs for different schemes are developed, and the corresponding problem-solving methodologies are introduced. The methods mentioned above are used to optimize a numerical example. The final section summarizes conclusions and the future direction of research proposed based on the results of this study.

6.2 Literature Review

Mathematical programming has been widely used in numerous disciplines to resolve optimization problems. A typical approach is single objective programming, but this approach fails to fully take into account that there commonly exist conflicts and varying degrees of cooperation (or non-cooperation) in a predominantly hierarchical system (Moore and Bard 1990, Wen and Hsu 1991). This, in turn, has further stimulated the emergence of other types of optimization approaches in mathematical programming. For instance, multi-level programming has been put forward to deal with decentralized planning problems within a hierarchical administrative structure where multiple types of decision makers are involved (Wen and Hsu 1991, Talbi 2013). If there are only two types of decision makers representing stakeholders in the optimization problem, we have a bi-level programming problem (BLPP) the general form of which is defined as follows (Vicente and Calamai 1994):

$$\begin{aligned} &\min_{x,y} \ F(x,y) \\ &s.t. \ \ G(x,y) \le 0 \\ &\qquad \min_{y} \ f(x,y) \\ &\qquad s.t. \ \ g(x,y) \le 0 \end{aligned} \tag{6-1}$$

The BLPP is composed of the upper-level problem and the lower-level problem, and each level has its own objective function, constraints, and decision variables. For instance, $x(y)$ is the upper (lower)-level decision variable, while $F(x,y)(f(x,y))$ and $G(x,y) \le 0(g(x,y) \le 0)$ are the corresponding objective function and constraints, respectively, for the upper (lower) level. Furthermore, there may be constraints common to the entire problem. In general, at least one decision variable should occur both in the upper-level and lower-level problems, which further creates connections between problems at the two levels. In other words, although the two objective functions are independent of each other, the solution to one level of the problem is affected by the solution to the other one; and in such a case the upper-level problem has the decision-making priority (i.e., the execution of decisions is sequential) (Bialas and Karwan 1984, Wen and Hsu 1991, Marinakis et al. 2007). It is assumed that the first choice is given to the upper-level problem to select the solution for minimizing $F(x,y)$, based on which the solution for minimizing $f(x,y)$ is correspondingly yielded for the lower-level problem. According to the type of objective function, the BLPP can be classified as either linear, nonlinear, or fractional.

Three categories of methods are primarily used for solving linear and nonlinear bi-level programming (Wen and Hsu 1991, Vicente and Calamai 1994, Parvasi et al. 2017): (1) *Vertex enumeration approach*. The basic principle is that an extreme point from the set of optimal solutions to the lower-level problem also occurs at an extreme point in the feasible region of the entire problem. Moore and Bard (1990) developed a basic implicit enumeration scheme involving the brand and bound method in order to resolve the mixed-integer BLPP if the upper and lower levels had the common constraints. T-set algorithm and the simplex method were used to search extreme points among bounded decision variables for the lower-level problem (Candler and Townsley 1982, Bialas and Karwan 1984). (2) *Kuhn-Tucker approach*. The lower-level problem is transformed in the formulation of the Kuhn-Tucker conditions, which are then used as the additional constraints of the upper-level problem. Bard and Moore (1990) extended a modified brand and bound method to solve the quadratic BLPP after taking the Kuhn-Tucker transformation. (3) *Penalty function approach*. A penalty term, such as a duality gap function of the lower-level problem, is added to the objective function of the upper-level problem so as to satisfy the optimization of the lower-level problem. Another approach is that the objective functions of the upper-level and low-level problems are both penalized.

In fact, the BLPPs are commonly treated as NP-hard problems (Moore and Bard 1990). Although exact methods are the classical approaches for yielding the optimal solutions, they are extremely time-consuming for complex problems. For instance, the performance of a branch and bound method is particularly efficient in the medium-scale linear BLPP (Vicente and Calamai 1994). In this case, meta-heuristic algorithms combined with exact methods are then applied to solve the BLPPs, such as the GA (Marinakis et al. 2007), the ant colony algorithm (Calvete et al. 2011), particle swarm optimization (Ma and Xu 2014), and simulated annealing (Parvasi et al. 2017).

From a broad viewpoint, bus route optimization can be regarded as belonging to a large category of problems, that is, the vehicle routing problem. Two main sub-problems are involved in this process: location selection of stops and route generation. Many scholars have adopted bi-level programming in the research field of vehicle routing (Marinakis et al. 2007, Ma and Xu 2014, Ning and Su 2017, Parvasi et al. 2017). The model frameworks of these studies are diverse, since various conflicts (e.g., benefits and costs) and objectives are considered, and different decision makers are selected. Based on this, the present study adopts bi-level programming as the theoretical basis in order to more appropriately facilitate decision making in bus route optimization among different stakeholders (i.e., transit agencies and seniors). The reason for this is four-fold: (1) there is a research gap in bus routing optimization with respect to the investigation of seniors as a specific type of transit user and how their accessibility to nearby bus stops may be improved (Chien and Schonfeld 1997, Kuah and Perl 1998, Chien and Yang 2000, Chien et al. 2002, Chien and Qin 2004); (2) it is imperative to represent the mutual-action between different types of decision makers (e.g., transit agencies and seniors) by means of BLPP (Sun et al. 2008); (3) BLPP can be adopted to analyze two conflict objectives at the same time, and the decision making priority is directly given to the upper-level decision makers, while each problem by level is subject to its own constraints; and (4) if using single-objective programming as an alternative, it is common to merge two objectives with the same weights or with different weights under all the constraints. If we take Eq. (6-1) as an example, the aggregate objective can be expressed as $F(x,y)+f(x,y)$ or $\omega_1 F(x,y)+\omega_2 f(x,y), \omega_1(\omega_2)\in[0,1]$ and $\omega_1+\omega_2=1$ under the constraints $G(x,y)\leq 0$ and $g(x,y)\leq 0$. In this case, neither of the two approaches is able to demonstrate the decision making priority, while the latter generally needs to adopt subjective approaches, such as the analytic hierarchy process method or the Delphi method, for the purpose of weighting (ω_1 and ω_2). Meanwhile, the assumption for the above case is that the central decision maker is willing to accept the aggregate objective as their own objective (Wen and Hsu 1991).

6.3 Problem Statement

Age-restricted communities serving residents aged 55 or over constitute one of the emerging paradigms in urban development, especially given the increasing number of old adults in practically every country in the world (Ginzler 2009). These kind of communities have become a popular option for seniors due to the many advantages and benefits they offer (Chen et al. 2018a). For instance, in Edmonton, Canada, there are 116 age-restricted communities that fall into one of three classes based on the level of assistance provided: independent living (70), supportive living (26), and combined living (20) (ASHD 2017). Here, combined living communities include the first two types of living style. Several studies have investigated the level of connectivity/accessibility to bus transit for age-restricted communities (Engels and Liu 2011, WILMAPCO 2011, Oswald Beiler et al. 2016). However, the above studies, while informative, have confined themselves to assessing the issue of accessibility rather than proposing solutions to improve accessibility for seniors living in communities that are not sufficiently close to bus stops (i.e., the shortest distance exceeds a walkable distance threshold, that is, 400 m). Figure 6-1 presents an example of the bus route optimization problem for seniors defined in this study. There are two age-restricted communities located in this area and the 100 m × 100 m square cells refer to the street network (grid pattern). Utilizing the walking buffer of 400 m surrounding each age-restricted community as an approximate measure, it can be seen that all the bus stops along the nearest route are outside these buffers. In fact, the proximity as defined by means of the approximate measure is certainly larger than that measured based on the street network. As such, from Figure 6-1 it can be seen that there is no actual distance between a given community and any stop that meets the walkable distance requirement for seniors. Based on this, the nearest bus route is cut into a segment including five stops, which are much closer to the age-restricted communities. Meanwhile, stop A and stop B in Figure 6-1 are set as the initial stop and the terminal stop, respectively. This segmentation process can avoid influencing accessibility of residents along the remaining part of this route and disturbing operation management of other bus routes that share part of the excluded stops. Based on this, two schemes are considered as remedies to improve the accessibility of seniors to bus stops and optimize the existing bus route:

- *Scheme I:* add one or more stops near the two age-restricted communities to generate a new route segment. The advantage of this scheme is that the accessibility to bus stops is not affected for the residents living in the left-side of this original route segment, especially when the population density of the left side is relatively large.
- *Scheme II*: adjust the locations (and the number) of stops, except stop A and stop B, to generate a new route segment. This scheme is suitable for the situation wherein residents are primarily distributed close to the bus route and the shortest distances between their housing and the stops along the new route segment are still at the walkable level.

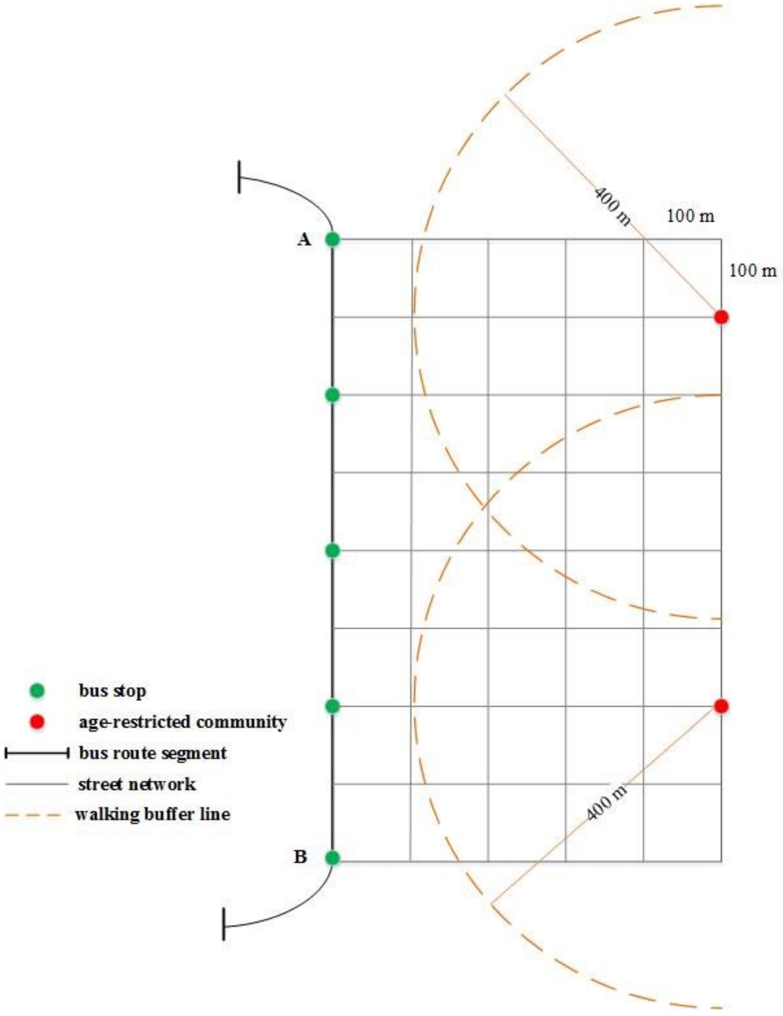

Figure 6-1. An example of the route optimization problem for seniors.

In the decision-making environment, transit agencies and seniors are the two main decision makers. From the perspective of seniors, the above two schemes aim to enhance the benefits seniors receive from bus transit services (i.e., accessibility to nearby bus stops within a walkable distance threshold). From the perspective of transit agencies, the transportation impedance by distance is considered the primary factor in scheme selection, where, the shorter the length of the new route is, the better the scheme will be. Furthermore, in order to control operation cost and mitigate transit users' complaint about a long travel time, the total length between stop A and stop B should not exceed a tolerable distance threshold. It should be noted that transit agencies primarily focus on the physical design problem of bus transit systems at the initial phase, which includes defining the topological structure of transit services and establishing routes in order to provide services to transit users; during the second phase, operational design problems pertaining to bus transit systems, such as service frequency for a given route, level of service, or reliability of service, receive more attention (dell'Olio et al. 2006). In contrast with travel distance, travel time—i.e., the time it takes for a bus to travel along a given route (or route segment)—is influenced by multiple factors including number of signalized intersections, number of stops, driver experience, weather, road features, traffic condition, number of passengers boarding, alighting, etc. (El-Geneidy et al. 2009). Furthermore, the use of travel distance results in the objective functions for transit agencies and seniors having the same unit in the optimization process. Based on the above considerations, the present research explores scenarios at the initial phase that can improve existing bus route design in order to provide seniors with good accessibility to nearby stops with a minimum total length of the new route segment for transit agencies, while satisfying all the requirements and constraints. A novel quantitative methodology called a BLDSM is proposed for the defined problem by integrating linear bi-level programming, which is then applied to the above two improvement schemes. In the following section, mathematical models and optimization procedures for the two schemes are illustrated in detail. Hence, relevant assumptions involved in the problem definition are summarized as:

- The selected bus route to be redesigned is the closest to the observed age-restricted communities.
- Seniors of independent living and a certain type of bus are considered.
- A bus route segment is analyzed in a single direction, which has initial and terminal stops.
- Accessibility of seniors is improved to nearby bus stops by walking.
- The seniors select the nearest stop to their communities for boarding.

- Locations of original and candidate stops as well as locations of age-restricted communities are assumed to be at intersections in the numerical example.
- Candidate stop locations are known beforehand.
- Service capacity is always sufficient (and, in fact, preferential) to satisfy demand from seniors. Demand distribution may not be a significant parameter considered at the initial stage, which is associated with user cost in unit of time (e.g., access time, wait time, or in-vehicle time) (Chien and Schonfeld 1997, Chien and Qin 2004).

6.4 Methodology Overview

We first present a description of the BLDSM from a systematic view, including the conceptual structure and relevant elements in the model. Then, the BLDSM is built for scheme I and scheme II, respectively, and the corresponding solution methodology is proposed.

6.4.1 The BLDSM description

The basic idea of the BLDSM is to optimize the existing bus route and enhance accessibility of seniors living in age-restricted communities to nearby bus stops. A conceptual structure of the BLDSM is presented in Figure 6-2. In this structure, seniors are considered as the upper-level decision makers, while transit agencies are regarded as the lower-level decision makers. As for the upper-level model (ULM), the objective function is to maximize accessibility of seniors to nearby bus stops and achieve the allocation of stops to age-restricted communities; as for the lower-level model (LLM), transit agencies seek to minimize the total length of the new route segment. During the process, the locations of all stops can influence generation of the new route segment and the accessibility of seniors to bus transit, so these stops act as the medium in the BLDSM to show the interactions between the two separate models. Either ULM or LLM contains the corresponding index sets, parameters, and decision variables. A summary of relevant elements by type in the BLDSM model is listed in Table 6-1.

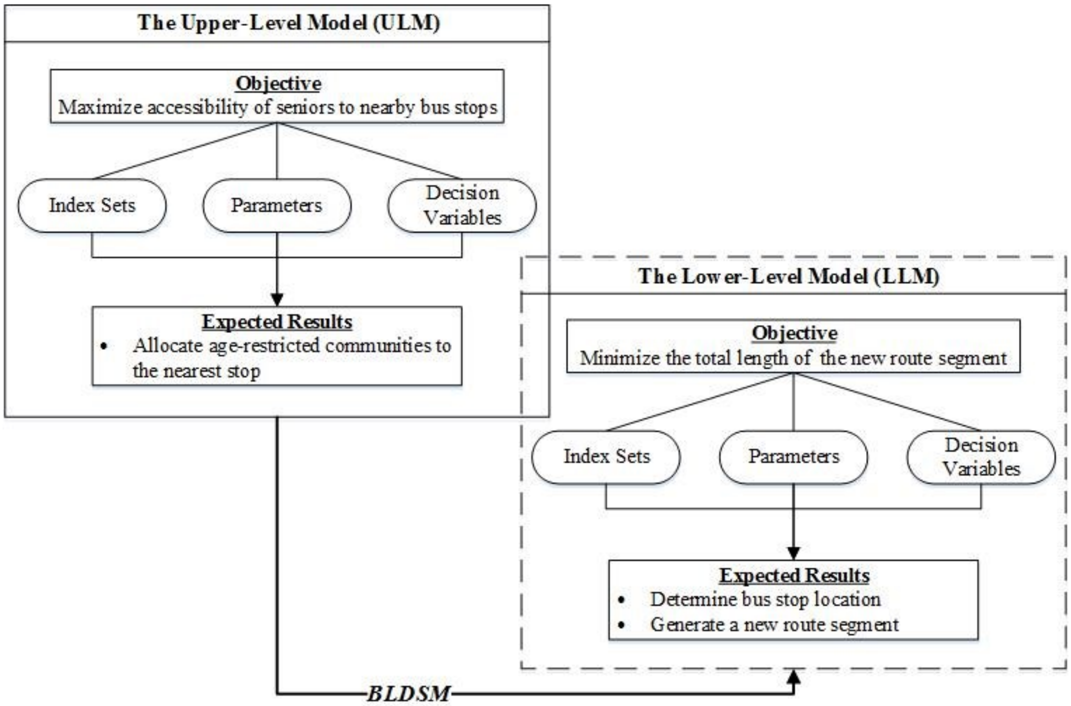

Figure 6-2. The conceptual structure of the BLDSM.

Table 6-1. Relevant elements in the BLDSM.

Index sets	
V	Set of bus stops including candidate stops and stops along the original route segment, $i, j \in V, V = \{1, 2, ..., n\}$. $i = 1$ or $i = n$ refers to the initial stop or the terminal stop of the new route segment.
V_1	Set of the stops along the original route segment, $i, j \in V_1, V_1 \subset V$
V_2	Set of the candidate stops, $i, j \in V_2, V_2 \subset V$
S	Subset of V
H	Set of age-restricted communities, $k \in H, H = \{1, 2, ..., m\}$
Parameters	
$X_i(X_k)$	X-coordinate for each facility, including stops and age-restricted communities

$Y_i(Y_k)$	Y-coordinate for each facility, including stops and age-restricted communities
d_{ij}	travel distance from stop i to stop j
$d_{\max}$	The maximum distance between any two adjacent stops (i.e., stop spacing)
$d_{\min}$	The minimal distance between any two adjacent stops (i.e., stop spacing)
d_0	Total length of the original route segment
d_{ki}	Walking distance from age-restricted community k to stop i
d_{walk}	The maximum walking distance from age-restricted communities to the nearest stop
N_0	The number of bus stops in the original route segment
N	The number of bus stops in the new route segment, $N \geq N_0$
δ	The tolerance coefficient for the total length of the new route segment, $\delta > 1$
Decision variables	
x_{ij}	1 if a bus traverses an arc from stop i to stop j; 0 otherwise
y_i	1 if a bus visits stop i; 0 otherwise
z_{ki}	1 if seniors living in age-restricted community k select stop i; 0 otherwise

As for the parameter d_{ij} or d_{ki}, several methods can be used to measure the distance based on the coordinates of any two facilities: (a) the Euclidean distance, given that an accurate distance is not required; (b) the Manhattan distance, if the street network is relatively rectangular such as the case in Figure 6-1 (i.e., grid pattern); (c) travel distance matrix calculated by network analysis in the geographic information system (GIS) for actual street layout (e.g., grid, radial, or any combined pattern). Researchers and practitioners can adopt other methods to calculate the distance (d_{ij} or d_{ij}) based on a specific street pattern for different purposes.

6.4.2 BLDSM for scheme I

6.4.2.1 Modeling BLDSM (I)

$$ULM: Min\frac{1}{m}\sum_{k=1}^{m}\sum_{i=1}^{n}d_{ki}z_{ki} \qquad (6-2)$$

$$s.t.\sum_{i=1}^{n}z_{ki}=1, k\in H \qquad (6-3)$$

$$\sum_{i=1}^{n}d_{ki}z_{ki}\le d_{walk}, k\in H \qquad (6-4)$$

$$z_{ki}\le y_i, k\in H, i\in V \qquad (6-5)$$

$$z_{ki}\in\{0,1\}, k\in H, i\in V \qquad (6-6)$$

$$LLM: Min\sum_{i\ne j}d_{ij}x_{ij} \qquad (6-7)$$

$$s.t.\sum_{j=1}^{n}x_{ij}=y_i, i=1,2,...,n-1 \qquad (6-8)$$

$$\sum_{j=1}^{n}x_{ji}=y_i, i=2,3,...,n \qquad (6-9)$$

$$\sum_{i,j\in S}x_{ij}\le|S|-1 \qquad (6-10)$$

$$S\subseteq V, 2\le|S|\le n-1 \qquad (6-11)$$

$$\sum_{i=1}^{n}y_i=N, N>N_0 \qquad (6-12)$$

$$\sum_{i\ne j}d_{ij}x_{ij}\le\delta d_0, \delta>1 \qquad (6-13)$$

$$d_{ij}x_{ij}\ge d_{\min}x_{ij} \qquad (6-14)$$

$$d_{ij}x_{ij}\le d_{\max}x_{ij} \qquad (6-15)$$

$$x_{ij}\in\{0,1\}, i,j\in V, i\ne j \qquad (6-16)$$

$$y_i=1, i\in V_1; y_i\in\{0,1\}, i\in V_2 \qquad (6-17)$$

Eq. (6-2) – Eq. (6-6) indicate the upper level of the model, while Eq. (6-7) – Eq. (6-17) denote the lower level of the model. The objective function of the ULM (Eq. (6-2)) is to minimize the average walking distance from all age-restricted communities to the nearest stops, in order to enhance the accessibility of bus transit for seniors. Here, the mean of all walking distances is used instead of calculating the total distance, as it can directly reflect the relationship between the optimized average distance and the walkable distance. Constraint (6-3) ensures seniors from each age-restricted community can be picked up at only one stop along the new route segment. Constraint (6-4) guarantees the distance from a given age-restricted community to its nearest stop does not exceed the maximum walking distance. Constraint (6-5) shows if seniors in age-restricted community k select stop i, this stop must be visited by the bus. Finally, Eq. (6-6) indicates all upper level of the model adopts the binary decision variables to allocate age-restricted communities to nearby bus stops.

The objective function of the LLM, given as Eq. (6-7), is to minimize the total length of the new route segment. Constraints (6-8) and (6-9) are degree constraints, which specify that each stop along the route segment is entered exactly once and left exactly once, respectively, except for the initial stop and the terminal stop. Constraints (6-10) and (6-11) are subtour or tour elimination constraints in order to prohibit the formation of subtours or tour in the new route segment. Constraint (6-12) indicates the total stops that the bus visits is equal to the sum of the number of stops in the original route segment and the added new stops. Constraint (6-13) guarantees the length of the new route segment should not exceed the maximum length that the trip users can tolerate. Constraints (6-14) and (6-15) are considered to limit the distance between any two adjacent bus stops (i.e., stop spacing). Eq. (6-16) and Eq. (6-17) impose that the lower level of the model adopts the binary decision variables to select the bus stops and generate the new route segment. From the built BLDSM (I), it can also be seen that y_i is the common decision variable in both the ULM and the LLM, which renders the two models interdependent. Furthermore, the built BLDSM can be regarded as a general model, which is applicable to different types of street patterns (e.g., grid, radial, or a combination). In other words, the primary difference between different uses of the BLDSM has to do with the method selected for measuring the distance (d_{ij} and d_{ki}) based on the specific street pattern.

6.4.2.2 Modeling BLDSM (I)

The location-allocation-routing strategy and the allocation-routing-location strategy are the two primary heuristic solution approaches aimed at bus routing problems (Parvasi et al. 2017). Based on Eq. (6-2) to Eq. (6-17), the location-routing-allocation strategy is proposed to solve the built BLDSM for scheme I (see Table 6-2). Furthermore, the entire process follows the principle of vertex enumeration approach in order to tackle the linear bi-level programming. As for scheme I, the number of decision variables y_i to be determined is relatively small, since the new stops are added on basis of the original route segment. Hence, exact methods are used in the optimization process, which can also be applied for model validation and comparison with other methods that have inaccurate performance.

Table 6-2. The proposed strategy for solving the built BLDSM for scheme I.

	Decision type	Decision variable	Decision maker	Output
Step 1	Location	y_i	LLM	Activate bus stops that will be added to the new bus route segment
Step 2	Routing	x_{ij}	LLM	The new route segment is generated for the bus
Step 3	Allocation	z_{ki}	ULM	Age-restricted communities are allocated to their nearby bus stops along the new route segment

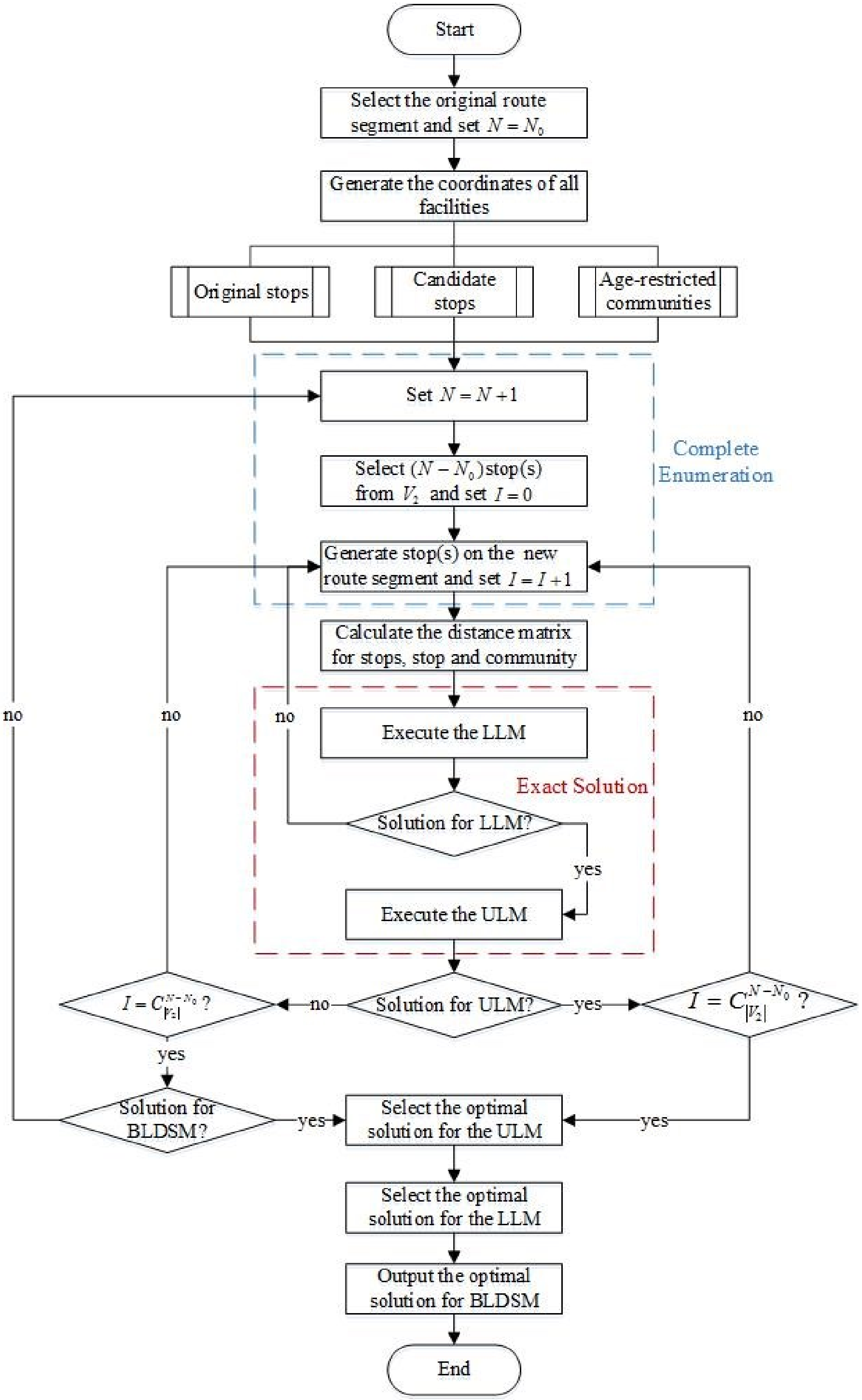

Figure 6-3. Flowchart for solving BLDSM (I).

To clearly display the application steps of the proposed methods, a flowchart for solving BLDSM (I) is shown in Figure 6-3. Based on the coordinates of all facilities, we first start to add at least one candidate stop as the activated stop to the new route segment by means of complete enumeration until yielding the optimal solution for the built BLDSM with the minimal number of activated stops. This is because in terms of a bus route with a given length, more stops tend to trigger more cost spending on station setting-up and a longer total stopping time while the bus is running its route. During each iteration, there are original stops and activated stops. First, the distance matrix for any two stops and the distance matrix between each stop and each age-restricted community are generated. The exact solution derived from such, as a branch and bound algorithm or a cutting plan algorithm, is then used to execute the LLM and the ULM in order to judge whether there is a solution for the two models. Based on the feature of BLPP, the solution for the ULM has the decision-making priority to the optimal solution for the BLDSM. Therefore, the ULM has the first choice to select the optimal solution (z_{ki}) for minimizing the average walking distance to the nearest stop among all age-restricted communities. Then, x_{ij} and y_i in the LLM are correspondingly solved to minimize the length of the new route segment. Based on this, the length of the new route segment is equal to the value of the objective function of the LLM, that is, $\sum_{i \neq j} d_{ij} x_{ij}$. The walking distance from a given restricted community to its nearest bus stop, then, is equal to d_{ki} when the value of z_{ki} is equal to one.

6.4.3 BLDSM for scheme II

6.4.3.1 Modeling BLDSM (II)

In scheme II, we leave stop A and stop B unchanged and adjust the locations (and the number) of activated stops to generate a new route segment. Compared with the BLDSM for scheme I, Eq. (6-12) is replaced with a loose constraint, that is, $N \geq N_0$; Eq. (6-17) is replaced with a new constraint, that is, $y_1 = y_n = 1, y_i \in \{0,1\}, i \in V \setminus \{1,n\}$. Then, the BLDSM for scheme II can be yielded as Eq. (6-18). As such, the main difference between the models in the two schemes is that the number of fixed stops along the original route segment.

$$
\begin{aligned}
ULM: & Min \frac{1}{m}\sum_{k=1}^{m}\sum_{i=1}^{n} d_{ki} z_{ki} \\
& s.t. \sum_{i=1}^{n} z_{ki} = 1, k \in H \\
& \sum_{i=1}^{n} d_{ki} z_{ki} \le d_{walk}, k \in H \\
& z_{ki} \le y_i, k \in H, i \in V \\
& z_{ki} \in \{0,1\}, k \in H, i \in V \\
LLM: & Min \sum_{i \ne j} d_{ij} x_{ij} \\
& s.t. \sum_{j=1}^{n} x_{ij} = y_i, i = 1,2,...,n-1 \\
& \sum_{j=1}^{n} x_{ji} = y_i, i = 2,3,...,n \\
& \sum_{i,j \in S} x_{ij} \le |S| - 1 \\
& S \subseteq V, 2 \le |S| \le n-1 \\
& \sum_{i=1}^{n} y_i = N, N \ge N_0 \\
& \sum_{i \ne j} d_{ij} x_{ij} \le \delta d_0, \delta > 1 \\
& d_{ij} x_{ij} \ge d_{\min} x_{ij} \\
& d_{ij} x_{ij} \le d_{\max} x_{ij} \\
& x_{ij} \in \{0,1\}, i, j \in V, i \ne j \\
& y_1 = y_n = 1, y_i \in \{0,1\}, i \in V \setminus \{1, n\}
\end{aligned}
\tag{6-18}
$$

6.4.3.2 Solving BLDSM (II)

The proposed strategy (i.e., location-routing-allocation) in Table 6-2 is also used for solving the built BLDSM for scheme II. In this case, it will be time-consuming if still using all exact methods to execute the flowchart in Figure 6-3, since there are substantial combinations of at least three stops selected from a set of candidate stops (V_2) in order to generate a new route segment. In fact, the routing step of the strategy can be seen as a traveling salesman problem (TSP) with the fixed start and end points under some constraints, i.e., Eq. (6-12) to Eq. (6-15). The TSP being a NP-hard problem, it is better to solve all TSP instances to optimality by means of heuristics and meta-heuristics within reasonable execution time (Laporte 1992). The GA, a typical example of meta-heuristics, mimics the process of natural selection and genetics through stochastic search techniques. This approach has performed efficiently and effectively in solving various optimization problems, especially for large-scale and complex issues (Agrawal and Mathew 2004). Furthermore, a GA has been implemented to solve the TSP and also demonstrated a good performance (Potvin 1996, Moon et al. 2002). Therefore, following the location-routing-allocation strategy, the exact solution in the routing step is replaced with the GA, while the location and allocation steps still adopt the exact methods to resolve the BLDSM of scheme (II). Based on Figure 6-3, the primary difference between the flowcharts for solving BLDSM (I) and BLDSM (II) is highlighted in Figure 6-4.

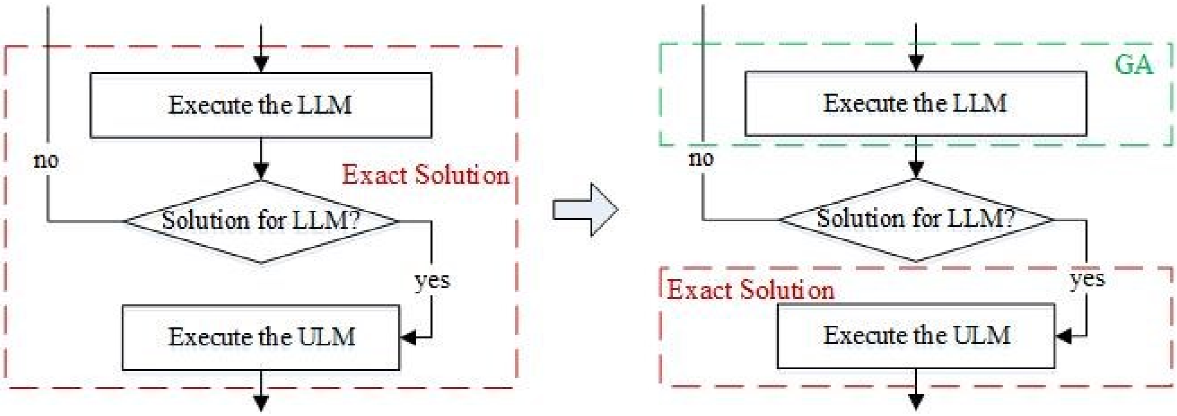

Figure 6-4. Difference between flowcharts for solving BLDSM (I) and BLDSM (II).

The GA should operate on a constant-sized population of chromosomes during the iteration. Each chromosome is represented as a bit string, which can be regarded as an encoded candidate solution for a given objective function. As for TSP, each chromosome encodes a solution to a tour. For instance, if there are five bus stops in the TSP with the fixed start- and end-points, we assume two chromosomes [1 3 4 2 5] and [1 4 3 2 5] are based on the path representation of a tour (on stops 1 to 5). In this case, the digit of the string ranges between one and the number of genes (or the total number of stops), in which the order of these digits refers to the priority of the gene. Once an initial population is generated, the fitness of each chromosome is measured by comparing with the objective function in order to improve the candidate solutions. In the routing step for solving BLDSM (II), the fitness function used for GA is represented by $\sum_{i \neq j} d_{ij} x_{ij}$ (i.e., the objective function of the LLM). After probabilistically selecting the parent chromosomes based on the fitness values, three GA operators (i.e., reproduction, crossover, and mutation) are used to generate offspring. Here, reproduction is an operator that selects some better chromosomes in the population according to the principle of survival of the fittest; crossover is an operator that is used to recombine two selected chromosomes to generate a new one; mutation is an operator that introduces a random change in some chromosomes when the population is lack of heterogeneity. As such, the new chromosomes derived from the three operators can form the next generation by repeating the above process until the system ceases to improve. In general, some parameters should be determined before execution of GAs, such as population size, number of generation, crossover probability, and mutation probability. A more detailed introduction for GAs can be seen from Goldberg (1989). Based on this, a pseudo-code of the proposed methods for solving the BLDSM of scheme (II) is shown in Figure 6-5.

```
Procedure: a bus route segment generation
  Input: coordinates of all facilities.
  Initialization: value of $N$; combination of $N-2$ stops selected from $V \setminus \{1, n\}$
  For each combination
    Input: a distance matrix ($N \times N$) of each pair of bus stops
    Initialization: population size; number of generation (G); crossover probability; mutation probability;
    Repeat
      Select a certain number of chromosomes according to the fitness function ($\sum_{i \neq j} d_{ij} x_{ij}$)
      Apply genetic operators (reproduction, crossover, mutation)
      Update the current population
    Until stopping criteria is satisfied (e.g., generation= G)
    If the generated route segment satisfies Eq. (6-13) – Eq. (6-15)
      Execute the ULM to obtain the average shortest distance ($\frac{1}{m}\sum_{k=1}^{m}\sum_{i=1}^{n} d_{ki} z_{ki}$) by means of exact solution
    End If
  End For
  Find the minimal objective function for the ULM
  Find the minimal objective function for the LLM
  Output: Optimal solutions
End Procedure
```

Figure 6-5. Pseudo-code of the methods for BLDSM (II).

6.5 Numerical Example

This study takes Figure 6-1 as a numerical example of the bus route optimization problem for seniors. The values of index sets and parameters in the built BLDSM are summarized in Table 6-3 under the relevant assumptions mentioned in the problem statement. All the proposed methods for solving the BLDSM of scheme I and scheme II are encoded in MATLAB R2017b software, while the computer used in the process has the following configurations: Intel Core i7-4770 CPU

@ 3.4 GHz, 16 GB installed memory (RAM), and Window 7 Professional 64-bit operating system.

Table 6-3. Index sets and parameters in the BLSDM for the example.

	Element	Value	Source
Index sets	V	$\lvert V\rvert = 48$	Refer to Figure 6-1; the candidate stops are at the intersections except for those along the original route segment
	V_1	$\lvert V_1\rvert = 5$	
	V_2	$\lvert V_2\rvert = 43$	
	H	$\lvert H\rvert = 2$	
Parameters	X_i		Set the coordinate axis with stop B as the origin
	Y_i		
	d_{ij}	$d_{ij} = \lvert X_i - X_j\rvert + \lvert Y_i - Y_j\rvert$	The Manhattan distance based on Figure 6-1
	$d_{\max}$	400 m	Furth and Rahbee (2000); stop distribution data of the City of Edmonton
	$d_{\min}$	100 m	
	d_0	800 m	The Manhattan distance based on Figure 6-1
	d_{ki}	$d_{ki} = \lvert X_k - X_i\rvert + \lvert Y_k - Y_i\rvert$	The Manhattan distance based on Figure 6-1
	d_{walk}	400 m	A walkable distance (Engels and Liu 2011, WILMAPCO 2011, Oswald Beiler et al. 2016)
	N_0	5	Refer to Figure 6-1
	δ	2	A sensitivity analysis is conducted in the bus routing result

6.5.1 Bus routing layout for scheme I

After following the proposed strategy in Table 6-2 and collecting all data according to Table 6-3, bus routing layout for the built BLDSM of scheme I is yielded as Figure 6-6. It can be seen that two additional stops (the blue circles) are added to the new route segment, that is, $N = 7$. In the optimal solutions, the average walking distance from the two age-restricted communities to the nearest stops is 250 m, while the length of the new route segment is 1,600 m. There are two routing layouts to achieve the above goal, since the objective function of the ULM cannot reflect the dispersion degree of the shortest distances (d_{ki}). Nevertheless, with respect to seniors, layout (II) is the most suitable for redesigning this route due to the smaller variance of d_{ki}.

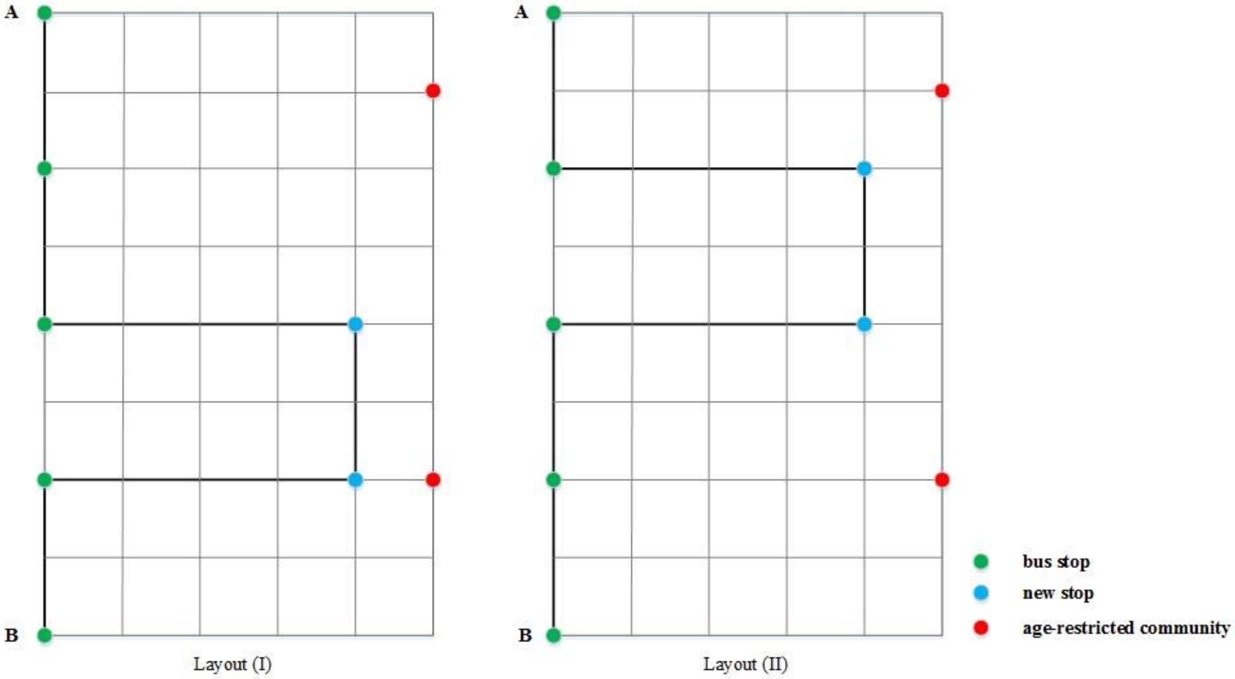

Figure 6-6. Bus routing layout for Scheme I.

Besides the above two optimal solutions, there are 45 candidate solutions in total for scheme I throughout the entire process. The values of the objective functions for the ULM and LLM in scheme I are displayed in Figure 6-7, where Arabic numerals on these bubbles indicate the number of solutions to achieve these values. If lowering the tolerance coefficient (δ), the number of candidate solutions will decrease accordingly. Furthermore, the values of the objective functions corresponding to the optimal solution are the bubbles that are much closer to left-bottom corner in terms of a given tolerance level.

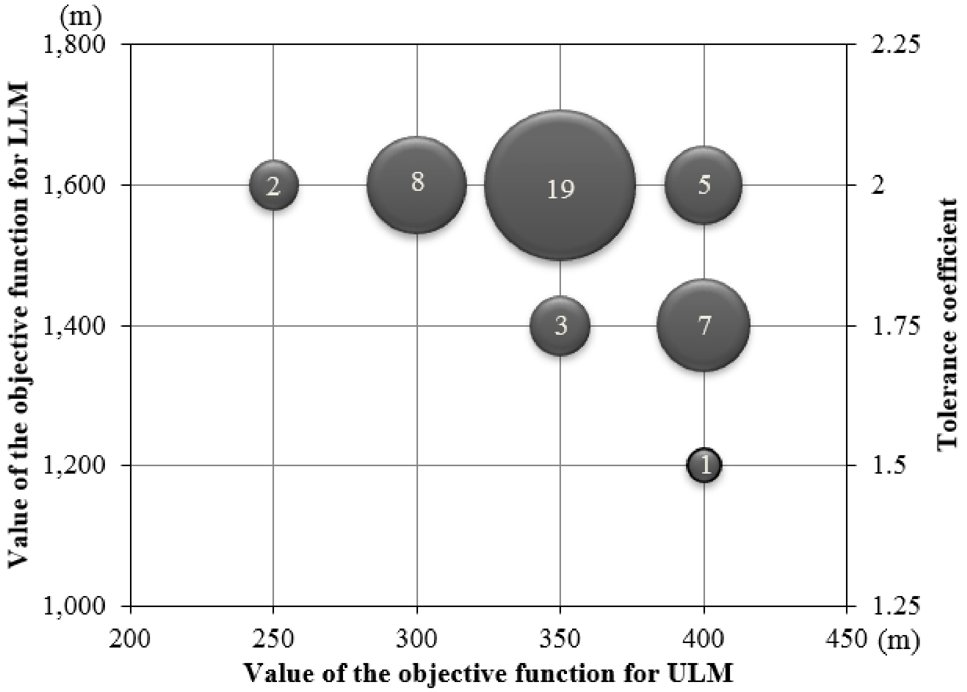

Figure 6-7. Values of the objective functions for the BLDSM of scheme I.

6.5.2 Bus routing layout for scheme II

As for the proposed strategy in Table 6-2, a GA, rather than exact methods, is used for the routing step in order to reduce the execution time. The genetic parameters are set as: number of generation (500), population size (100), crossover probability (0.5), and mutation probability (0.2). For further discussion on determining the parameters for crossover probability and mutation probability, the interested reader can refer to Goldberg (1989) and Potvin (1996). Fixing stop A and stop B, three additional stops are finally added to the new route segment, that is, $N = 5$. There are 15 solutions in total to achieve the optimal objectives for the ULM and the LLM, that is, the average walking distance from the two age-restricted communities to the nearest stops is 250 m (i.e., (200+300)/2), while the length of the new route segment is 1,400 m.

Specifically, the coordinates of the three added stops in all the optimal solutions are shown in Table 6-4, where the coordinates of stop B is set as the origin. Although the mean of stop spacing is 350 m (i.e., 1,400/4), its SD is diverse. It can be seen that 40% of these solutions in this table have a relatively smaller difference in stop spacing. In reality, a more suitable alternative for redesigning this route in scheme II can be selected from the 15 optimal solutions according to population density distribution along the right side of the original route segment. In order to validate the above optimal solutions, the methods used for scheme I are also applied to scheme II. The finding shows that the optimal solutions found by the two sets of methods are identical, but the combination method that includes a GA is found to perform better (i.e., less CPU time).

Table 6-4. Coordinates of new bus stops for Scheme II.

No.	Coordinate (X, Y)			Stop Spacing		
				Min (m)	Max (m)	Standard Deviation (SD)
1	(100, 100)	(300, 300)	(300, 700)	200	400	86.6
2	(100, 200)	(300, 300)	(300, 700)	300	400	50.0
3	(100, 300)	(300, 300)	(300, 700)	200	400	86.6
4	(200, 0)	(300, 300)	(300, 700)	200	400	86.6
5	(200, 100)	(300, 300)	(300, 700)	300	400	50.0
6	(200, 200)	(200, 400)	(300, 700)	200	400	86.6
7	(200, 200)	(200, 500)	(300, 700)	300	400	50.0
8	(200, 200)	(200, 600)	(300, 700)	200	400	86.6
9	(200, 200)	(300, 300)	(300, 700)	200	400	86.6
10	(200, 200)	(300, 400)	(300, 700)	300	400	50.0
11	(200, 200)	(300, 500)	(300, 700)	200	400	86.6
12	(300, 0)	(300, 300)	(300, 700)	300	400	50.0
13	(300, 100)	(300, 300)	(300, 700)	200	400	86.6
14	(300, 100)	(300, 400)	(300, 700)	300	400	50.0
15	(300, 100)	(300, 500)	(300, 700)	200	400	86.6

Besides the above optimal solutions, there are 181 candidate solutions in total for scheme II throughout the entire process. The values of the objective functions for the ULM and LLM in scheme II are shown in Figure 6-8, where the Arabic number on the smallest bubble refers to four solutions.

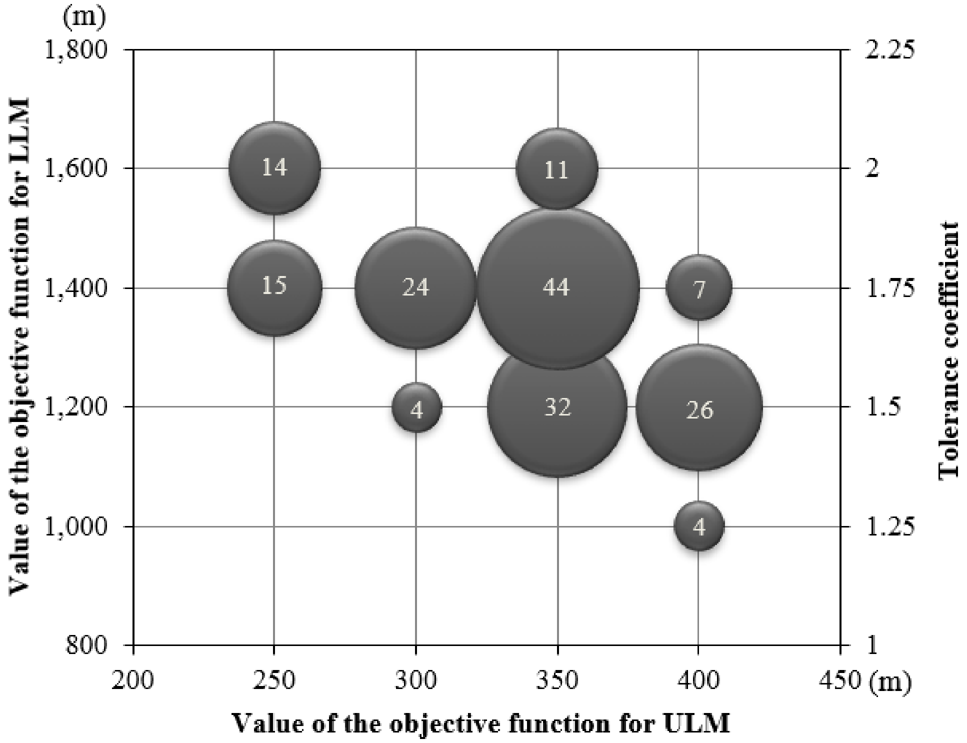

Figure 6-8. Values of the objective functions for the BLDSM of scheme II.

6.5.3 Discussion

In the built BLDSM for either scheme I or scheme II, seniors are regarded as the upper-level decision makers. If the interest of transit agencies is the primary concern, improving accessibility of seniors to nearby bus stops accordingly acts as the auxiliary objective. In this case, the BLDSMs can be rebuilt for scheme I and scheme II by allocating transit agencies and seniors as decision makers in the ULM and the LLM, respectively. Take scheme I as an example. In this case, the ULM of the BLDSM consists of Eq. (6-7) – Eq. (6-17), while the LLM is composed of Eq. (6-2) – Eq. (6-6). As such, the strategy for solving the rebuilt BLDSM for scheme I and scheme II is set as location-allocation-routing. The detailed description for each decision in the strategy can refer to Table 6-2. Similarly, exact methods are used in the optimization process for scheme I, while a combination of exact methods and a GA is applied to solve the rebuilt BLDSM of scheme II. The new bus routing layouts for the two schemes are shown in Figure 6-9 with the optimal solutions. Compared with Figure 6-1, part of the new bus routing is identical to the original layout so as to avoid introducing larger changes between them. In terms of scheme II, layout II-2 has the smallest total deviation of the distances between the three added stops and their corresponding original locations. Furthermore, it is clear to display the influences of adjusting the roles of decision makers (i.e., seniors and transit agencies) on the optimal solutions for the corresponding built BLDSMs, if comparing the new layouts in Figure 6-9 with the previous solutions for scheme I and II (i.e., Figure 6-6 and Table 6-4).

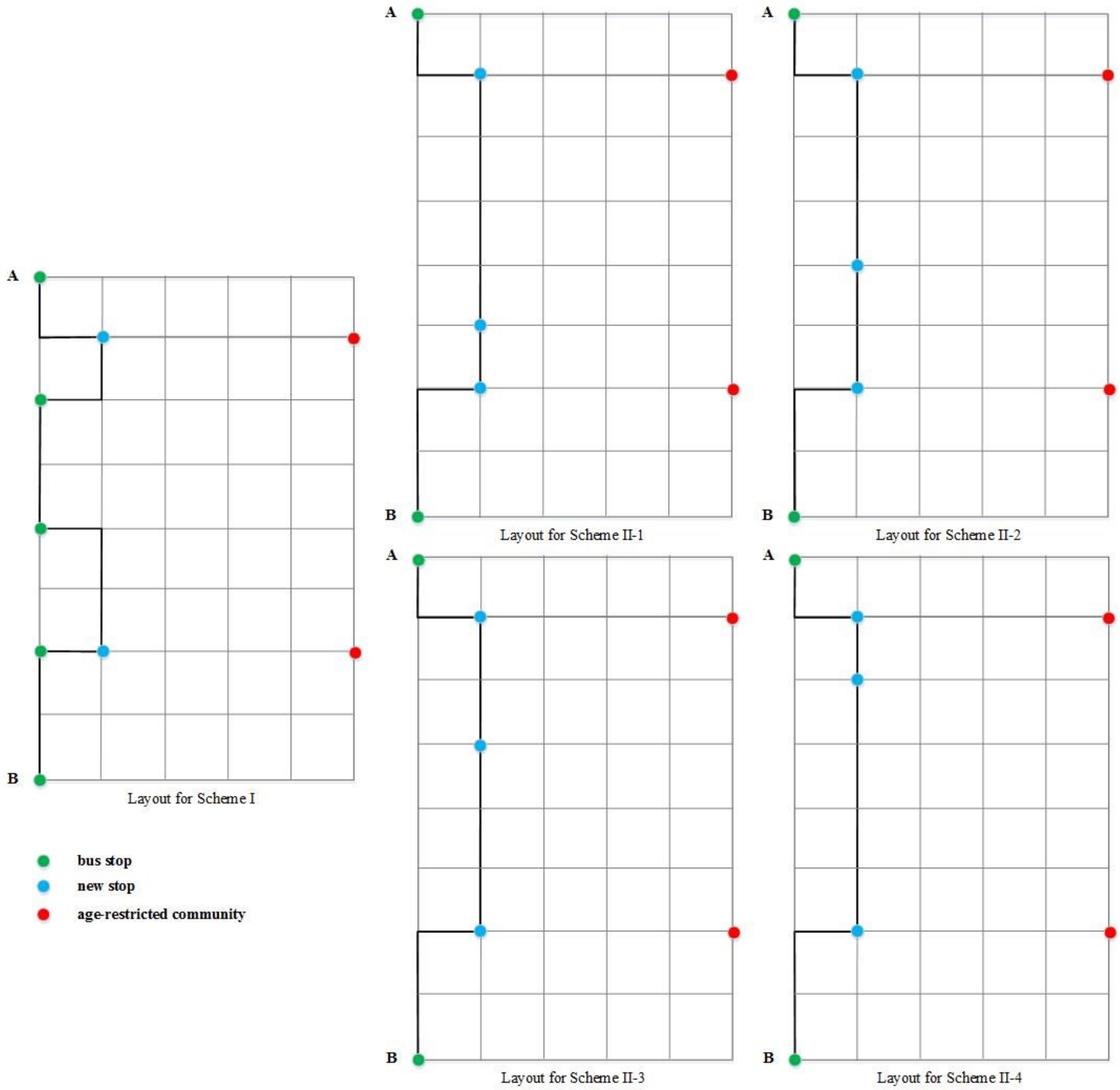
Layout for Scheme I
Layout for Scheme II-1
Layout for Scheme II-2
Layout for Scheme II-3
Layout for Scheme II-4

Figure 6-9. Bus routing layout for Scheme I (II) by means of the new BLDSM.

6.6 Conclusions

This chapter has presented a novel quantitative methodology, called the BLDSM, for optimizing existing bus routes and enhancing the benefits that seniors receive from transit services. Considering that two types of decision makers with conflicting interests are involved in the decision-making environment, bi-level programming provides the theoretical basis for the mathematical decision support model. Specifically, seniors are regarded as the decision makers for the ULM, the objective of which is to maximize accessibility to nearby bus stops for seniors living in their housing. Meanwhile, transit agencies, as lower-level decision makers, seek to minimize the total length of the new route segment in order to facilitate transit operation management. In the proposed model, seniors from the ULM have the decision-making priority for the optimal solution for the BLDSM. Since two schemes are considered as remedies for the identified problem, the BLDSMs are built following the location-routing-allocation strategy. To address the two models, scheme I adopts exact methods for each step of the proposed strategy, while a combination of exact methods and a GA is applied to scheme II in order to reduce the execution time of the entire optimization process. Furthermore, the solution methodology for scheme I can be used for model validation and comparison of that for scheme II.

The main contributions of this study include: (1) An optimization method is proposed for bus route plan and redesign in consideration of the interests of transit agencies and SDGs in the decision-making environment. (2) A heuristic solution strategy is developed for the built BLDSM integrating exact solutions and meta-heuristics, which is suitable for different optimization schemes. (3) Accessibility studies of bus transit to senior housing are extended from the conventional assessment to improvement approaches. (4) A tolerance coefficient of the bus travel distance is considered in the mathematical modeling, which can help to analyze influences of different optimal solutions on operation cost and satisfaction of transit users in reality. (5) The proposed methodology provides a helpful tool for researchers and practitioners by which to optimize the bus route, enhance bus transit efficiency and SEV, and strengthen social inclusion of SDGs in usage of public transport services.

A numerical example designed based on the grid street pattern was illustrated to demonstrate the applicability of the proposed BLDSM for redesigning the bus route in consideration of bus operation cost and service accessibility to seniors. The BLDSM can also be extended to other situations (e.g., diverse street patterns, different distributions of age-restricted communities, or a larger-scale problem). To collection data for developing the BLDSM in practice cases, it will be helpful to integrate GIS with other available data such as General Transit Feed Specification (GTFS) data for the transit system, facilities location, street network, and demographic information in a specific city. A discussion was then conducted in order to better understand differences in the optimal bus routing layouts for the two schemes after exchanging the decision makers in the ULM and the LLM. At the routing step for scheme II, a GA was used to solve the TSP with the fixed start and end points. For this numerical example, it should be noted, more than one routing solution may exist with the identical total distance due to the grid street network, while the GA can only output one solution. After checking the output with the constraints—i.e., Eq. (6-13) to Eq. (6-15)—the generated route may satisfy these constraints or not. As such, it further makes the candidate solutions of the BLDSM inconstant, in spite of no effects on the optimal solutions. To address the issue, multiple experiments were conducted for the BLDSM by means of MATLAB. This updating can be conducted by considering other innovative methods or optimizing the proposed solution strategy. Although, in the numerical example, the use of a GA for the routing step reduces the time required for solving the BLDSM in comparison with exact methods, future study can focus more on performance testing of the proposed approach on larger-scale problems. Furthermore, it should be noted that only one bus route is considered in the present research, so future study can extend the mathematical modeling to multiple bus routes and balance the interests of different stakeholders. Minimizing the length of the new route segment and minimizing the average walking distance for seniors are regarded as the objectives for the LLM and the ULM at the initial stage of bus service planning, so future study can also rebuild these two models for the purpose of operational design of transit systems. For instance, transit user cost can consider waiting time, access time, and in-vehicle travel time in the optimization process (Chien et al. 2002).

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Chapter 7: CONCLUSIONS

7.1 Research Summary

Several unprecedented challenges accompany the increase in the population of seniors, such as allocating regional resources effectively from the social perspective and renewing/designing the existing/future urban built environment from the engineering perspective. The problems identified for the latter consist primarily of issues related to the accessibility of facilities and services that are important to seniors in this environment and the equity degree of access to resources in comparison with the general population. In this context, this research develops an accessibility-based framework in order to enhance the development of a socially-sustainable urban built environment for seniors. The research is composed of five primary modules:

1) *Difference analysis of regional population ageing*. This study develops a temporal-spatial analysis framework. For the temporal analysis, regional population ageing trends, the concentration degree, and regional differences are explored using stacked column graphs, a Lorenz curve, Gini coefficients (GCs) and coefficient of variation (CV). For the spatial analysis, spatial clusters, spatial autocorrelation, and evolution of population ageing among regions are analyzed by means of spatial clustering, global Moran's I and Moran scatterplot. Based on the findings of a case study, some suggestions and policy implications are provided for regional population ageing. Meanwhile, the macro study provides the theoretical basis and background for the following four modules aimed specifically at urban built environments.

2) *A spatial analysis framework for age-restricted communities*. The proposed framework consists of two parts: regional and local. Regional analysis is employed to investigate geographical locations of age-restricted communities by type and their relationship with

neighboring population ageing. The findings indicate that not all communities are located in neighborhoods with higher degrees of population ageing. The local analysis focuses on the accessibility evaluation of age-restricted communities. First, the accessibility measure of these communities is conducted with respect to neighboring facilities that are necessary and important to seniors. Based on the established distance thresholds for different types of facilities, age-friendly communities are then identified. Third, comprehensive accessibility is evaluated using a normalization approach and the weighed sum model in order to reveal the level of accessibility of each age-restricted community to all facilities.

3) *Spatial gap analysis of urban public transport services.* A systematic methodology is developed for performing an analysis of relative spatial gaps in public transport supply and demand from seniors at the statistical area (SA) level in consideration of social equity. First, a comprehensive public transport supply index (PTSI) is measured based on the established transport supply indicators using partial least squares (PLS) path modeling and the normalization method. Second, the public transport demand index (PTDI) for seniors is described by the ratio of the senior population to the total population. Based on this, global relative public transport gaps among seniors are assessed by means of Lorenz curves and the GC, while local relative public transport gaps are identified using gap measurement, which evaluates the relative discrepancies between transport supply and demand from seniors in each SA. The findings based on the above methods are visualized using the geographic information system (GIS).

4) *Accessibility-based service effectiveness (ABSEV) and social equity assessment for urban bus transit.* A systematic methodology is developed for measuring the service effectiveness (SEV) of bus transit in terms of accessibility and by investigating the SEV distribution

among various population groups including seniors in consideration of social equity. The ABSEV of urban bus transit is first defined as the ratio of accessibility available to transit riders to the existing bus transit supply, which involves two stakeholders—service providers and transit riders. Then, the data envelopment analysis (DEA) model is employed to achieve the ABSEV assessment at the SA level based on the established input and output indicators for urban bus transit services. Lorenz curves and GCs are used to compare distribution of ABSEV between the senior population and the total population in order to demonstrate social equity in urban transit services in the context of ABSEV.

5) *Accessibility improvement for seniors by optimizing bus route.* An optimization model, called bi-level decision support model (BLDSM), is proposed for bus route redesign in order to facilitate transit operation management and enhance the benefits that seniors receive from transit services. Specifically, in this study seniors and transit agencies are regarded as upper-level and lower-level decision makers, respectively. The objective of the upper-level model (ULM) is to maximize accessibility of seniors living in their housing to nearby bus stops, while the objective of the lower-level model (LLM) is minimize operation cost for transit agency, which is indirectly described by the total length of the new route segment. To address the built BLDSM, the location-routing-allocation strategy is proposed and implemented in two schemes. Furthermore, exact methods and a combination of exact methods and genetic algorithms (GAs) are used to search the optimal solution for the two schemes. Finally, an in-depth discussion for the built BLDSM is presented in consideration of the priority of stakeholders in the identified problem.

7.2 Research Contributions

In the context of population ageing, the research presented in this thesis combines knowledge of construction with knowledge of other disciplines, such as urban planning and computational science, in order to contribute to developing a set of methods by which to achieve accessibility-related evaluation and improvement for urban facilities and services in the built environment, as well as social equity assessment for urban resources in the interest of seniors. The primary contributions of this research corresponding to the five modules described above are summarized as follows:

1) A temporal-spatial analysis framework can explore differences in regional population ageing. Meanwhile, each dimension is investigated from multiple aspects using the corresponding methods in order to provide a relatively comprehensive profile of regional population ageing. Specifically, time-based differences of population ageing are reflected in population distribution, population ageing trends, regional variations and the concentration degree; whereas, spatial-based differences of population ageing are reflected in population ageing clusters, and global and local autocorrelation. These ageing features are also explored in consideration of regional division (e.g., both the country and aggregated regions) in order to refine the difference analysis. In practice, this can help policy-makers to understand change trends and regional differences in population ageing and can provide the basis for regional population strategies in order to balance regional development and address the challenges associated with population ageing.
2) A set of quantitative indicators are established to help judge whether the level of accessibility between age-restricted communities and neighboring facilities is appropriate for seniors, a contribution which overcomes a key limitation of existing studies (i.e., lack of

quantitative indicators). Meanwhile, a criterion for age-friendly community selection is generated accordingly. In addition to traditional accessibility measures, comprehensive accessibility is defined in this study in order to achieve comparison among age-restricted communities for various assessment purposes. The proposed methodology can provide a basis for offering a resilient lifestyle for older adults, developing regional and local neighborhood policies aiming to improve quality of life for older adults, developing/renewing age-restricted communities, and facilitating decision making in urban development for multiple stakeholders and across different stages of the urban development lifecycle.

3) To quantify public transport supply more comprehensively, a systematic index system is built from multiple dimensions. An approach is used to objectively determine the weights of different supply indicators and yield a comprehensive PTSI, which effectively make up the shortcomings of subjective methods in the weight determination. Relative transport gaps in supply and demand from seniors are analyzed from both the global and local perspectives by means of corresponding methods, which enriches the spatial gap analysis of public transport services. The results can help enhance social equity in transport services and improve service efficiency for various populations.

4) ABSEV of urban bus transit is defined in consideration of two stakeholders—service providers and transit riders, which embodies the concept of SEV of bus transit from the accessibility perspective and extends the accessibility study from traditional measures to effectiveness analysis. The DEA model is first employed to evaluate the ABSEV of bus transit, the precondition of which is to determine the quantitative input and output indicators. GIS technologies are used to better visualize spatial characteristics and regional differences

of ABSEV. Methods used in quantitative analysis are provided to explore social equity in ABSEV distribution among various population groups.

5) An optimization model is proposed for bus route plan/redesign and accessibility improvement, which differs from previous studies where transit agencies are generally the primary decision makers. In this case, another stakeholder, socially disadvantaged groups (SDGs), is also involved in the bus route optimization. Furthermore, it extends the traditional accessibility studies of bus transit to senior housing from the conventional assessment to improvement approaches. Various solutions are developed for the built models following the heuristic solution strategy proposed in this study, which can also be applied to different optimization schemes. Researchers and practitioners can use the proposed model as a tool to help optimize bus routes and strengthen social inclusion of SDGs in usage of public transport services.

7.3 Limitations and Future Research

In order to improve the performance of the proposed accessibility-based framework, the following directions can be pursued in future research:

1) The established distance thresholds for different facilities do not vary according to the physical condition of seniors when measuring facility accessibility and identifying age-friendly communities. Furthermore, in this study the distances between facilities and age-restricted communities are measured based on the street network using GIS, which amplifies the actual service area of each type of facility and does not consider the distribution of sidewalks or crosswalks. As such, future work can capture the service area of a facility using sidewalks and paths developed in GIS and then investigate accessibility for age-restricted

communities. Considering different types of communities, the distance thresholds for facilities can then be adjusted accordingly.

2) In this research the cumulative opportunity measure is used as the primary approach for accessibility measurement, and this puts more emphasis on the opportunity counting within the corresponding threshold while not taking into account fully other factors, such as the service quality of these facilities. After all, satisfying the quantity demand is the first step in the initial phase based on which quality is pursued, according to Maslow's hierarchy of needs (Maslow 1943). Future research can consider adopting other methods for measuring accessibility, such as gravity-based measures and utility-based measures (Handy and Niemeier 1997), and could then make an accessibility comparison among different phases.
3) Using distance as the transportation impedance, accessibility to any facility may seem to be a constant value. On the contrary, accessibility measures should consider dynamic features along with the time per day (e.g., peak time and non-peak time), especially when using public transit or private vehicles as the mobility tools. As such, the temporal factor can be incorporated into spatial gap analysis and ABSEV assessment for urban public transit services and a temporal analysis can be conducted accordingly.
4) The primary achievements related to accessibility-issues in the urban built environment focus on the assessment level, although Chapter 6 illustrates an optimization model for improving accessibility of public transit to seniors. The analysis is static such that it tends to evaluate or improve accessibility of the existing facilities and services. To account for this shortcoming, in future research simulation should be employed in order to mimic influences on accessibility in different scenarios and reevaluate the metrics proposed in this study.

5) Assuming buildings are the divisional plane, the built environment can be divided into two components: inside and outside the building. The present research primarily explores the accessibility-issues outside the built environment. In fact, accessibility inside buildings, such as senior housing, also has a significant influence on quality of life and individual safety. For instance, falls occur in the home environment with a high probability among seniors, and 50% of falls among seniors will result in hospitalization (Afifi et al. 2014, 2015). In future research, potential hazards triggering a fall or an injury in senior housing should be explored under a 3D visual and interactive environment. 3D housing, including its interior design and outdoor environment, can be created in a building information modeling environment (Cerovsek 2011), in GIS, or using virtual-reality technology (Burdea and Coiffet 2003). Various stakeholders can then better identify potential hazards in the current house design and accordingly provide feedback to improve safety and accessibility.

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APPENDIX A

Table A-1. The total and aged population of China from 1998 to 2014.

(10,000 people)	1998		1999		2000		2002		2003		2004		2005		2006	
	total	65+	total	65+	total	65+	total	65+	total	65+	total	65+	total	65+	total	65+
Beijing	1,246	112	1,257	129	1,382	116	1,423	153	1,456	163	1,493	166	1,538	166	1,581	178
Tianjin	957	86	959	90	1,001	83	1,007	108	1,011	110	1,024	111	1,043	101	1,075	113
Hebei	6,569	441	6,614	437	6,744	463	6,735	514	6,769	512	6,809	544	6,851	560	6,898	586
Shanxi	3,172	203	3,204	205	3,297	204	3,294	229	3,314	235	3,335	235	3,355	259	3,375	236
Inner Mongolia	2,345	129	2,362	138	2,376	127	2,384	170	2,386	182	2,393	179	2,403	191	2,397	187
Liaoning	4,157	314	4,171	326	4,238	332	4,203	340	4,210	409	4,217	399	4,221	412	4,271	452
Jilin	2,644	178	2,658	180	2,728	160	2,699	180	2,704	191	2,709	202	2,716	208	2,723	225
Heilongjiang	3,773	194	3,792	205	3,689	200	3,813	242	3,815	254	3,817	259	3,820	290	3,823	308
Shanghai	1,464	192	1,474	204	1,674	193	1,713	230	1,766	289	1,835	283	1,890	226	1,815	262
Jiangsu	7,182	662	7,213	709	7,438	651	7,406	732	7,458	846	7,523	807	7,588	825	7,550	835
Zhejiang	4,456	402	4,475	427	4,677	414	4,776	533	4,857	558	4,925	482	4,991	528	4,980	500
Anhui	6,184	476	6,237	463	5,986	446	6,144	506	6,163	505	6,228	530	6,120	618	6,110	624
Fujian	3,299	256	3,316	266	3,471	227	3,476	264	3,502	278	3,529	300	3,557	311	3,558	333
Jiangxi	4,191	282	4,231	284	4,140	253	4,222	311	4,254	296	4,284	344	4,311	364	4,339	369
Shandong	8,838	737	8,883	764	9,079	729	9,082	772	9,125	827	9,180	846	9,248	920	9,309	889
Henan	9,315	657	9,387	664	9,256	644	9,613	710	9,667	778	9,717	790	9,380	773	9,392	757
Hubei	5,907	421	5,938	425	6,028	380	5,672	500	5,685	449	5,698	467	5,710	524	5,693	557
Hunan	6,502	504	6,532	521	6,440	469	6,629	569	6,663	598	6,698	588	6,326	641	6,342	669
Guangdong	7,143	551	7,270	573	8,642	523	8,842	684	8,963	725	9,111	721	9,194	680	9,304	661
Guangxi	4,675	351	4,713	375	4,489	320	4,822	416	4,857	442	4,889	412	4,660	445	4,719	424
Hainan	753	46	762	51	787	52	803	61	811	63	818	61	828	71	836	72
Chongqing	3,060	258	3,075	272	3,090	244	2,814	257	2,803	258	2,793	320	2,798	307	2,808	321
Sichuan	8,493	700	8,550	712	8,329	620	8,110	699	8,176	709	8,090	709	8,212	897	8,169	923
Guizhou	3,658	209	3,710	224	3,525	204	3,837	263	3,870	294	3,904	294	3,730	306	3,757	303
Yunnan	4,144	265	4,192	286	4,288	257	4,333	305	4,376	308	4,415	341	4,450	335	4,483	337
Tibet	252	14	256	10	262	12	268	17	272	17	276	18	280	17	281	18

Shaanxi	3,596	241	3,618	258	3,605	214	3,662	294	3,672	285	3,681	282	3,690	318	3,735	333
Gansu	2,519	146	2,543	143	2,562	128	2,531	159	2,537	169	2,541	168	2,545	184	2,606	193
Qinghai	503	26	510	28	518	22	529	29	534	31	539	32	543	33	548	38
Ningxia	538	22	543	24	562	25	572	27	580	33	588	33	596	36	604	36
Xinjiang	1,747	88	1,774	83	1,925	87	1,905	117	1,934	105	1,963	123	2,010	130	2,050	136
Total	123,282	9,161	124,219	9,479	126,228	8,799	127,320	10,393	128,189	10,920	129,023	11,045	12,8606	11,675	12,9130	11,876

Table A-1. (Continued).

(10,000 people)	2007		2008		2009		2010		2011		2012		2013		2014	
	total	65+	total	65+	total	65+	total	65+	total	65+	total	65+	total	65+	total	65+
Beijing	1,633	167	1,695	174	1,755	177	1,962	171	2,019	178	2,069	178	2,115	181	2,152	184
Tianjin	1,115	121	1,176	144	1,228	136	1,299	111	1,355	132	1,413	148	1,472	169	1,517	177
Hebei	6,943	615	6,989	611	7,034	623	7,194	593	7,241	591	7,288	663	7,333	672	7,384	689
Shanxi	3,393	248	3,411	269	3,427	277	3,574	271	3,593	279	3,611	288	3,630	289	3,648	311
Inner Mongolia	2,405	196	2,414	196	2,422	205	2,472	187	2,482	171	2,490	196	2,498	213	2,505	234
Liaoning	4,298	457	4,315	489	4,319	497	4,375	451	4,383	472	4,389	436	4,390	448	4,391	534
Jilin	2,730	240	2,734	250	2,740	243	2,747	230	2,749	239	2,750	213	2,751	266	2,752	280
Heilongjiang	3,824	342	3,825	349	3,826	331	3,833	319	3,834	306	3,834	339	3,835	343	3,833	360
Shanghai	1,858	265	1,888	246	1,921	271	2,303	233	2,347	185	2,380	215	2,415	257	2,426	235
Jiangsu	7,625	850	7,677	901	7,725	929	7,869	857	7,899	854	7,920	910	7,939	973	7,960	960
Zhejiang	5,060	538	5,120	545	5,180	574	5,447	509	5,463	468	5,477	479	5,498	506	5,508	530
Anhui	6,118	643	6,135	659	6,131	622	5,957	606	5,968	625	5,988	618	6,030	635	6,083	634
Fujian	3,581	361	3,604	360	3,627	364	3,693	291	3,720	285	3,748	322	3,774	308	3,806	289
Jiangxi	4,368	391	4,400	369	4,432	358	4,462	339	4,488	342	4,504	364	4,522	407	4,542	420
Shandong	9,367	913	9,417	918	9,470	923	9,588	944	9,637	1,036	9,685	1,018	9,733	1,069	9,789	1,123
Henan	9,360	709	9,429	738	9,487	843	9,405	786	9,388	826	9,406	830	9,413	840	9,436	827
Hubei	5,699	563	5,711	579	5,720	582	5,728	521	5,758	582	5,779	622	5,799	574	5,816	596
Hunan	6,355	656	6,380	671	6,406	716	6,570	643	6,596	691	6,639	737	6,691	707	6,737	732
Guangdong	9,449	696	9,544	721	9,638	721	10,441	705	10,505	689	10,594	740	10,644	771	10,724	887
Guangxi	4,768	438	4,816	450	4,856	452	4,610	426	4,645	443	4,682	437	4,719	439	4,754	453
Hainan	845	75	854	76	864	76	869	68	877	60	887	64	895	73	903	69
Chongqing	2,816	329	2,839	340	2,859	331	2,885	333	2,919	362	2,945	380	2,970	393	2,991	422

Sichuan	8,127	893	8,138	932	8,185	998	8,045	881	8,050	969	8,076	954	8,107	1,034	8,140	1,139
Guizhou	3,762	312	3,793	309	3,798	314	3,479	298	3,469	316	3,484	319	3,502	325	3,508	324
Yunnan	4,514	336	4,543	358	4,571	393	4,602	351	4,631	356	4,659	361	4,687	375	4,714	411
Tibet	284	19	287	19	290	20	300	15	303	15	308	17	312	16	318	17
Shaanxi	3,748	361	3,762	361	3,772	373	3,735	319	3,743	318	3,753	348	3,764	370	3,775	401
Gansu	2,617	205	2,628	215	2,635	220	2,560	211	2,564	228	2,578	238	2,582	230	2,591	231
Qinghai	552	36	554	38	557	39	563	36	568	34	573	40	578	41	583	41
Ningxia	610	38	618	40	625	42	633	41	639	35	647	43	654	46	662	45
Xinjiang	2,095	143	2,131	153	2,159	144	2,185	135	2,209	146	2,233	152	2,264	144	2,298	157
Total	12,9919	12,155	13,0827	12,479	13,1661	12,794	13,3384	11,879	13,4043	12,236	13,4789	12,669	13,5517	13,117	13,6246	13,713

Table A-2. Evolution process of regional population ageing in China from 1998 to 2014.

Region		1998	1999	2000	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Eastern	Beijing	+	+	+	+	+	+	+	+	+	+	+	*	+	^	^	^
	Tianjin	+	+	+	+	+	+	+	+	+	+	+	–	*	*	*	*
	Hebei	^	^	+	^	^	^	^	^	^	^	^	^	^	+	^	^
	Liaoning	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	+
	Shanghai	+	+	+	+	+	+	+	+	+	+	+	+	^	+	+	+
	Jiangsu	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	Zhejiang	+	+	+	+	+	+	+	+	+	+	+	+	^	^	^	+
	Fujian	+	+	^	^	^	+	^	*	*	*	*	–	–	–	–	–
	Shandong	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	Guangdong	+	+	^	^	–	^	^	^	^	^	^	^	^	^	–	–
Central	Shanxi	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Jilin	–	–	–	–	–	–	–	–	^	^	^	^	*	–	*	+
	Heilongjiang	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	^
	Anhui	+	+	+	+	^	+	+	+	+	+	+	+	+	+	+	+
	Jiangxi	^	^	^	^	^	^	^	^	^	^	^	^	^	^	^	–
	Henan	–	–	+	^	–	–	^	^	^	^	^	^	+	^	^	^
	Hubei	^	^	^	+	–	^	+	+	+	+	+	+	+	+	+	+

	Hunan	+	+	*	+	*	+	+	+	+	*	*	+	+	+	+	+
Western	Guangxi	*	*	*	*	*	*	*	–	–	–	–	*	*	*	*	–
	Hainan	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Chongqing	*	*	*	+	*	*	+	+	+	+	+	+	+	+	+	+
	Sichuan	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	Guizhou	^	^	^	^	^	^	^	^	^	^	^	+	+	+	+	^
	Yunnan	–	–	–	–	–	–	–	–	–	–	–	–	^	–	–	–
	Tibet	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Shaanxi	–	–	–	–	–	–	–	–	*	*	*	+	^	+	+	+
	Gansu	–	–	–	–	–	–	–	–	–	–	–	–	*	*	–	–
	Qinghai	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Ningxia	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	^
	Xinjiang	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Inner Mongolia	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

Note: + (HH), − (LL), * (HL), ^ (LH).

APPENDIX B

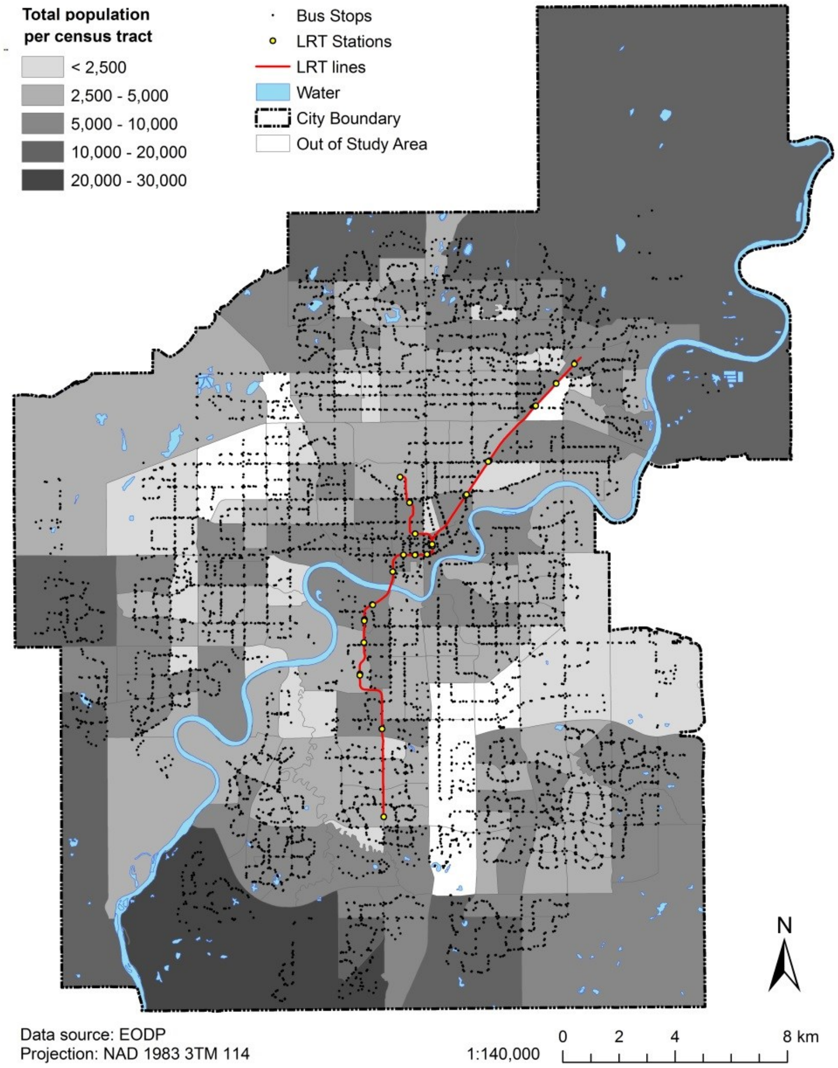

Figure B-1. Map of Edmonton, Canada, showing its public transport system.

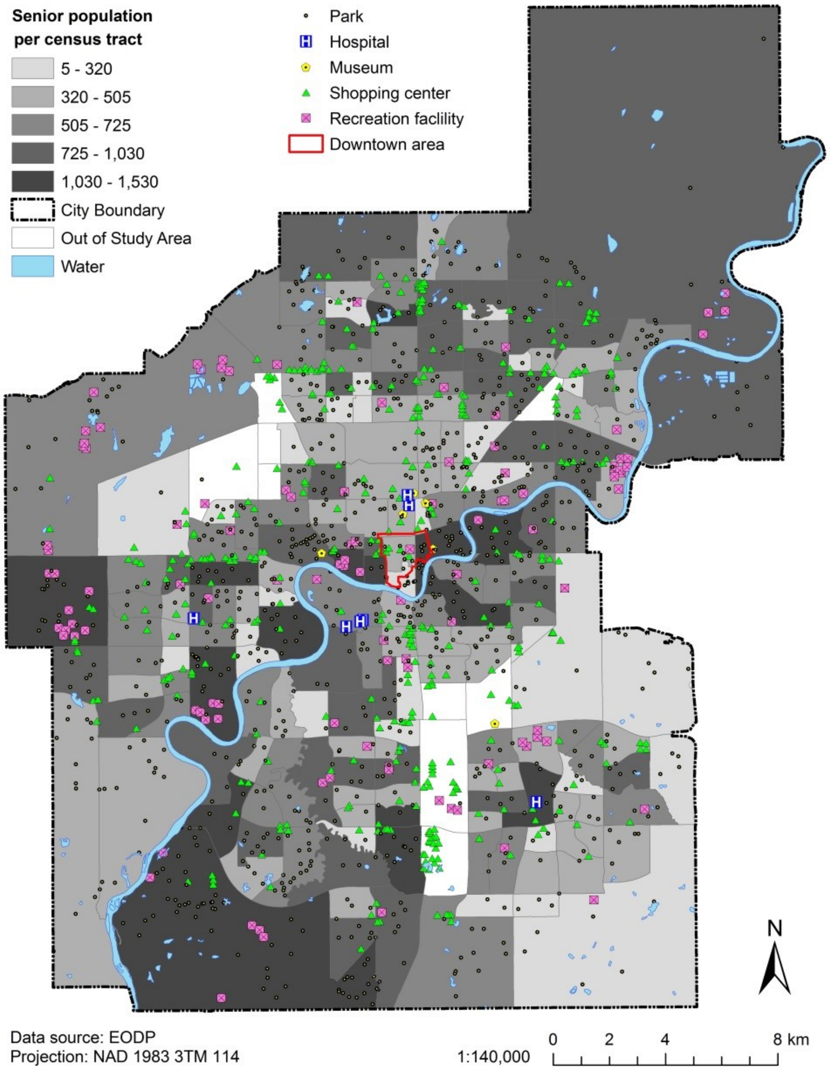

Figure B-2. Distribution of senior population and urban facilities in Edmonton.

APPENDIX C

Neighborhood Design and Regional Accessibility of Age-Restricted Communities from Resiliency and Spatial Perspectives[7]

C.1 Overview

The central aim of this research, operating from resiliency and spatial perspectives, is to propose a set of methods to analyze regional accessibility of age-restricted communities in terms of four types of facilities. The specific research objectives include: (1) exploring geographical locations of age-restricted communities for independent living; (2) analyzing spatial distribution of neighborhood facilities by type (i.e., hospitals, recreation facilities, shopping centers, and parks); (3) measuring accessibility of communities to each type of facility; and (4) providing related suggestions and policy implementations based on the research results. The proposed method is applied to a case study in Edmonton, Canada. The implementation of this methodology can facilitate accessibility analysis of age-restricted communities for the purpose of neighborhood improvement for different stakeholders at different stages of the community lifecycle. It can also provide a basis for urban planning strategies and approaches to solving population ageing issues, offer recommendations to developers of future communities, and enable seniors to lead a resiliency lifestyle.

C.2 Methodology

C.2.1 Analysis framework

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[7] A version of this chapter has been published in the Proceedings of the 2018 Construction Research Congress as follows. Chen, Y., Bouferguene, A., and Al-Hussein, M. (2018). "Neighborhood design and regional accessibility of age-restricted communities from resilient and spatial perspectives." *Proceedings, Construction Research Congress*, New Orleans, LA, USA, Apr. 2-5.

This study proposes a spatial analysis framework to analyze age-restricted communities on a regional scale, integrating spatial distribution and accessibility measures. A geographic information system (GIS) is utilized as the primary tool to realize the research objectives. Currently, this tool has been widely applied to spatial analysis in academic circles (Fotheringham and Rogerson 2013). Additionally, several scholars have assessed connectivity of nearby transit and pedestrian routes for age-restricted communities by means of GIS (Oswald Beiler et al. 2016). In order to clearly illustrate the relationship between the research method and research objectives, and to support generic applicability of the method to other regions for age-restricted community study, the framework underlying the methodology is presented in Figure C-1.

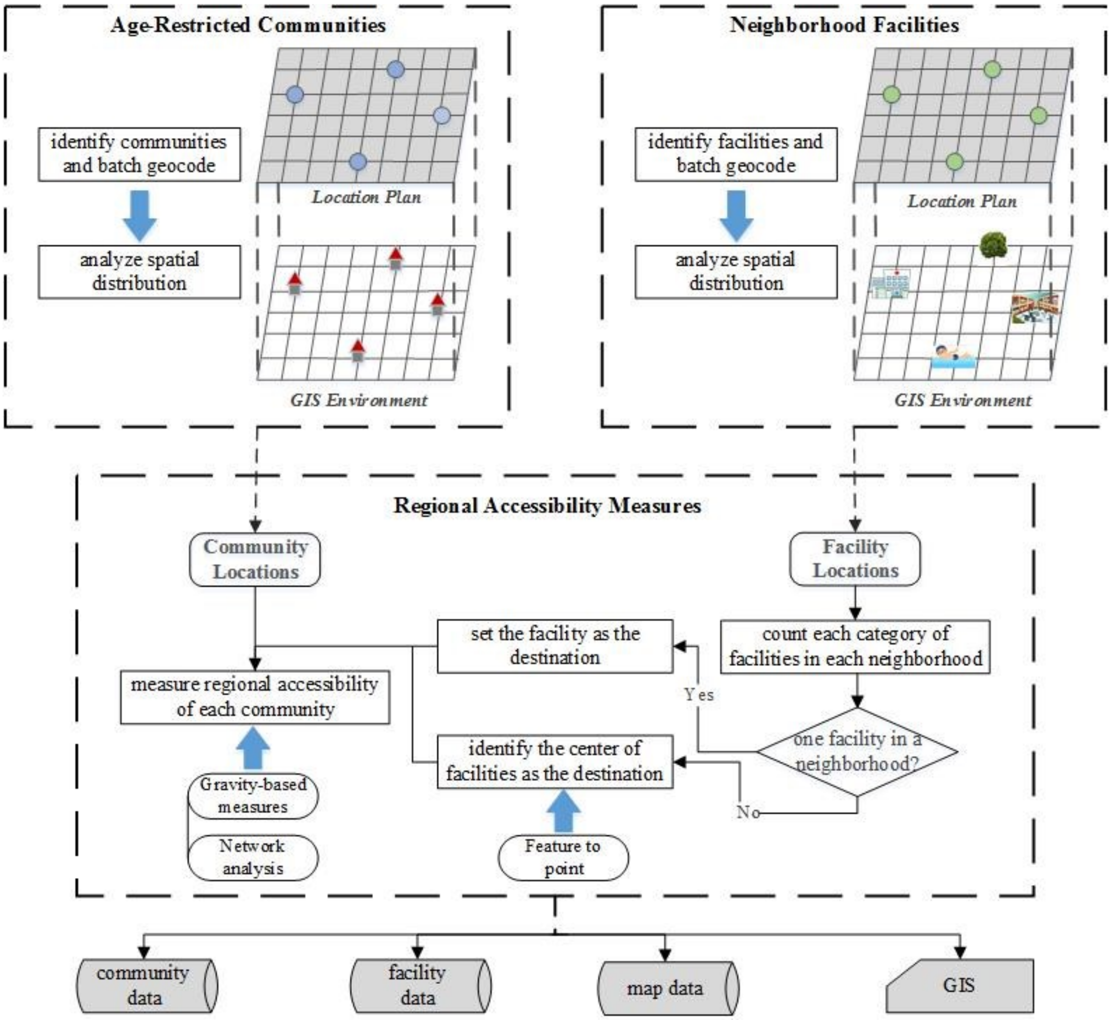


Figure C-1. Methodological framework.

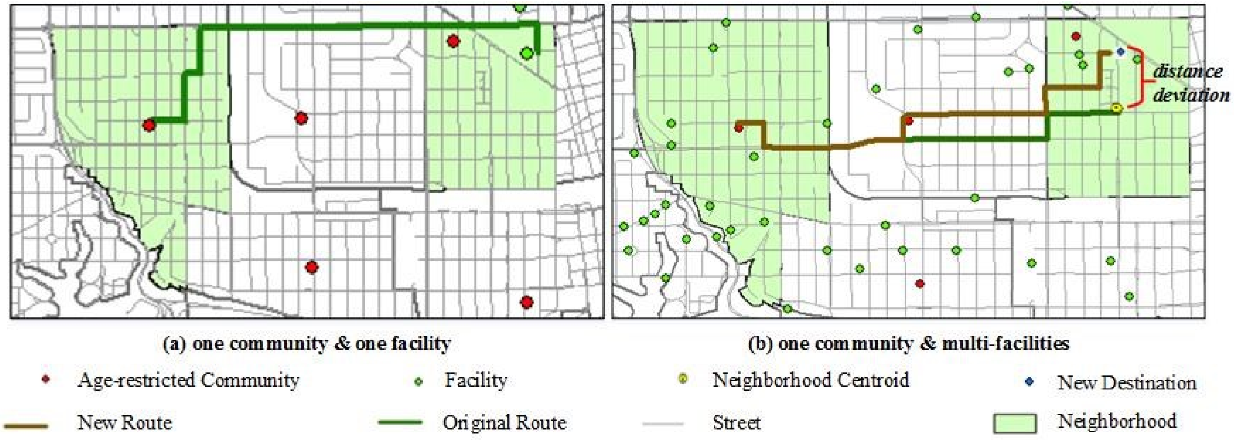
C.2.2 Accessibility measures

In urban planning, accessibility is regarded as a measure of potential opportunities relative to other opportunities in an area (Hansen 1959). Measures of accessibility are mainly composed of two parts: transportation impedance (or resistance), and attraction of an activity (Koenig 1980), where travel time and distance are widely used as impedance measures (Koenig 1980, El-Geneidy et al. 2016). Since mobility is dependent upon the performer's skills and abilities, the activity requirement, transportation modes, and environmental challenges (Frank and Patla 2003), these factors will influence the time seniors spend commuting on a given route. Furthermore, the transportation habits of seniors are diverse, ranging from driving to taking public transit or walking. In order to avoid these influences in considering accessibility from the region perspective, travel distance is used in this study as the transportation impedance metric for accessibility analysis. The common methods for measuring accessibility can be loosely organized into four types: spatial separation measures, cumulative opportunity measures, gravity-based measures, and utility-based measures (Shimbel 1953, Hansen 1959, Handy and Niemeier 1997). It is important to note that, for urban accessibility, what matters the most is not a micro-level view of the results. Quantitative-based approaches cannot be constructed based on first principles, since it is practically impossible to capture all the influencing factors. As a result, researchers in urban studies strive to build empirical models based on common sense and, to a certain extent, by finding parallels with physical problems (Koenig 1980). In other words, while it is expected that different methods for measuring accessibility will show discrepancies at the micro-level, the overall trends are likely to be similar. The choice of the metric to be used is therefore often chosen based on the available data, the objectives of the research, its ease for computer implementation, and, most importantly, its practical interpretability by urban planners and city managers. In this respect, accessibility indicators must be expressible in terms that can be understood by practitioners (i.e., by those not necessarily specializing in mathematical modeling) and be linkable to elements for which data can be collected. Among these methods, gravity-based measures discount the attractiveness of the destinations with increasing time or distance from the origin (Hansen 1959, Handy and Niemeier 1997, Geurs and van Wee 2004). This measure has been widely used in neighborhood accessibility studies (Handy and Clifton 2001). Hence, gravity-based measures are used in the present study as described below (Bhat et al. 2002), forming the foundation of the proposed framework.

$$A_i^k = \ln\left[\frac{1}{J}\sum_j \frac{O_j^k}{d_{ij}^{k\alpha}}\right] \tag{C-1}$$

where A_i^k is the accessibility from age-restricted community i to all facilities of type k in all neighborhoods; O_j^k is the number of facilities belonging to type k in neighborhood j; $d_{ij}^{k\alpha}$ is the shortest distance from age-restricted community i to facilities belonging to type k in neighborhood j; α is the travel friction coefficient or the distance decay parameter; J is the total number of neighborhoods which contain type k of facilities; ln is the logarithmic function, which is used for shifting the accessibility values into dimensionless quantities, and comparing accessibility among different groups.

As for the shortest distance $d_{ij}^{k\alpha}$, if there is only one facility of a type in a neighborhood, the distance is directly equal to the shortest distance based on the street network. Otherwise, the distance is measured from a community to the centroid (or geometric center) of a neighborhood. This method is simple, but it may result in a large deviation from the actual distance if the distribution of facilities is relatively scattered or the concentration point is far away from the centroid of the given neighborhood. To reduce the above effects, the new point is calculated as a facility destination based on the density distribution of the existing facility locations. The two calculation methods are displayed graphically in Figure C-2. It should be mentioned that the distance is not a straight line, but rather is constrained by the layout of the street network.



(a) one community & one facility

(b) one community & multi-facilities

Figure C-2. A graphical representation of distance measure.

In particular, the travel friction coefficient, α, to be determined requires additional data and effort to define and may be region-specific (Huff 2000). It can be estimated by the regression method (Wang 2012), linear programming (O'Kelly et al. 1995), the particle swarm optimization (Xiao et al. 2013), and the Monte Carlo simulation (Liu et al. 2012). Bhat et al. (2002) conducted three types of gravity-based measures for work, shopping, and recreation, resulting in the following corresponding travel friction coefficients: $\alpha_{work} = 2.0347$, $\alpha_{shopping} = 2.5000$, and $\alpha_{recreation} = 3.0751$. This study will use the above three measures for the regional accessibility measure of age-restricted communities.

C.3 Case Study

C.3.1 Data description

In 2006, people aged 55 and over in Edmonton, Canada, represented approximately 21% of the population. This number is projected to be nearly 32% by 2041 (City of Edmonton 2010), and therefore represents a significant potential market for age-restricted community development.

Furthermore, Edmonton introduced in 2011 an action plan for developing an age-friendly city, aiming to build a city that values, respects, and actively supports the well-being of seniors and advances the goal of improving livability. Given its demographic realities and this particular focus on age-friendly development, Edmonton is taken as a case study in this research exploring the regional accessibility of age-restricted communities from resiliency and spatial perspectives. The data sources primarily comprise neighboring facility locations (i.e., recreation facilities, shopping centers, and parks) and the street network, which are retrieved from Edmonton's Open Data Portal (EODP 2017); locations of 46 age-restricted communities for independent living in Edmonton from Alberta Senior Housing Directory (ASHD 2017); and locations of seven hospitals in Edmonton from Alberta Health Services (AHS 2017).

C.3.2 Results and analysis

Based on the methodological framework displayed in Figure C-1, network analysis in GIS and gravity-based measures expressed in Eq. (C-1) are utilized to measure regional accessibility of age-restricted communities to facilities in all potential neighborhoods. The results of regional accessibility are then divided by different types of facilities.

- *Hospitals*

From Figure C-3, it can be observed that age-restricted communities are relatively concentrated in the central area of the city, which is separated by the river into two parts. The neighborhoods containing these communities tend to be adjacent to at least one other neighborhood with similar communities. However, there are some age-restricted communities scattered throughout the surrounding areas of the city. It is clear that the neighborhoods containing age-restricted communities typically feature better developed street networks, which enhances the convenience and provides more opportunities for neighborhood commuting and connection. In fact, the condition of public transport is one of the factors influencing decision making about site selection by housing developers (Krisnaputri et al. 2016). Thus, older adults living in these communities are provided with basic transportation opportunities.

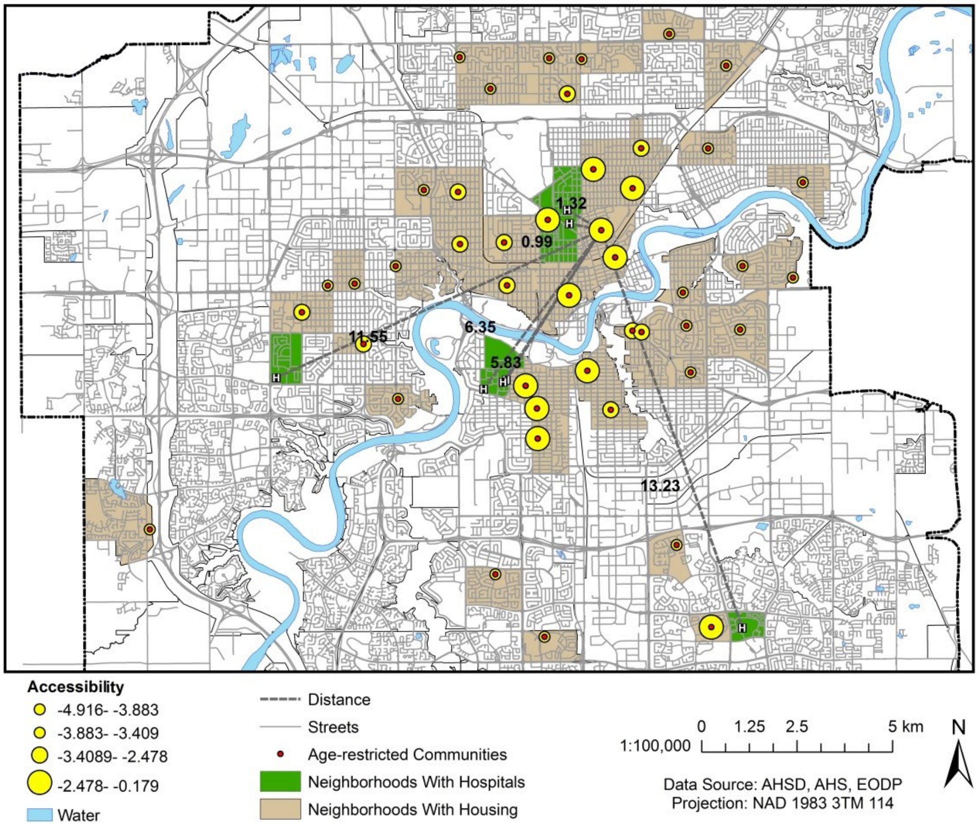


Figure C-3. Regional accessibility to hospitals.

Five hospitals are located in the center of the city, three of them in the same neighborhood on the University of Alberta campus. The distance values in Figure C-3 give the shortest distance from an age-restricted community to a hospital, a distance which is measured according to the street network (see an example in Figure C-2). Overall, there are large variances in regional accessibility of age-restricted communities to hospitals, and the communities in the central area obviously have better access to hospitals than other communities. Since the number of hospitals is limited, regional accessibility based on cumulative gravity-based measures is mainly determined by distance. In other words, as can be seen in Figure C-3, the closer a community is located to one or more hospitals, the larger the accessibility value.

- *Recreation facilities*

The City of Edmonton maintains more than 100 public recreation facilities, including golf courses, swimming pools, and other indoor and outdoor facilities spread across 60 neighborhoods. However, Figure C-4 indicates that the geographical locations of these facilities tend to be scattered throughout the central and surrounding areas. Additionally, some neighborhoods have recreation facilities distributed in a relatively dense pattern, while other neighborhoods have no facilities. Hence, the distribution of recreation facilities is not balanced among all neighborhoods, and thus it fails to equitably serve the disadvantaged group (older adults with limited mobility) in age-restricted communities. Similar to regional accessibility to hospitals, seniors who are provided with more opportunities within a shorter distance will have better accessibility to recreation facilities. An example of this is the community with four distance values presented in Figure C-4.

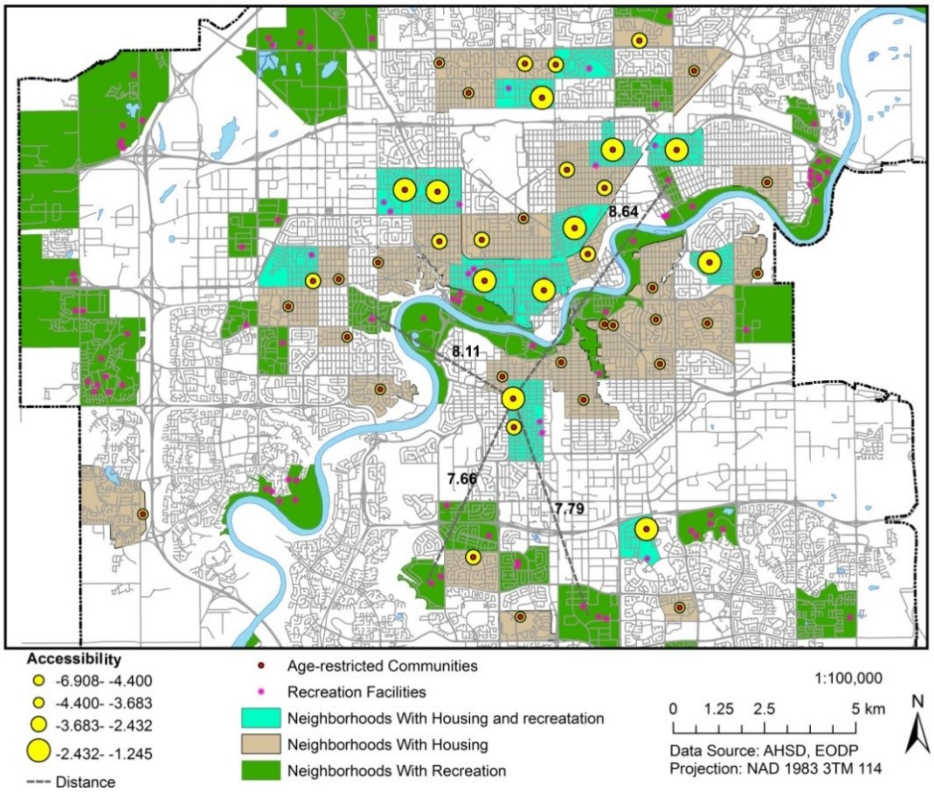


Figure C-4. Regional accessibility to recreation facilities.

- *Shopping centers & parks*

Since there are many shopping centers and parks in Edmonton, heat maps are used to represent the density of these two types of facilities, as presented in Figure C-5. Here a darker color refers to a higher-density distribution. It can be observed that the heat map for shopping centers forms several concentric irregular-circles, the centers of which are independent from one another. Conversely, the centers of the circles in the heat map of parks appear to overlap. Thus, regional accessibility to shopping centers and parks is influenced by both the attractiveness of the facility and the transportation distance. To a great extent, investigations of accessibility to the two types of facilities reveal nearly identical distributions in regard to the divided quantiles. In short, in comparing the two heat maps, the sizes of the accessibility circles are almost identical for a given location of age-restricted communities.

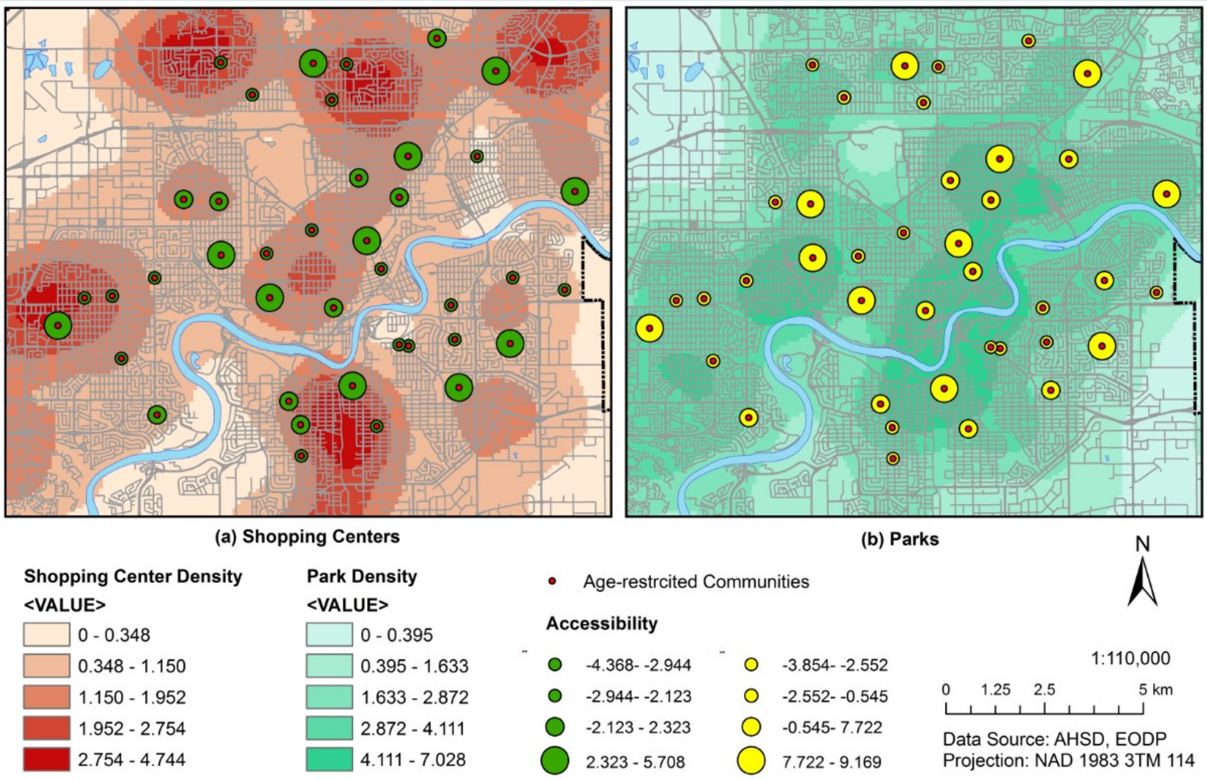


Figure C-5. Regional accessibility to shopping centers and parks.

C.4 Conclusion

Within the context of population ageing, it is essential to improve the accessibility of age-restricted communities among neighborhoods and to maintain a resiliency lifestyle for older adults. This research proposes a set of spatial methods to measure regional accessibility of age-restricted communities to different facilities, including hospitals, recreation facilities, shopping centers, and parks at the neighborhood level. As for the case study of Edmonton, age-restricted communities are found to be concentrated in the central area of the city. Although the neighborhoods that contain age-restricted communities are not always adjacent to one another, the street network surrounding these communities is relatively well developed. Hospitals are mainly located in the center of the city, while recreation facilities are scattered in both the central and surrounding areas of the city. Both types of facilities are scattered unevenly at the neighborhood level, inhibiting their accessibility by seniors in these communities. Shopping centers and parks are abundant in Edmonton, and several concentric irregular-circles are formed separately in their density distribution. Overall, there are large variances in regional accessibility of age-restricted communities to all facilities regardless of type, since the values of accessibility when divided into four quantiles show significant discrepancies in terms of the numbers of communities. In other words, older adults in these communities have inequitable access to different facilities depending on the neighborhood. Specifically, regional accessibility to hospitals and recreation facilities is primarily determined by transportation impedance, since access to these facilities is limited in all neighborhoods. Meanwhile, the attractiveness of facilities and transportation distance are the two factors that most influence regional accessibility to shopping centers and parks. Furthermore, accessibility quantiles of these two types of facilities reveal a nearly identical distribution.

Decisions about where to locate facilities in neighborhoods under development influence the accessibility level of age-restricted communities at the earliest stage. Taking into account accessibility at this early juncture can help to meet the basic demands of older adults, thereby enhancing resiliency in their daily life. Some more specific recommendations and policy implementations can be proposed based on the research results: (a) the geographical distribution of facilities serving seniors should be improved in order to offer at least one of each type of facility, provide a variety of facility choices, and attract more older adults; (b) facilities should be evenly distributed based on their demand density within a neighborhood, especially for those which include age-restricted communities; (c) two aspects—facility attractiveness and transportation impedance—can be undertaken to adjust the balance of regional accessibility with regard to specific cases; (d) improving the level of development of the street network and adding public transport infrastructure can improve neighborhood connections and enhance public transportation opportunities; and (e) developers should consider locations with better accessibility to facilities as potential sites for age-restricted communities. These policies as an outcome at the micro level, while they are expected based on the results of this research to enhance accessibility in age-restricted communities, may turn out to have little or no effect in specific cases. However, as mentioned above, the objective of a given municipal policy is to have the expected effect on a large scale, namely, at the city level.

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APPENDIX D

D.1 Journal Papers

1. Chen, Y., Bouferguene, A., Shen, Y.H., and Al-Hussein, M. 2019. Difference analysis of regional population ageing from temporal and spatial perspectives: a case study in China. Regional Studies, **53**(6): 849–860. doi:10.1080/00343404.2018.1492110.
2. Chen, Y., Bouferguene, A., Shen, Y.H., and Al-Hussein, M. 2019. Assessing accessibility-based service effectiveness (ABSEV) and social equity for urban bus transit: A sustainability perspective. Sustainable Cities and Society, **44**: 499–510. doi:10.1016/j.scs.2018.10.003.
3. Yin, X., Liu, H., Chen, Y., and Al-Hussein, M. 2019. Building information modelling for off-site construction: Review and future directions. Automation in Construction, **101**: 72–91. doi.org/10.1016/j.autcon.2019.01.010.
4. Islam, M. S., Chen, Y., Bouferguene, A., and Al-Hussein, M. 2019. Rethinking urban open space distribution for municipal financial sustainability. Journal of Computing in Civil Engineering, **33**(3): 04019012. doi.org/10.1061/(ASCE)CP.1943-5487.0000818.
5. Chen, Y., Bouferguene, A., Li, H.X., Liu, H.X., Shen, Y.H., and Al-Hussein, M. 2018. Spatial gaps in urban public transport supply and demand from the perspective of sustainability. Journal of Cleaner Production, **195**: 1237–1248. doi:10.1016/j.jclepro.2018.06.021.
6. Li, H. X., Chen, Y., Gül, M., Yu, H., and Al-Hussein, M. 2018. Energy performance and the discrepancy of multiple NetZero Energy Homes (NZEHs) in cold regions. Journal of Cleaner Production, **172**: 106–118. doi.org/10.1016/j.jclepro.2017.10.157.

7. Chen, Y., Bouferguene, A., and Al-Hussein, M. 2018. Analytic hierarchy process–simulation framework for lighting maintenance decision-making based on the clustered network. Journal of Performance of Constructed Facilities, **32**(1): 04017114.doi.org/10.1061/(ASCE)CF.1943-5509.0001101.

D.2 Book Chapters

1. Chen, Y., Lei, Z., Han, S.H., Bouferguene, A., Li, H.X., and Al-Hussein, M. 2018. Applications of discrete event simulation in construction engineering. *In* Advances in Engineering Research, **21**, Petrova, V.M. (Ed.), Nova Science Publishers, Hauppauge, NY, USA, pp. 1–44.

D.3 Conference Papers

1. Chen, Y., Yin, X.F., Zhang, Q., Bouferguene, A., Zaman, H., Al-Hussein, M., Russell, R., and Kurach, L. 2019. Productivity analysis of manual condition assessment for sewer pipes based on CCTV monitoring. *In* Canadian Society for Civil Engineering conference. Montréal, Canada. (Accepted)
2. Yin, X.F., Chen, Y., Zhang, Q., Bouferguene, A., Zaman, H., Al-Hussein, M., Russell, R., and Kurach, L. 2019. A neural network-based application for automated defect detection for sewer pipes. *In* Canadian Society for Civil Engineering conference. Montréal, Canada. (Accepted)
3. Chen, Y., Wang, M., and Li, L. 2019. A framework for contract management system in cloud-based ERP for SMEs in the construction industry. *In* International Conference of Construction and Real Estate Management. Banff, AB, Canada. (Accepted)
4. Chen, Y., Yin, X.F., Bouferguene, A., Zhang, Y.X., and Al-Hussein, M. 2019. Accessibility-based location selection for building panelized housing for seniors. *In* Modular and Offsite

Construction Summit. Banff, AB, Canada. (Accepted)

5. Yin, X.F., Chen, Y., Bouferguene, A., Zaman, H., Al-Hussein, M., Russell, R., and Kurach, L. 2019. Standard closed-circuit television (CCTV) collection time extraction of sewer pipes with machine learning algorithm. *In* International Symposium on Automation and Robotics in Construction. Banff, AB, Canada. (Accepted)
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8. Chen, Y., Li, L., Shen, Y.H., and Liu, B.S. 2017. A simulation optimization method for design and control of signalized intersections in urban areas. *In* European Modelling and Simulation Symposium. Barcelona, Spain. pp. 1–7.
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