Integration of GIS and soft computing for suitability evaluation of high-density urban development: The Logic Scoring of Preference method

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Abstract

The Logic Scoring of Preference (LSP) method is based on soft computing principles for complex spatial decision-making that integrates large number of criteria and capture human logic reasoning. The main objective of this study is to develop, implement and apply the LSP method in the Geographic Information System (GIS) environment for the land suitability evaluation for high-density urban development. Two different stakeholders, urban developer and urban planner, were considered. The geospatial datasets of Metro Vancouver Region, Canada, were used to implement the GIS-based LSP method. Several LSP aggregator groups have been compared and the results indicate that there are differences between the two stakeholder's perspectives on suitable locations for high-rise urban development. The GIS-LSP method provides an effective way for identifying the best location for high density urban developments and thus contribute to more sustainable urban practices that can minimize the impact of the urban sprawl.

Keywords: land use densification; land suitability evaluation; Logic Scoring of Preference (LSP) method; soft computing; multicriteria evaluation (MCE); geographic information systems (GIS)

Dedication

To my loved ones, your wholehearted support is always with me even when I reach the nadir.

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Chapter 1.

Introduction

As indicated by the United Nations (UN)'s population projections, a 33% increase of world population is projected by 2050 (Gerland et a l., 2014). The fast growth of population and spread of economic activities have induced the horizontally expansion of urban area from current urban centre (Paulsen, 2012). Urban sprawl, which refer to the excessive horizontal growth of cities, is a complex process and has caused environmental problems by devouring agricultural and forested lands (Kline, Azuma, & Alig, 2004). Therefore, the sustainable urban development is necessary, which in essence encompass needs of humans but with ecosystem and environmental protection (Tracey & Anne, 2008). Urban densification is a form of growth that meet the need of sustainability (Burton, Jenks, & Williams, 2004). It aims to restrict the urban sprawl by limiting the space for residential development and eventually leads to a denser urban area (Brueckner, 2000).

Urban densification is characterized by the high-rise buildings and mixed land use such as the combination of commercial and residential (Burton, 2002; Turkington, van Kempen, & Wassenberg, 2004), directly impacting the structure and form of urban area. In the highly populated cities where the problem of population growth and shortage of land are increasingly significant, the high-density building development is commonly used to mitigate these issues (Ibrahim, 2007). Therefore, urban planning that incorporate densification is oriented in a long-term towards sustainable goals (Næss, 2001).

Urban planners and developers are having significant roles in urban growth process (Morgan, 2010). They are identifying and reacting to the housing market, which is influenced by the changes of society and demography (Fincher, 2007). In the context of urban developers, they can identify the gap in local housing market and try to fill this gap by constructing the appropriate housing, from which their profit can be maximized (Almagor, Benenson, & Alfasi, 2018; Czamanski & Roth, 2011; Magliocca, McConnell, & Walls, 2015). On the other hands, urban planners are in charge of approving and opening new urban zones in the urban area for building construction (Almagor et al., 2018; Coiacetto, 2000; Peiser, 1990). However, their interactions are frequently inconsistent and complicated, which are affecting by many factors and that are usually hard to capture (Fincher, 2004, 2007; Turkington et al., 2004).

Therefore, there is a need for spatial decision methods to facilitate the decision-making process in urban context. Approaches such as Multicriteria Evaluation (MCE) can assist in decision-making process by considering various criteria developed by stakeholders and further applied to evaluate the performance of multiple-choice alternatives (Malczewski, 2004; Malczewski & Rinner, 2015). MCE can be integrated with Geographic Information Systems (GIS) to achieve the decision-making process in a spatial context (Carver, 1991; Jankowski, 1995).

1.1. Theoretical Background and Research Problems

Instead of making decision according to only one criterion, multiple criteria evaluation approach allows the comprehensive integration of different criteria for assisting the decision-making process. MCE is a group of evaluation methods that employ a list of decision criteria to solve a certain decision problem. It always requires the decision maker to choose from different alternatives with a certain level of compromise based on their preferences. MCE methods have been widely used in the last several decades for different application, from water and energy management (Özelkan & Duckstein, 1996; Raju & Pillai, 1999), forest management (Phua & Minowa, 2005), agriculture (Ceballos-Silva & López-Blanco, 2003; Sánchez-Lozano, Teruel-Solano, Soto-Elvira, & Socorro García-Cascales, 2013) and landslide susceptibility (Dragićević, Lai, & Balram, 2015) to land use suitability (Aburas, Abdullah, Ramli, & Asha'ari, 2017; Feizizadeh & Blaschke, 2013; X. Zhang, Fang, Wang, & Ma, 2013).

1.1.1. MCE Methods

MCE methods are mainly consisting of three steps: (1) identify the criteria and alternatives for a certain evaluation project; (2) measure the relative importance of criteria based on the preference of stakeholder(s); (3) combine the criteria to generate a integrated ranking of alternatives (Triantaphyllou, 2000). Therefore, two major issues characterize the MCE methods are how the relative importance of criteria can be measured in a numerical way and how an alternative can be ranked by simultaneously employing all the criteria.

Numerous MCE methods are developed and used: multi-attribute utility theory (MAUT) (Fishburn, 1967; Fishburn & Keeney, 1974; Keeney, 1977), simple additive weighting (SAW) (Malczewski, 2000), analytic hierarchy process (AHP) (Saaty, 1980), outranking (Roy, 1990) and ordered weighted average (OWA) (Yager, 1988).

MAUT is a commonly used method in solving natural resource management problem by considering multiple objectives and uncertainty (Fishburn, 1967; Fishburn & Keeney, 1974; Keeney, 1977). It is developed from the Multi-Attribute Value Theory (MAVT). The way MAUT involved human decision-making logic into evaluation is by using a utility function for each criterion, which is a function defined to measure the impact of individual criterion on the overall result. Although it can incorporate the preferences of stakeholder, the preferences must be precisely weighted, which can lead to a relative subjective result. Furthermore, it requires a large dataset for processing at each step, which make it difficult to apply in smaller scale problem (Velasquez & Hester, 2013).

SAW, or known as Weighted Linear Combination (WLC), is one of the most widely used MCE method in GIS environment due to its easy-to-use and understand. The human reasoning logic is reflected on its use of weighted average and standardization of criteria (Jiang & Eastman, 2000). By weighting the criteria, the low score can be compensated by high score. Moreover, the fuzzy set theory is applied to standardize the criteria, rescaling its values into a statement of set membership, which reflects a strong human logic process (Jiang & Eastman, 2000). However, due to its oversimplicity, the result can not always represent the real-world scenario, and thus, leading to its limited application.

AHP is another widely used MCE method that extends the SAW in solving real-world problems. By using AHP, decision maker can structure their criteria and alternatives on different level in a hierarchy way. Then, each criterion on a certain level is pair-wisely compared and calibrated on a numerical scale from 1 to 9. It can also be flexibly integrated with other method to address the complexity in real life problems. For example, combining the AHP with fuzzy logic, or integrating it with other techniques like linear programming and artificial neural network (Vaidya & Kumar, 2006). However, although it can be easily used by decision maker to determine the weights and compare different alternatives, it relies heavily on the knowledges and preferences of decision maker, which can cause the inconsistency of preference on the same criterion.

Outranking method is proposed to deal with the outranking relation between the criteria, which is suitable for solving real-world problem. Its way of capturing human reasoning is by using a pair-wise comparison between alternatives under each of the criterion to determine the decision maker's preference of alternatives. Two main representatives of outranking method are ELECTRE and PROMETHEE (H. Zhang, Wang, & Chen, 2016). Various versions of ELECTRE have been developed to solve different decision-making problems. However, ELECTRE can lead to the obscurity of strength and weakness of the alternative (Velasquez & Hester, 2013).

OWA is a generalization of Boolean overlay operations and WLC method that considers more scenarios of risk taking and provides a wider spectrum between the AND and OR operators. Decision making logic is represented in its measurement of Orness and tradeoff (Jiang & Eastman, 2000; Malczewski, 2006b). Orness measures the similarity degree between an OWA operator and the OR operator. It can identify the behavior of the decision maker about considering multiple criteria simultaneously. On the other hand, tradeoff is a measurement of the substitutability of criteria, in which they can be compensated by each other. Therefore, OWA has the strength to represent the decision maker's reasoning by adjusting the Orness and tradeoff when assessing criteria in different scenarios. However, when dealing with a large group of criteria, OWA has limited capability in addressing the relationship between criteria (Gorsevski, Donevska, Mitrovski, & Frizado, 2012a; Malczewski, 2006b).

1.1.2. GIS-based MCE

When making decision in a spatial context, for example in land use planning, difficulties will arise if an alternative is affected by its location and surrounding environment. Therefore, a spatial decision support system (SDSS) (Malczewski, 1999, 2006a) is needed in order to evaulate alternatives spatially. GIS is considered as a support system that perform numerous tasks on the spatially referenced data. It can be integrated in SDSS by converting and combining geographical data with decision maker's reasoning logic, and subsequently deriving information to facilitate the decision-making process (Malczewski, 1999). Thus, by combining GIS capabilities of spatial data retrieval, storage, analysis and visualization, and MCE capabilities of making decision support from human reasoning, the spatial decision making can be achieved.

GIS-based MCE has been widely used in various applications: agriculture (Ceballos-Silva & López-Blanco, 2003; Feizizadeh & Blaschke, 2013; Hossain, Chowdhury, Das, & Rahaman, 2007; Sánchez-Lozano et al., 2013; van Haaren & Fthenakis, 2011), forest management (Phua & Minowa, 2005; Store & Kangas, 2001), urban planning (Abdullahi, Pradhan, & Jebur, 2015; Aburas et al., 2017; Marinoni, 2004; Mohammed, Elhadary, & Samat, 2016) and site selection (Gorsevski, Donevska, Mitrovski, & Frizado, 2012b; Nas, Cay, Iscan, & Berktay, 2010). In general, it is usually used to perform land suitability analysis (Malczewski, 2006a), in which maps are integrated with criteria to determine the suitable location (Jankowski, Andrienko, & Andrienko, 2001).

In the software aspect, MCE can be coupled with GIS loosely, tightly or even full integration (Malczewski, 2006a). In a loosely-coupled way, the GIS and MCE software can either use a file exchange module or share a common database (Jankowski, 1995). In this way, files or values generated from decision maker's preference in GIS can serve as the input of MCE to further make the decision. On the other hand, the tightly-coupled approach is achieved by sharing both the data and user interface for GIS and MCE. For example, the DECADE module developed on the basis of a dynamic mapping software that share a common user interface (Jankowski et al., 2001) and the MapModels created based on ArcGIS environment (Riedl, Vacik, & Kalasek, 2000). Furthermore, the full integration of GIS and MCE is achieving by embedding MCE into GIS software as a function or embedding GIS analysis into MCE software. For example, the built-in ModelBuilder and Map Algebra in ArcGIS (ESRI, 2019) and the Macro Modeler in TerrSet (Clark Labs, 2019). The built-in functions in ArcGIS and Idrisi provide a user-friendly interface for transforming decision maker's preference into logical expressions, which are commonly used for making spatial decision. However, in case of modelling a more complex spatial problem, the above built-in functions are rather difficult to fully capture the human reasoning logic (Malczewski, 2004).

1.1.3. High-density Development Suitability Analysis

High-density urban development is involving the complex interaction among social, economic and environmental aspects. Urban developer and planner are the main characters participating into the construction of new high-rise building (Almagor et al., 2018; Coiacetto, 2000; Peiser, 1990). On one hand, urban developers are those who have the money and resource to construct new building. On the other hand, urban planners are the policy maker that guide the development of urban area. They can interact with each other and their narratives are complicated (Fincher, 2007, 2004; Turkington et al., 2004). Therefore, the perspectives of urban developer and planner needed to be investigated in order to perform the suitability analysis of high-density development.

A decentralized development of high-rise residential is argued to be more favored by policy maker as it is consistent with aspirations of sustainability, in which urban planner is focus more on the accessibility to facilities and public transportations (Burton et al., 2004). Furthermore, some social factors such as population density, population distribution and transportation facilities are considered by decision maker (Turskis, Zavadskas, & Zagorskas, 2006; Zagorskas, Burinskienė, Zavadskas, & Turskis, 2007). At the same time, closer to existing residential area, high dense commercial and street networks are proved to be more suitable for development in the perspectives of urban developer. Since transport infrastructure such as major roads and stations is essential for improving the connectivity in the urban area and can add speed and efficiency to the urban development progress, it is considered to be an important factor for high-density growth. Therefore, urban developer and planner would place more importance on the accessibility to services, recreational amenities, and job centers (Abdullahi et al., 2015). However, a systematic composite of these criteria is hard to determine in different area as they present with various characteristics. Studies have indicated that in a developed country, the proximity to the main road, public transportation, city center, and shopping center are the major criteria in urban developer's perspectives (Alonso, 1964; Mills, 1967; Muth, 1969). Furthermore, a survey of 140 developers were conducted in the Province of British Columbia, Canada, showing that urban developers are rather concerning more on the accessibility to shopping area and availability of developable land (Goldberg, 1974; Goldberg & Ulinder, 1976).

Therefore, the criteria involved in determining the perspectives of urban developer and planner are complicated and comprised of different aspects that differ in various regions. They need to be justified in the context of study area, in which a list of criteria can be created and elaborated for land suitability analysis. A recent study has performed the GIS-based MCE land suitability analysis of high-density urban development in Surabaya, Indonesia, in which a list of criteria including market size, accessibility to facilities, land price, land topography and infrastructure availability are created to represent the perspectives of urban planner (Aulia, Rahmawati, & Ariastita, 2014). Moreover, a GIS-based MCE are also performed in Metro Vancouver Region where urban developer and planner would put more insight on the seven groups of criteria comprising transportation facilities, environment, land use, services and amenities, population density, recreation and community, and job opportunity (Koziatek & Dragićević, 2017).

The above two land suitability analysis are using the AHP method for representing the decision-making process, which are deficient in two aspects. Firstly, the common MCE method such as AHP and OWA have limited capability in coupling with a large group of criteria (especially more than 10-12). Secondly, although some MCE such as OWA can capture human reasoning by using aggregation structure, they are insufficient in representing the full intuitive human logic and the mandatory, optional or sufficient requirements of decision maker (Dujmovic, De Tré, & Dragicevic, 2009; Dujmović & Tré, 2011). Since the land suitability analysis of high-density development involves complex processes and perspectives, a method such as Logic Scoring of Preference (LSP) that can aggregate large number of criteria and capture a wider spectrum of human decision logic must be used.

LSP is a soft computing method that allows for the stepwise aggregation of criteria to represent the full range of human decision logic without losing individual significance of the criteria. It provides a wide selection of formal logic aggregators from simultaneity (andness) to substitutability (orness) in aggregation structures (Dujmovic, 2007; Dujmović, 1975; Dujmović & Tré, 2011). The crisp granulation of andness and orness can offer a more complex analysis of tradeoff between choice alternatives and a more precise modeling of human evaluation reasoning. Therefore, its use of logic operators and structure extends the original representations of human reasoning. With the advantage of LSP method offering a variety of specific types of aggregation procedure, it is possible to capture the complexity of criteria related to high-density urban development and the preference of both developer and planner.

However, the use of LSP method in GIS software such as ArcGIS and TerrSet are inconvenient and time-consuming. For example, by using the LSP in ArcGIS environment, a complicated conditional function must be written in the Map Algebra tool, which may lead to unexpected error. Furthermore, it is hard to maintain and modify as the Map

Algebra does not provide a saving option. Therefore, both GIS software environments are lacking the capability to model a more complex spatial problem.

In order to addresses these limitations of existing GIS-based MCE methods and existing GIS software to implement the LSP method, and help better understand what role urban developer and planner play in the high-density urban developments, the proposed research raises the following research questions:

1. Can GIS-based LSP method be useful for land suitability analysis of urban densification and representation of perspectives of different stakeholders such as urban developer and planner reasoning?

2. How can LSP method be implemented as an independent module in GIS software and thus become a user-friendly decision-making tool?

1.2. Research Objectives

In order to answer the research questions, the main objectives of this research study are to incorporate LSP method for identifying suitable locations for high density urban growth with consideration of urban developer and planner’s goals and interests.

The following research objectives are the main parts of the thesis that address the questions:

1. Develop a GIS-based LSP method for identification of the areas suitable for urban densification in the perspectives of two stakeholders, urban developer and urban planner.

2. Combine the outputs of two stakeholders by using several LSP aggregators that represent different scenarios for the calculation of overall integrated suitability.

3. Compare the outputs of several LSP aggregators groups in the perspective of urban developer and evaluate the sensitivity of LSP suitability outputs on different locations.

4. Develop an LSP module that operates in a GIS software environment that can facilitate the use of LSP method with geospatial data.

1.3. Study Area and Datasets

The Metro Vancouver region (Figure 1.1) is in south-western British Columbia, Canada, which is the Canada's largest metropolitan area and comprising of 22 municipalities, 1 electoral area and 1 treaty First Nation (Metro Vancouver, 2019). It is a highly populated region which taking approximately 50% of the population of British Columbia. In the past three decades, Metro Vancouver has a significant population growth of 1 million (Statistics Canada, 2017). The population is continually increasing by 6.5% from 2011 to 2016 (Government of Canada, 2017). It is projected to achieve 3.4 million by 2041 (Metro Vancouver, 2011). The Metro Vancouver Region is facing a significant problem for accommodation of this large number of inhabitants in a livable and sustainable way. Therefore, in order to accommodate such growth without experiencing urban sprawl, the region needs to advance urban planning for greater density, but also should establish the transportation infrastructures and public service facilities to reach sustainable goals.

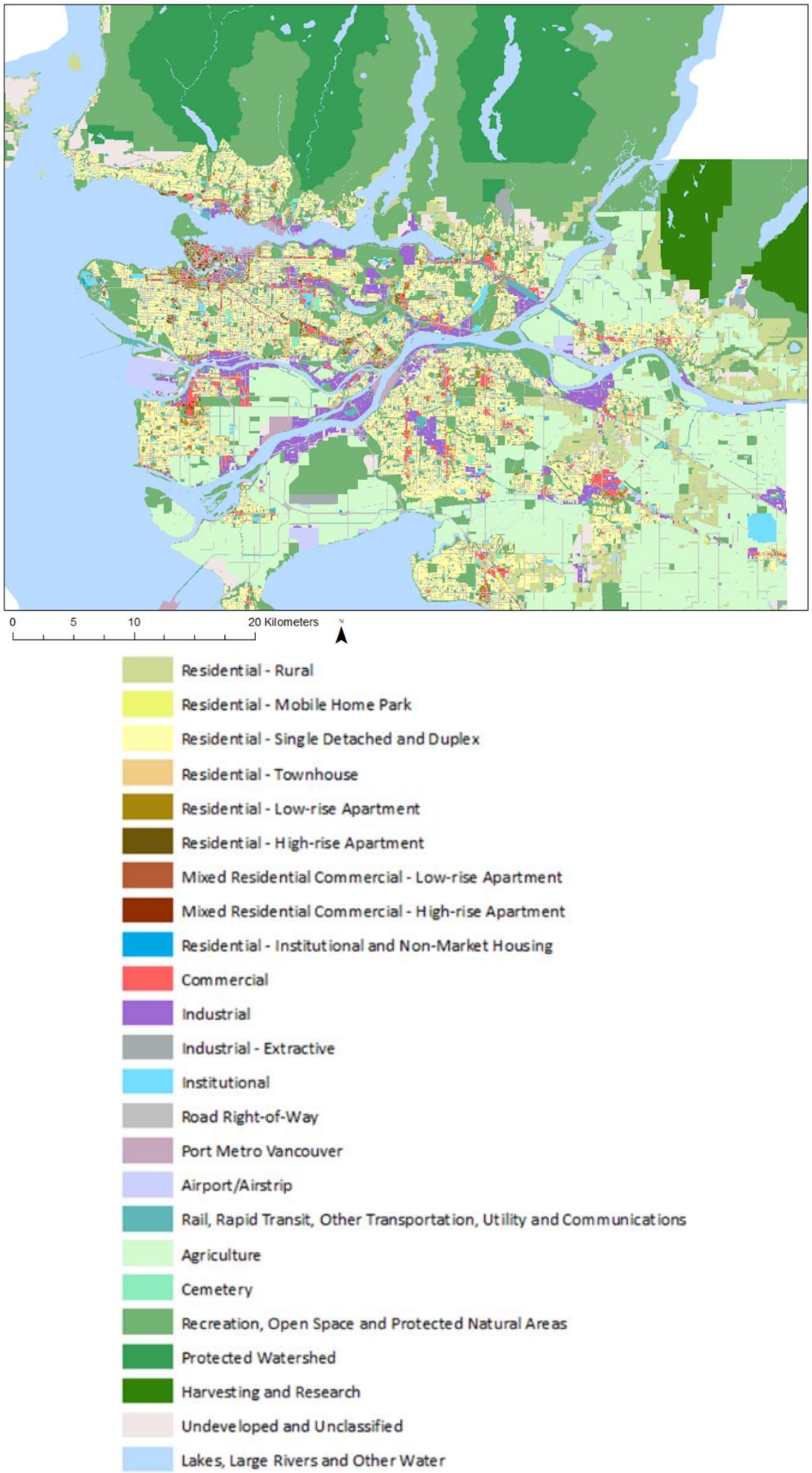

Figure 1.1. Study Area Metro Vancouver Region, British Columbia, Canada with land use for year 2011 (Metro Vancouver 2016).

The Metro Vancouver region has its advantages of advancing high-density development. First, the Agricultural Land Commission (ALC) (Agricultural Land Commission, 2019) is created to prevent the agricultural land from transforming into urban land use, which can constrain the urban sprawl to suburban area. Furthermore, an industrial lands inventory (Metro Vancouver, 2015) is proposed to monitor the decrease of industrial land, which can ensure the industrial land are sufficient for urban development. Second, the Frequent Transit Network (FTN) offered by TransLink can provide frequent and reliable transportation facilities that serve for the region (TransLink, 2019). Third, the 'EcoDensity Charter' (Toderian, 2008), 'Sustainability Charter' (City of Surrey, 2016) and the 'Energy and emission policies' (Ministry of Energy and Mines, 2017) adopted by City of Vancouver, City of Surrey and Province of British Columbia is aiming to reach a high-dense, sustainable and efficient living environment in existing built-up areas. Fourth, the Community Amenity Contribution (CAC) Policy (City of Vancouver, 2018) is proposed and implemented by urban developer in order to alleviate the impacts of high-density area on its neighborhood community.

Therefore, in order to develop the LSP method in the suitability analysis in Metro Vancouver region, a geospatial dataset is used to analyze and obtain the final suitability maps. Data for this study is obtained through (City of Surrey, 2019; DMTI Spatial, Inc., 2016; Government of British Columbia, 2018; Metro Vancouver, 2016; Statistics Canada, 2012; TransLink, 2018). Slope and elevation data are processed into 10 meters resolution raster based on the Digital Elevation Model Dataset (Open Government Portal, 2018). An assumption is made during the process of slope and elevation data, in which assuming the high-rise building is always built on flat ground. The remaining datasets are converted into ArcGIS raster format with 10 meters resolution. Eight groups of criteria were determined to be the key factors affecting the decision-making process of urban developer and planner, which can be classified into the following five aspects: environment and facilities, development possibility and economic opportunity, land use and terrain, restrictions and demography.

1.4. Thesis Overview

The thesis is comprised of five chapters, starting with the introduction. Chapter two aims to address the first objective of this thesis. It develops and implements the GIS-based LSP method on the land suitability analysis of high-density urban development in Metro

Vancouver Region, Canada. Urban developer and planner were identified as two key stakeholders for this study. Their preferences were investigated through research literature and government documentations for Metro Vancouver Region, and subsequently, used to define the list of criteria in this study. Then, the LSP attributes tree, elementary attribute criteria and LSP aggregation structure were developed according to the goals and interests of developer and planner. Datasets for the study are obtained from (DMTI Spatial, Inc., 2016; Government of British Columbia, 2018; Metro Vancouver, 2016; TransLink, 2018). Population densities are processed at the Dissemination Area level by using 2011 census population data (Statistics Canada, 2012). Slope and elevation are derived from the 18 meters resolution Digital Elevation Model Dataset (Open Government Portal, 2018) and resampled based on the assumption that the most parts where the densification will happen in Metro Vancouver will be flat areas. Data were resampled into 10 meters resolution for the GIS-LSP method implementation. Furthermore, the suitability maps of urban developer and planner were compared in a certain region to elaborate the similarities and differences of two suitability values generated from two different perspectives.

Chapter three is focused on delivering the combination of output suitability maps of urban developer and planner, which responds to the second objective of this thesis. They are combined based on three scenarios: Concurrent Stakeholder scenario, Alternative Stakeholder scenario and Tradeoff scenario, which can represent the different decision-making processes and different relationships of urban developer and planner.

Chapter four presents the use of LSP method for high-density suitability analysis with different LSP aggregators groups using data for Metro Vancouver Region. First, the seven aggregators groups provided in LSP method with different granulation of andness and orness were presented. Second, three aggregators groups with the same LSP attributes tree were implemented in the perspectives of urban developer in Metro Vancouver Region. The output suitability maps were compared and discussed. Third, a single aggregators group with five different threshold andness values were implemented and compared according to seven satisfaction levels. Fourth, a sensitivity analysis was conducted for two criteria at three different locations, following the comparison and discussion. Fifth, the cost/suitability analysis was used to elaborate the impacts of different important levels of low cost on the suitability result, which was implemented in the City of Surrey, as part of Metro Vancouver Region, with the land price data. This chapter aims to give an insight on the differences among various LSP aggregators groups and present the use of LSP method within ArcGIS software environment. It also introduces the basic structure and processing approach of the self-developed GIS-based LSP module, namely GIS.LSP developed for this thesis research. The detailed information on the GIS.LSP module is presented in the thesis Appendix. Lastly, chapter five provides the thesis overall conclusions, including the summary of obtained results, discussion of limitations, future research work and contributions of this thesis research. This thesis aims to advance the use of the LSP method with GIS environment as a complex MCE method for the applications in land suitability analysis for the urban densification process.

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Chapter 2.

GIS-based Logic Scoring of Preference method for suitability analysis of urban densification[1]

2.1. Abstract

Urban sprawl profoundly influences the natural environment and ecological systems, while urban densification can alleviate some of the damage of this process. There is a necessity to investigate the approaches that can provide evaluation of suitability locations for high density urban development to facilitate the decision-making process and thus help more sustainable urban planning. In order to effectively address this issue, the main objective of this research study is the implementation of the GIS-based Logic Scoring of Preference (LSP) method to evaluating suitable areas for urban densification. The LSP method is based on soft computing that assist the decision-making process and can integrate large number of criteria while capturing the human logic reasoning. The LSP method is then implemented using geospatial data for Metro Vancouver Region. Main criteria representing the characteristics of densification: recreation, transportation, existing development, economy, demography, terrain and restrictions. The LSP method has been deployed by using two different stakeholders – urban developer and urban planner, both playing important roles in urban densification process. The obtained results indicate that the suitability locations for two stakeholders in Metro Vancouver Region differ for 23%. The GIS-based LSP method is a useful tool for measuring the similarities and differences in stakeholders' views and thus facilitating decision-making process for urban densification.

2.2. Introduction

Urban sprawl is inevitable due to constant growth of population. The rapid increase in economic needs accompanied by the demand for improving the quality of daily life will in turn challenge the limit of urban capacity and further lead to social problems (Galster et

[1] The version of this chapter co-authored with S. Dragicevic and J. Dujmovic will be submitted to the scientific journal for peer review.

al., 2001). This situation entails urban areas to expand in order to accommodate the fast-growing population and thus, it continues contributing to the negative consequences on natural environment (Clinton & Gong, 2013; DeFries, Rudel, Uriarte, & Hansen, 2010; Fang et al., 2016; Fazal, 2000) and its disruption (Ewing, 1997; Xiangzheng Deng, Jikun Huang, Rozelle, & Uchida, 2010). Urban sprawl is therefore characterized as an excessive horizontal growth of urban area (Bruegmann, 2006).

In contrast to the expanding urban sprawl, urban densification is a process characterized by its compact form, benefits of efficient infrastructure and shorter distances between urban services, which are further improving the energy efficiency (Brebbia, Martin-Duque, & Wadhwa, 2002). High-density urban growth or vertical urban growth can mitigate some of the problems caused by urban sprawl due to its high-density structure (Burton, 2002). It is considered as a sustainable urban development that is meeting the current social needs which can alleviate the pressure on the natural environment (Burton, Jenks, & Williams, 2004). Consequently, densification development has increasingly been considered as part of urban planning strategies (Burton, 2002; Dajani, 1974; Hess & Sorensen, 2015). Urban densification is in most cases governed by urban planners and urban developers as stakeholders with key role in the decision-making process. They are dominating the urban development in the context of the housing and residential development (Morgan, 2010) by involving initial financing, planning, building and eventually affecting the urban environment (Almagor, Benenson, & Alfasi, 2018; Coiacetto, 2000; Peiser, 1990a). However, relatively few research studies have been conducted to address the detailed reasoning of urban developers and urban planners and their influence on planning urban development and the densification process. Accompanied by the development of geographic information system (GIS), spatial decision-making and suitability analysis methods are providing a more meaningful and effective approach in making decision (Malczewski, 2004; Malczewski & Rinner, 2015). With the use of Spatial Decision Support Systems (SDSSs) in GIS framework, the spatial decision-making for multi-dimensional and semi-structured decision tasks are facilitated (Densham, 1991). The integration of GIS and multi-criteria evaluation (MCE) methods helps supporting the land use planning and management in various suitability analysis by deriving knowledge from different sources in wider array (Malczewski, 2004, 2006).

Previous studies have employed several multicriteria evaluation (MCE) methods to evaluate land suitability. Frequently, such methods have been relied on the use of weighted linear combination (WLC) (Eastman, Jin, Kyem, & Toledano, 1995), multi-attribute value technique (MAVT) (Pereira & Duckstein, 1993), multi-attribute utility technique (MAUT) (Store & Kangas, 2001), ordered weighted average (OWA) (Gorsevski, Donevska, Mitrovski, & Frizado, 2012), outranking methods (Joerin, Thériault, & Musy, 2001), and the analytical hierarchy process (AHP) (Chen, Yu, & Khan, 2010). MCE methods are expected to investigate the complicated trade-offs in decision making in a way that is consistent with human decision logic. However, many of traditional methods available in common GIS software, such as AHP and OWA, usually do not adequately incorporate a sufficiently large number of attribute criteria in their analysis (Montgomery & Dragićević, 2016) and lack the capability to sufficiently capture a wide range of reasoning patterns present in human decision making. Frequently deficiencies in the ability to comprehensively satisfy the decision-making perspectives due to the oversimplification of human reasoning have been identified (Dujmović, Tré, & Weghe, 2008, Dujmovic, De Tré, & Dragicevic, 2009; Dujmović & Tré, 2011).

The Logic Scoring of Preference (LSP) method has been designed to overcome these shortcomings. An initial version of the LSP method was introduced in 1970s and used for evaluation of computer systems (Dujmović, 1975, 1996; Dujmović & Nagashima, 2006). The current version of the LSP method (Dujmović, 2018) possesses the properties for analyzing complex trade-offs between different human choices, basing on improved representation of human reasoning for decision-making in stepwise gradual manner, which are not available in traditional AHP or OWA (Dujmović & Fang, 2004). It also utilizes the soft computing for evaluating criteria, in which logic operators and structure are used to aggregate attributes in order to further extend the representations of human reasoning (Dujmović, Tré, & Weghe, 2008). The LSP method has been recently applied in the land use suitability analysis (Dragićević, Dujmović, & Minardi, 2018; Hatch, Dragićević, & Dujmović, 2014) but not yet in the context of urban densification. With the advantage of the LSP method offering a variety of specific types of aggregation procedures, it is therefore possible to capture the complexity of criteria related to urban development and human decision making based on various stakeholder interests linked to urban densification.

Research studies have been focused on measuring the high-density urban growth in order to assist in decision-making for the urban development (Abdullahi, Pradhan, & Jebur, 2015; Aulia, Rahmawati, & Ariastita, 2014; Koziatek & Dragićević, 2017a).

Therefore, the main objective of this research study is to develop the LSP method within GIS environment and use it for finding suitable locations for high density urban growth from the perspectives of urban developer and urban planner. The GIS-based LSP method has been implemented using geospatial datasets from Metro Vancouver Region, Canada.

2.3. Overview of the LSP method

The LSP method is a more advanced MCE method developed in 1970s with its primary use for evaluation of computer system (Dujmović, 1975, 1996; Dujmović & Nagashima, 2006) and is based on soft computing. It is functioned by a generalization of continuous logic in which input criteria are scaled and aggregated into an evaluative format with the introduction of various degree of conjunction and disjunction (Dujmović, 2018). Three components featured the LSP method: attributes tree, elementary attribute criteria and logic aggregation structure. Criteria used for evaluation are firstly categorized according to their similarity and further represented by the LSP attributes tree. After the categorization, they are scaled by elementary attribute criteria. At last, they are further combined using LSP aggregators which represented a wide spectrum of human reasoning ranging from simultaneity (andness) to substitutability (orness). Criteria are aggregated within the same group step by step starting from leaves to root of attributes tree until they generate a final suitability score.

The veracity of LSP results depends on how completely and accurately the selection of LSP attributes tree and aggregators can reflect the decision makers' perspectives and reasoning logic. Two strengths of LSP method over other MCE methods are identified: its consistency with human evaluation reasoning and capacity of involving large number of input criteria. The mathematical foundation of LSP method basing on soft computing of simultaneity and substitutability makes it a good representation of human reasoning (Dujmović, Tré, & Weghe, 2010), while different LSP aggregators can further take human decision-making process into account. Its ability to model considerable factors without losing individual significance for any single factor due to the characteristics of logic structure used in the LSP method. These all make the LSP an unique evaluation method.

The incorporation of GIS-based MCE methods, LSP has been used in the context of spatial decision-making (Dragićević et al., 2018; Dujmović & Scheer, 2010; Dujmović & Tré, 2011). The LSP was implemented for spatial suitability analysis to calculate land use suitability based on natural and social factors (Dujmović et al., 2008). After that, the framework for constructing LSP suitability maps, which is also known as s-maps, was introduced and further expanded the use of LSP on suitability analysis (Tré, Dujmović, & Weghe, 2010).

LSP suitability analysis can be connected to raster GIS-based environment in which the value of each raster is defined as the suitability score representing the suitability for a certain use at particular location. Raster GIS data layer can serve as the inputs for LSP function as attributes for the calculation of the final suitability scores. The LSP function is characterized by the LSP attributes tree and LSP aggregators that are used to combine criteria and calculate the overall suitability. The LSP values than can be visualized as suitability maps in raster GIS environment.

The LSP method consists of four main steps: (1) identifying the decision problem and the stakeholders involved in the decision process, (2) developing the suitability attribute tree, (3) defining the elementary attribute criteria and (4) developing the logic aggregation structure to combine the attributes in order to obtain suitability scores and maps (Dujmović, 2018).

2.3.1. Characterization of Stakeholder

The first step in the LSP method is to identify the decision problem and the stakeholders to derive the detailed evaluation process according to stakeholder's justifiable goals and interests. A stakeholder can be an organization, individual person, expert, environmentalist or government representative etc. aiming to gain a reasonable evaluation result during their decision making. With the aim to find suitable locations for urban densification, the key stakeholders in this study are the urban developer and the urban planner.

2.3.2. Development of the Suitability Attribute Tree

The LSP attributes tree is developed through a systematic suitability decomposition process to that contains all relevant attribute criteria. During the decomposition process of structure, sub-categories can be defined. The attribute criteria must represent the stakeholder's goals and can truly reflect their opinion of the characteristic of these attributes. Therefore, those irrelevant and redundant attributes must be excluded, and all attributes must be correctly grouped (Dujmović, 2018). Normally, these attributes data set should be available and can be formatted for the final evaluation. Furthermore, they should have the ability to stand for the major interests of stakeholders.

After the attributes are chosen, they are further classified into three basic categories: mandatory, sufficient and optional. Mandatory means the input requirements must be satisfied in order to rank an overall satisfactory, if any attribute is not satisfied, then the final result is unsatisfied. Sufficient means a single completely satisfied sufficient attribute can satisfy the overall result regardless to the degrees of satisfaction of other attributes. Optional means the input's satisfaction is desired but not mandatory and is not necessary for the final score.

2.3.3. Elementary Attribute Criteria

Based on the stakeholder requirements, each attribute should be reassigned into value ranging from totally undesirable (denoted 0) to completely satisfied (denoted either 100% or 1) in order to measure their degree of satisfaction. In this study, the canonical forms of elementary attribute criteria are used (Dujmović & Tré, 2011), which can be represented using vertex notation denoted as:

Preferred large values: $\text{Crit(x)} = \{(A,0),(B,1)\}$

Preferred small values: $\text{Crit(x)} = \{(C,1),(D,0)\}$

Preferred range of values: $\text{Crit(x)} = \{(A,0),(B,1),(C,1),(D,0)\}$

where A, B, C, D are the vertex that justify the stakeholder's requirement. The corresponding graph notation of these three elementary attribute criteria forms are shown in Figure 2.1.

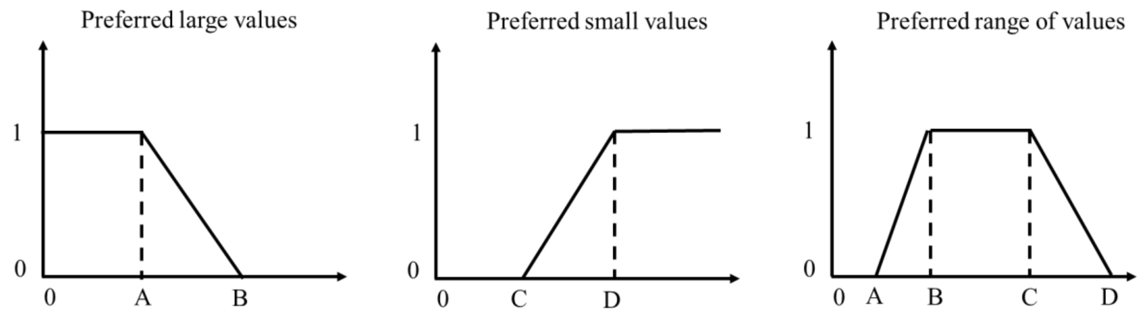

Figure 2.1. Canonical forms of elementary attribute criteria.

Such function would normally use the simple linear interpolation of straight lines between the selected breakpoints proposed by decision makers. For example, the elementary attribute criteria for proximity to the bus station can be denoted as:

Distance to bus stations {(0, 0), (200, 1), (800, 1), (1500, 0)}

In this case, the distance to the closest bus station is evaluated for a certain location. The stakeholders want to be 200 meters far from the railway station because closer to them can induce noise, pollution, and safety problems. At the same time, they do not like to be too far away (more than 800 meters) from the station to avoid the cost of long commute time. Then, their satisfaction keeps decreasing until 1500 meters away from the railway station that will eventually become unacceptable.

These elementary attribute criteria are set based on stakeholder's opinions, or expert discussions on the subject or from pervious literature and surveys on the particular topic. Furthermore, these elementary attribute criteria can be redefined based on stakeholders' opinions and discussion in face-to-face meetings for changing the evaluation scheme or when more specific information are available.

2.3.4. Logic Aggregation of Suitability

By using the elementary attribute criteria, suitability values (degree of satisfaction) are created for each criterion. These suitability values are aggregated into a single value, which represent the overall suitability. The principle LSP aggregation is according to the LSP attributes tree and using different aggregators to combine these attributes step by step.

Each aggregator is belonging to one of the nine aggregator categories that represent a wide range of stakeholder's reasoning (Table 2.1). Their corresponding general form for application is presented in Dujmovic (2018). They gradually move along the spectrum from neutrality (A, the arithmetic mean) to pure disjunction, the aggregator appears to be stronger in degree of substitutability. While it moves to another direction, from neutrality (A) to pure conjunction, the aggregator presents a stronger capability in simultaneously integrating among different inputs. Neutrality (A) is used to deliver the equilibrium status of simultaneity and substitutability. Based on this spectrum range from simultaneity to substitutability, there are nine basic categories of LSP logic aggregators: (1) pure conjunction (C), (2) hard partial conjunction (HPC), (3) soft partial conjunction (SPC), (4) neutrality (A), (5) soft partial disjunction (SPD), (6) hard partial disjunction (HPD), (7) pure disjunction (D), (8) conjunctive partial absorption (CPA), and (9) disjunctive partial absorption (DPA). The first seven categories are basic aggregators, while the last two are compound aggregators. Different aggregator is selected based on the stakeholders' needs in expressing the relationship between input criteria within the same group.

Table 2.1. Logic properties of nine aggregator categories.

Category	Logic properties
D: Pure disjunction	Define: Represent the highest/extreme degree of substitutability. The output suitability is defined by the largest input suitability value (all other inputs do not affect the output). Completely Satisfied Condition: Any input is sufficient to completely satisfy this criterion.
HPD: Hard partial disjunction	Define: Representing the very high degree of substitutability that supports sufficient requirements. Completely Satisfied Condition: An individual completely satisfied input is sufficient to completely satisfy the output. Between Completely and Incompletely Satisfied: All inputs would affect the output if no input is completely satisfied. High input suitability values have a more significant impact on the output than low input suitability values. Completely Unsatisfied Condition: The criterion is not satisfied only if all inputs are not satisfied.

Category	Logic properties
SPD: Soft partial disjunction	Define: Representing the relatively low to medium degree of substitutability that does not support sufficient requirements. Completely Satisfied Condition: All inputs must be completely satisfied. Between Completely and Incompletely Satisfied: All inputs affect the output. High input suitability values affect the output more significantly than the low input suitability values. Completely Unsatisfied Condition: The criterion is not satisfied only if all inputs are not satisfied.
A: Neutrality	Define: The weighted arithmetic mean of inputs. Equal importance on simultaneity and substitutability requirements. Low and high inputs have an equal opportunity to affect output. Completely Satisfied Condition: All inputs are completely satisfied. Completely Unsatisfied Condition: All inputs are not satisfied.
SPC: Soft partial conjunction	Define: Representing the relatively low to medium degree of simultaneity that does not support mandatory requirements. Completely Satisfied Condition: All inputs must be completely satisfied. Between Completely and Incompletely Satisfied: All inputs affect the output. Low input suitability values affect the output more significantly than the high input suitability values. Completely Unsatisfied Condition: The criterion is not satisfied only if all inputs are not satisfied.
HPC: Hard partial conjunction	Define: Representing the very high degree of simultaneity that supports mandatory requirements. Completely Satisfied Condition: All inputs must be completely satisfied. Between Completely and Incompletely Satisfied: All inputs would affect the output if no input is completely satisfied. Low input suitability values have a more significant impact on the output than high input suitability values. Completely Unsatisfied Condition: One completely unsatisfied input is sufficient to completely not satisfy the entire criterion.
C: Pure conjunction	Define: Represent the highest/extreme degree of simultaneity. The output suitability is defined by the smallest input value (all other inputs do not affect the output). Completely Satisfied Condition: All input requirements must be simultaneously fully satisfied.
CPA: Conjunctive partial absorption	Define: Output affected by a mandatory input x and an optional input y. Between Completely and Incompletely Satisfied: If the mandatory input suitability value is positive, and the optional input suitability value is zero, then the output is positive. For a partially satisfied mandatory input, a higher/lower optional input suitability value can increase/decrease the output suitability value according to an adjustable degree of reward/penalty. Completely Unsatisfied Condition: The mandatory input is completely unsatisfied and has a zero-suitability value.

Category	Logic properties
DPA: Disjunctive partial absorption	Define: Output affected by a sufficient input x and an optional input y. Completely Satisfied Condition: The sufficient input is fully satisfied. Between Completely and Incompletely Satisfied: If the sufficient input is partially satisfied, and the optional input is completely satisfied, then the output is incompletely satisfied. For a partially satisfied sufficient input, a higher/lower optional input suitability value can increase/decrease the output suitability value according to an adjustable degree of reward/penalty.

If an attribute group has only two criteria to aggregate, the aggregation process should follow a few simple rules: the selection of aggregators type should be based on the mandatory, sufficient or optional types of the criteria. When (a) both criteria are mandatory, a HPC aggregator must be used, (b) both criteria are optional, a aggregator in SPC, neutrality, or partial disjunction should be used, (c) both criteria are sufficient, a HPD aggregator must be used (d) one criterion is mandatory while another criterion is optional, a CPA should be used, (e) one criterion is sufficient while another criterion is optional, a DPA should be used. If more than two criteria in a group are aggregated, only a Graded Conjunction/Disjunction (GCD) aggregation structure should be considered (as shown in above (a, b, c)). Above all, the first step of LSP criterion aggregation development is to determine the aggregator type as either GCD or partial absorption in the aggregation structure.

Logic Aggregation Using Graded Conjunction/Disjunction (GCD)

An appropriate aggregator must be selected from the GCD aggregators group in the logic aggregation process and there is a wide range of aggregators groups (Dujmović, 2018). Due to its wide range of decision-making abilities, for this research study, the UGCD.15 aggregators group, presented in Table 2.2, has been chosen for the purpose of implementation of the GIS-based LSP method. During the process of aggregation structures designation, a canonical aggregation structures should be followed. Specifically, logic justification must exist in the process of aggregation structures designation because some aggregation structures are logically correct while some are logically incorrect. Consequently, there are justifiable patterns and design rules in the aggregation structures, and it is not totally subjective. For example, the conjunctive canonical aggregation structures must follow increasing andness from the initial aggregator to the root aggregator (an aggregator that generate overall suitability), while disjunctive canonical aggregation structures must follow increasing orness. After finishing the selection of an aggregator for criteria within a group, the next step is to input the andness value, threshold andness, attribute suitability values generated by elementary attribute criteria, and weight values into the general from of GCD aggregator for final computation of suitability score.

Table 2.2. UGCD.15 aggregators.

Desired type of aggregator	Category	Level	Symbol	Andness
Substitutability	Pure disjunction (D)	Extreme	D	0
	Hard partial disjunction (HPD)	High	HD+	1/14
		Medium	HD	2/14
		Low	HD-	3/14
	Soft partial disjunction (SPD)	High	SD+	4/14
		Medium	SD	5/14
		Low	SD-	6/14
Neutrality			A	7/14
Simultaneity	Soft partial conjunction (SPC)	Low	SC-	8/14
		Medium	SC	9/14
		High	SC+	10/14
	Hard partial conjunction (HPC)	Low	HC-	11/14
		Medium	HC	12/14
		High	HC+	13/14
	Pure conjunction (C)	Extreme	C	1

Logic Aggregation Using Partial Absorption (PA)

The partial absorption aggregation structure is needed when attributes in the same group are not in the same type. For example, sometimes it is possible that a mandatory criterion has to combine with an optional criterion, or a sufficient to combine with an optional. There are two types of PA, as aforementioned, one is CPA, and another is DPA. For both of the CPA and DPA, a neutral arithmetic mean (A) and a harmonic mean (H) are usually used to aggregate the criteria due to its simplicity (Dujmović, 2018). The aggregation structures of CPA and DPA aggregator are shown in Figure 2.2. The weights W1 and W2 are the only two adjustable parameters, which can be determined by user-defined desired penalty and reward using table provided in (Dujmović, 2018). By using this Partial Absorption (PA) aggregation structure, an optional criterion can actually reward or penalize the suitability values of the group.

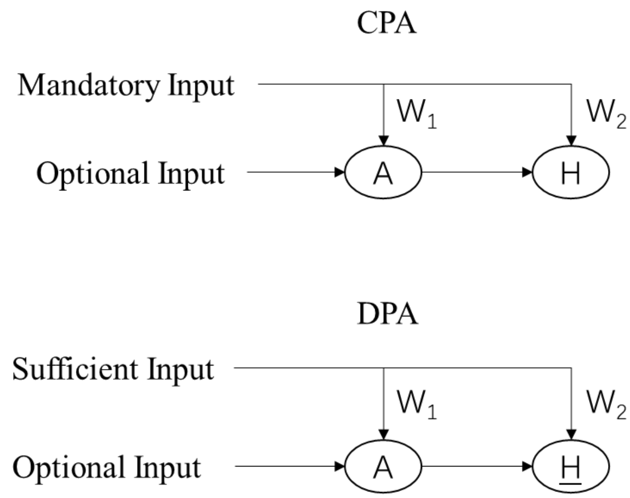

Figure 2.2. The example of Partial Absorption (PA) aggregators for Conjunctive Partial Absorption (CPA) and Disjunctive Partial Absorption (DPA).

LSP Aggregation Structure

Following the attributes tree, the computation of suitability scores is operated by using LSP aggregation structure that carry aggregators and weights. As presented in Figure 2.3, a general example is showing the basic idea of aggregation structure. There are totally four attributes in an evaluation process. Attribute 1, 2 and 3 are mandatory criteria while Attribute 4 is optional. For aggregating Attribute 1 and 2 in Group 1, the GCD aggregation structure are chosen in which a HPC aggregator is used. During the aggregation, the importance of criteria is represented by the assigned Weight 1 and 2. Weight values are used according to personal observation, previous studies and the expert knowledge in the related research area. For Group 2, the partial absorption aggregation structure is selected, while the desired Penalty of 20% and Reward of 10% are the representation of importance of criteria. Finally, the GCD are again used in Group 3 for aggregation of the suitability values generated by Group 1 and 2 using a HPC aggregator while the relative importance of them are characterized by Weight 3 and 4, and consequently, output the overall suitability score.

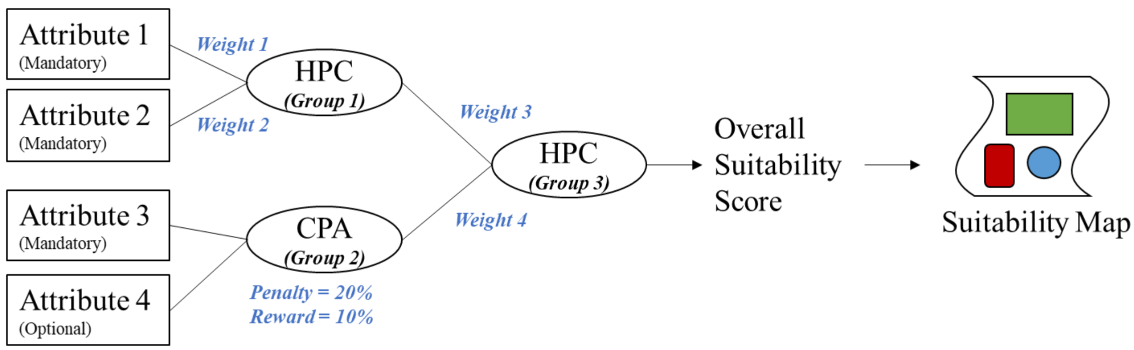

Figure 2.3. Example of simple LSP aggregation structure with four attributes.

Within the LSP method described in (Dujmović, 2018), a wider variety of aggregators such as WPM (Weighted Power Mean), UGCD (Uniform Graded Conjunction/Disjunction) and GGCD (General Graded Conjunction/Disjunction) aggregators are introduced, in which users can explore various aggregating scheme with different precision and even adjustable threshold andness according to their mathematical background and proficiency of LSP aggregators. Above all, the human reasoning process can be greatly captured by using the mandatory, sufficient and optional attribute of a criteria, moreover, by using the GCD and PA in a logic way.

2.4. LSP-GIS Method for High Density Urban Growth Suitability

2.4.1. Study area and data sets

The Metro Vancouver region covering an area of 2832 km2 is located in the south-western British Columbia, Canada. Metro Vancouver has experienced substantial population growth over the past three decades, for which an influx of more than 1, 000, 000 people is expected for this region (Metro Vancouver, 2011). Population increased by 6.5% between 2011 and 2016 (Government of Canada, 2017) and it is estimated that will reach 3, 400, 000 by 2041 (Metro Vancouver, 2011). While Metro Vancouver region is also experiencing a significant urban expansion, which need enhanced urban planning in order to avoid social and environmental impacts (Fox, 2010). As such, it is necessary to focus on the high-density growth in order to meet sustainable development to minimize the impact on the natural environment in the Metro Vancouver region.

The Regional Growth Strategy of Metro Vancouver Region (Metro Vancouver, 2019) is recommending the slow-down of the urban sprawl process by urban densification and improvement of public transportation. The transportation network such as SkyTrain and bus route provided by TransLink offers an opportunity for Metro Vancouver Region to densify areas, and slow or minimize the urban sprawl in the region. Policies on urban structure such as the 'EcoDensity Charter' (Toderian, 2008), 'Sustainability Charter' (City of Surrey, 2016) and the 'Energy and emission policies' (Ministry of Energy and Mines, 2017) adopted by City of Vancouver, City of Surrey and Province of British Columbia respectively, are encouraging many municipalities in the region to plan for urban densification.

Data for the study are obtained from DMTI Spatial, Inc (2016), Government of British Columbia (2018), Metro Vancouver Open Data (2016) and Translink (2018). Popuslation densities are processed at the Dissemination Area level by using 2011 census population data (Statistics Canada, 2012). Slope and elevation are derived from the 18 meters resolution Digital Elevation Model Dataset (Open Government Portal, 2018) and resampled into 10m resolution based on the assumption that the most parts where the densification will happen in Metro Vancouver will be flat areas. The GIS datasets are converted into raster GIS data format with 10m spatial resolution.

2.4.2. Attributes Tree

Eight main groups of criteria are selected to represent the recreation and community, transportation, potential for development, economic opportunity, terrain, demography, floodplain restrictions and land use restriction. Further descriptions and justifications of the chosen attributes with supporting literature are presented in Table 2.3.

Table 2.3. Detailed descriptions and justifications of the chosen attributes used in this study.

Group	Criteria	Description	References
Recreation and Community	Cycling Path	Closer to cycling path can provide a more sport-friendly environment.	Abdullahi et al., 2015; Boulange et al., 2017; Saelens, Sallis, & Frank, 2003
	Golf Courses	Sites with golf courses surrounding mean a better living environment and recreational opportunity.	Abdullahi et al., 2015; Casalegno, Bennie, Inger, & Gaston, 2014

Group	Criteria	Description	References
	Park and Recreational Area	Closer to park and recreational area mean a better living environment.	Abdullahi et al., 2015; Almeida, Mariano, Agostinho, Liu, & Giannetti, 2018; Sutton & Anderson, 2016
	Waterfronts	Proximity to waterfronts provide a good view and usually comes with better recreational environment surrounding.	Abdullahi et al., 2015; Gupta, 2017
Transportation	Bus Stops	Closer to bus stops would mean better commute opportunity.	Boulange et al., 2017; Rodriguez & Vergel-Tovar, 2018
	SkyTrain Stations	SkyTrain stations are linked to frequent transit area and closer to these locations there is higher potential for location for new high-rise buildings.	Abdullahi et al., 2015; Sung & Oh, 2011; Zacharias & Zhao, 2018
	Airports	Closer to airports mean better connection to other cities or countries, thus provide potential suitable location for high-rise building. According to Vancouver International Airport Zoning Regulations, higher buildings cannot be built closer than 1500m to the airport.	Federal laws of Canada, 2006; Freestone, 2009
	Railway Stations	Proximity to railway stations of West-Coast Express can provide better commute to work or between cities with Mero Vancouver area.	Smith Wilbur S., 1984; Sung & Oh, 2011; Tong & Wong, 1997
	Major Roads	Proximity to major road mean better commute and greater accessibility.	Abdullahi et al., 2015; Burton, 2002; Koomen, Rietveld, & Bacao, 2009; Min, Fengjun, & Fath, 2010; Roychansyah, Ishizaka, & Omi, 2005
	Highways	Proximity to highways mean better commute and greater accessibility.	Abdullahi et al., 2015; Burton, 2002; Koomen et al., 2009; Min et al., 2010; Roychansyah et al., 2005
Facilities	Schools	Proximity to schools mean better educational environment and opportunities.	Abdullahi et al., 2015; Roychansyah et al., 2005
	Emergency services	Proximity to service area of police stations, fire departments, hospitals can provide better emergency services to citizens in this area.	Abdullahi et al., 2015; Roychansyah et al., 2005

Group	Criteria	Description	References
Potential for Development	High-rise buildings	Reflects the density level of the area where high-rise buildings already exist and can become a cluster to attract more potential high-rise building to build around.	Koziatek & Dragićević, 2017a, 2017b
	Mid- rise buildings	Reflects the density level of the area where mid-rise buildings exist and thus can attract potential high-rise building to be built nearby.	Koziatek & Dragićević, 2017a, 2017b
	Convertible Lands	Open area and undeveloped area have greater potential to convert into areas with high density buildings. While some of the commercial areas and low-rise buildings near the SkyTrain or shopping malls can possibly be rezoned (destroyed) and used as potential site for high-rise building.	Almagor et al., 2018; Czamanski & Roth, 2011; Li & Liu, 2007; Magliocca et al., 2015; Tian, Ouyang, Quan, & Wu, 2011
	Land Use Designation for General Urban	High- and mid- rise buildings would likely to be built on land that is designated for urban use in the future. General Urban and Mixed Employment are considered as suitable land use types.	Almagor et al., 2018; Czamanski & Roth, 2011
Economic Opportunity	Urban Centres	Sites closer to urban centres would likely develop into high dense area and can provide better opportunity for future development and job accessibility for people living in that area.	Abdullahi et al., 2015; Burton, 2002; Frenkel, 2007
	Retail and Shopping Centres	Proximity to retail and shopping centres can provide more convenient daily living and access to wider range of services and facilities.	Abdullahi et al., 2015; Roychansyah et al., 2005
Terrain	Slope	A flat surfaces and gentle slope would be more suitable for high rise building construction.	Hatch et al., 2014; Martinuzzi, Gould, & Ramos González, 2007
	Elevation	Area in higher elevation would be less accessible and less safe to build high rise buildings.	Hatch et al., 2014
Restriction	Floodplain	High-rise or any buildings are not likely to be built on floodplain.	Berke, Song, & Stevens, 2009; Holway & Burby, 1990; Koziatek & Dragićević, 2017b
Demography	Population Density	High-density area would often occur where near higher population density.	Abdullahi et al., 2015; Burton, 2002; Filipowicz, 2018
Land restrictions	Land Use Restriction	Some land use types are unsuitable for development for various reasons.	Abdullahi et al., 2015; Burton, 2002; Hatch et al., 2014

Group	Criteria	Description	References
Unsuitable land use types for future development include: Industrial, Agricultural, Airport/Airstrip, Cemetery, Harvesting and Research agricultural, Institutional, Lakes, Large Rivers and Other Water, Port Metro Vancouver, Protected Watershed, Rail, Rapid Transit, Utility and Communication, Recreation, Open Space and Protected Natural Areas, Institutional and Non-Market Housing, Retail and Shopping Centres, Roads			

After the criteria are chosen, the Attributes Tree is structured based on the hierarchy relationship between criteria. The attributes tree for this study are shown in Table 2.4. For example, the suitability for high density urban growth is decomposed into three main groups. In the next step those sub-categories can be continually decomposed: the environment and facilities criterion is decomposed into recreation and community, service and amenities, and transportation.

Table 2.4. The attributes tree for suitability for high density urban development.

1. Environment, Service and Facilities	2. Development Possibility & Economic Opportunity	3. Terrain, Restriction and Demography
1.1. Recreation 1.1.1. Cycling Path 1.1.2. Golf Courses 1.1.3. Park and Recreational Area 1.1.4. Waterfronts 1.2. Transportation 1.2.1. Transportation Facilities 1.2.1.1. Mandatory 1.2.1.1.1. Bus Stops 1.2.1.1.2. SkyTrain Stations 1.2.1.2. Optional 1.2.1.2.1. Airports 1.2.1.2.2. Railway Stations 1.2.2. Road System 1.2.2.1. Major Roads 1.2.2.2. Highways	2.1. Potential for Development 2.1.1. Dense Area 2.1.1.1. High-rise Buildings 2.1.1.2. Medium-rise Buildings 2.1.2. Convertible Lands 2.1.2.1. Commercial Area 2.1.2.2. Open Area 2.1.2.3. Undeveloped and Unclassified Area 2.1.2.4. Low-rise Buildings 2.1.3. Land Use Designation for General Urban 2.2. Economic Opportunity 2.2.1. Urban Centres 2.2.2. Retail and Shopping Centres	3.1. Terrian 3.1.1. Slope 3.1.2. Elevation 3.2. Floodplain 3.3. Population Density

The decision of whether a criterion should be mandatory, sufficient or optional can reflect the stakeholders' reasoning of how a criterion can affect the final decision and in this study was based from the literature. It has chosen the transportation facilities as mandatory requirement because it measures the traffic accessibility and connectivity of the site (Beimborn, Greenwald, & Jin, 2003). An area with adequate transportation facilities mean better commute and greater accessibility where locations would likely to be develop into high dense area and provide better opportunity for future development (Abdullahi et al., 2015). If an area does not have enough transportation facilities, then such area is not suitable for high density urban development, and the overall suitability would be zero or close to zero. On the other hand, some criteria can be characterized as optional during decision making process. For example, far away from the highways does not mean the area is not suitable, because an area with perfect transportation facilities and dense road network can still be a great location for high density urban development.

2.4.3. Elementary Attribute Criteria

The entire elementary attribute criteria list representing attributes which featured the functions for determining high density urban development suitability are presented in Table 2.5 in the vertex notation format of elementary attribute criteria as aforementioned. With the set of these elementary attribute criteria, suitability scores can be created for each criterion. Next step is to generate a single overall suitability degree by using logic aggregation of attribute suitability scores.

Table 2.5. Elementary attribute criteria characterizing high density urban development suitability in vertex notation.

Group	Crit(attribute) = {(value1, suitability1), . . . , (value_n, suitability_n)}	Units
Recreation and Community	Crit(Cycling path) = {(0, 0), (15, 1), (200, 1), (350, 0)}	Meters
	Crit(Golf courses) = {(10, 0), (200, 1), (1500, 1), (3000, 0)}	Meters
	Crit(Park and Recreational Area) = {(0, 1), (300, 1), (900, 0)}	Meters
	Crit(Waterfronts) = {(0, 0), (30, 1), (600, 1), (1000, 0)}	Meters
Transportation	Crit(Bus stops) = {(0, 0), (20, 1), (300, 1), (600, 0)}	Meters
	Crit(SkyTrain stations) = {(0, 1), (800, 1), (1500, 0)}	Meters
	Crit(Airports) = {(1500, 0), (2000, 1), (10000, 1), (15000, 0)}	Meters
	Crit(Railway stations) = {(0, 0), (100, 1), (800, 1), (1500, 0)}	Meters
	Crit(Major roads) = {(0, 1), (150, 1), (600, 0)}	Meters
	Crit(Highways) = {(0, 1), (500, 1), (1000, 0)}	(a)
Potential for Development	Crit(High-rise buildings) = {(10, 1), (500, 1), (1500, 0)}	Meters
	Crit(Mid-rise buildings) = {(5, 1), (450, 1), (1000, 0)}	Meters
	Crit(Commercial area) = {(0, 0), (1, 1)}	(a)
	Crit(Open area) = {(0, 0), (1, 1)}	(a)
	Crit(Undeveloped and unclassified area) = {(0, 0), (1, 1)}	(a)
	Crit(Low-rise buildings) = {(0, 0), (1, 1)}	
	Crit(Land use designation for general urban) = {(0, 0), (1, 1)}	(a)

Group	Crit(attribute) = {(value1, suitability1), . . . , (value_n, suitability_n)}	Units
Economic Opportunity	Crit(Urban centres) = {(0, 1), (500, 1), (1200, 0)}	Meters
	Crit(Retail and shopping centres) = {(0, 1), (600, 1), (1200, 0)}	Meters
Terrain	Crit(Slope) = {(0, 1), (20, 1), (60, 0)}	Degrees
	Crit(Elevation) = {(0, 1), (300, 1), (1000, 0)}	Meters
Restriction	Crit(Floodplain) = {(10, 0), (50, 1)}	Meters
Demography	Crit(Population density) = {(0, 1), (350, 1), (1000, 0)}	Meters

Units/option coding:
(a) 0 = Outside, 1 = Inside

2.4.4. LSP Aggregation Structure

The LSP aggregation structure for urban developers and urban planners are shown in Figure 2.4 and Figure 2.5 respectively. These two stakeholders are investigated in this study in order to reflect the flexibility of LSP to capture different human reasoning logic. The LSP structure and aggregation process are designed to combine eight groups of criteria, in which the aggregation logic and weight are adjusted to reflect their reasoning process. These criteria represent various important aspects in existing high-density urban development in Metro Vancouver region. In this study, the UGCD.15 Aggregators Group is used to aggregate criteria.

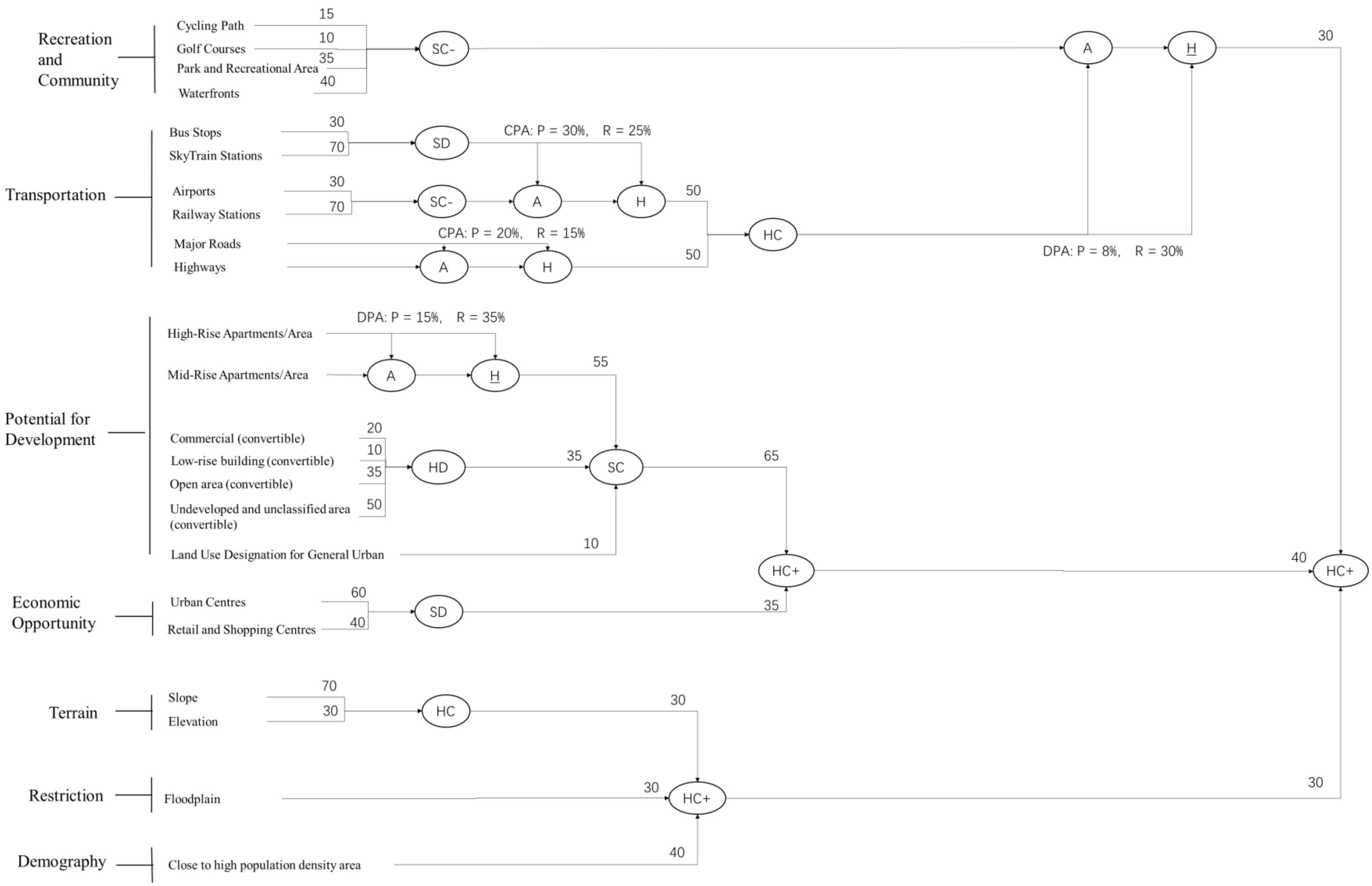

Figure 2.4. The LSP aggregation structure for high density urban development suitability of urban developer perspective.

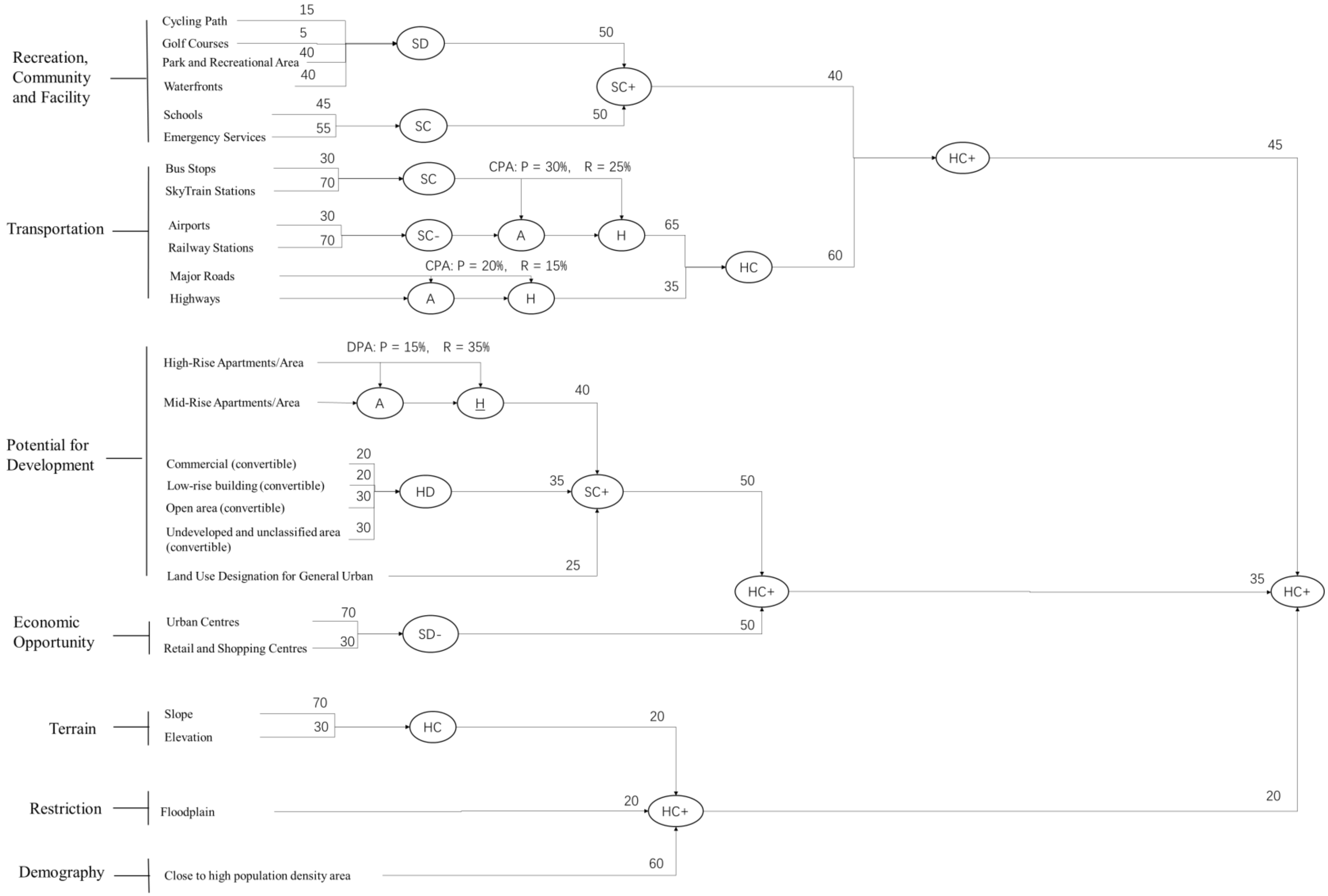

Figure 2.5. The LSP aggregation structure for high density urban development suitability of urban planner perspective.

Following are the examples of situations representing reasoning process of urban developer and the use of corresponding aggregators: (1) Urban developers would like to simultaneously have cycling path, golf courses, parks and waterfronts around their building location. However, their expectations are not very high. They would consider a location as perfect for high-rise building if some or all of them are missing. Therefore, the lowest level of soft partial conjunction (SC-) aggregator should be used; (2) Urban developer would prefer better access to bus stop and SkyTrain station, which can provide better commuting for those living in the high-rise building. They can choose the bus or SkyTrain in order to commute to their destinations. However, it cannot be completely substituted with each other as some locations are closer to bus stops and some to SkyTrain stations. Therefore, their substitution level is medium, which make the medium level of soft partial disjunction (SD) as the suitable aggregator; (3) Both proximity to transportation facilities and major roads and highways are the necessary infrastructure for a suitable location for building a high-rise. Therefore, a medium level hard conjunction (HC) is the suitable aggregator to describe such desirable situation.

An urban planner would typically prefer that the high-rise building has access to cycling path or golf courses, which can build up a more sustainable and sport-friendly environment for people that live in the building. Assuming that the cycling path and golf courses can substitute for each other, but not to the extent that the excellent value of one component makes the other component irrelevant. This means that one high-rise building can be accessible to either cycling path or golf courses, but they still cannot totally substitute each other. This reasoning of urban planner can be described with soft partial disjunction aggregators. The selection between SD-, SD, and SD+ aggregators is based on the assumption that in the given urban environment, the substitutability of cycling path and golf courses is low, and none of them is completely sufficient. This makes SD- the most appropriate aggregator to describe this stakeholder reasoning.

The combinations of mandatory with optional criteria, or sufficient with optional criteria need a clear understanding of the corresponding aggregating process. For example, a mandatory criterion (major roads) is aggregated with an optional criterion (highways). At the first step, these two criteria are aggregated using neutral arithmetic mean (A), then the result suitability from first step are aggregated with the mandatory criterion again which is major roads using conjunctive harmonic mean (H). In this example, if the mandatory input has a zero value (completely unsatisfied), then the output suitability score is also zero, regardless of the value of the optional input. If the mandatory input is positive, and the optional input is zero, then the output is still positive. When aggregating a sufficient and an optional criterion, the output suitability score is one if the sufficient criterion is completely satisfied. In above two situations, a higher or lower optional input can increase or decrease the output value depending on the desired penalty and reward.

For urban developer, the focus is on maximizing their profit and return of investment (Almagor, Benenson, & Alfasi, 2018; Czamanski & Roth, 2011; Magliocca, McConnell, & Walls, 2015). Studies related to survey of 140 developers across the Province of British Columbia, Canada, concluded that developers have a largely concern over accessibility to shopping area and availability of developable land (Goldberg, 1974; Goldberg & Ulinder, 1976). Similarly, proximity to the main road, public transportation, city, and shopping centers are considered of major importance for developers' decisions (Alonso, 1964; Mills, 1967; Muth, 1969). Furthermore, the land use plan established by urban planner would affect the land values and therefore affect the decision making of urban developer (Almagor, Benenson, & Czamanski, 2018). On the other hand, the costs of infrastructures for development would also affect the decision making of selecting sites (Mohamed, 2009). As such, the LSP aggregation structure of urban developer is developed by placing more importance on the aspect of proximity to transportation, urban centre, high population density and developable land (open area and undeveloped land), in which those are acting as more important ("hard") criteria such as mandatory or sufficient in LSP logic and are assigned higher weights.

For urban planner, municipal policies can always affect the idea and reasoning of their decision process. The OECD report (2012) suggests that the direction and goals of urban planning with urban densification. That report was translated into the reasoning of urban planner in this study. According to Compact City policy (OECD, 2012), the dense and proximate development is encouraged for regenerating existing residential areas, promoting transit-oriented development, and advocating walking and cycling environment. Therefore, the aggregation structure of urban planner stakeholder would consider the low-density residential areas as one of the developable land types and focus more on the environment and demography property compared to developers' perspective.

2.5. Results and Discussions

The geospatial data are processed in ESRI ArcGIS (2019) software environment in raster data format and according to Elementary Attribute Criteria and LSP aggregation structure. A self-developed GIS.LSP module is created within Python language to implement the LSP method in ArcGIS software environment to perform the analysis, create suitability values and suitability maps as raster GIS output layers.

Five high density urban development suitability levels are distinguished from the obtained suitability map for urban developer' and urban planner' perspectives using equal interval classification technique. Following range for suitability values are presented for high density growth: excellent [1.00–0.80], very good (0.80–0.66], good (0.66–0.52], average (0.52–0.38], poor (0.38–0.24], very poor (0.24–0.10], unacceptable (0.10–0.00]. The choice of this classification method is based on the review of locations of high-rise buildings according to Google 3D Maps and with the assumption that urban developer would have some previous knowledge of the area thus contribute the choice of the range for each level of suitability. Excellent suitability areas indicate the high satisfaction output of LSP logic aggregation structure with highest potential location for future high-density development. As the suitability value goes down, the satisfaction level goes down as well. Poor suitability values are those area that are potentially not suitable for high density development, which reflects the low satisfaction of stakeholder's reasoning.

The obtained suitability values and generated maps for urban developer and urban planner are presented in Figure 2.6. Table 2.6 presents the distribution of overall score values for both urban developer and urban planner. In developer perspective, excellent suitability lands for high density urban development are taking 0.76% (4.23km2) of the study area, while 62.88% are unacceptable. For urban planner, 2.48% (13.86km2) are excellent suitability lands while 69.03% are unacceptable for urban densification.

Furthermore, for the comparison purpose, the distributions of suitability values (Table 6) for developer and planner can be described as suitability distributions $D(d_1, \ldots, d_n)$ and $\mathrm{P}(p_1, \ldots, p_n)$ for each stakeholder separately, then $0 \leq \sum_{i=1}^{n} |d_i - p_i| \leq 2$ and $0 \leq 50 \sum_{i=1}^{n} |d_i - p_i| \leq 100$ can be interpreted. Therefore, the difference between urban developer and urban planner can be expressed as $Dif(\mathrm{D}, \mathrm{P}) = 50 \sum_{i=1}^{n} |d_i - p_i|$. The result 23.01% of difference shows that they are rather having similar goals and criteria. This can be justified by the fact that urban developers and planners are all having primary roles influencing the construction of high-rise buildings, in which they will simultaneously impact the urban fabric with its densified form and that can entail changes of urban social environment. However, difference will arise between them because planner is initially focused on regulation of zoning and urban land use (Calavita & Caves, 1994; Peiser, 1990b), while developer is motivated by the maximization of their profit (Almagor, Benenson, & Alfasi, 2018; Coiacetto, 2000; Peiser, 1990a).

Table 2.6. The distribution of high-density urban development suitability score values.

	Urban Developer		**Urban Planner**		**Abs (Developer-Planner)**	***Dif* (Developer, Planner)**
	%	Km^2	%	Km^2	%	%
Excellent	0.76	4.23	2.48	13.86	0.02	
Very Good	6.10	34.15	1.86	10.39	0.04	
Good	8.80	49.25	1.37	7.69	0.07	
Average	7.83	43.83	1.37	7.69	0.06	
Poor	6.81	38.12	1.92	10.74	0.05	
Very Poor	6.83	38.23	21.97	123.00	0.15	
Unacceptable	62.88	352.09	69.03	386.52	0.06	
Total	100.00		100.00		0.46	23.01

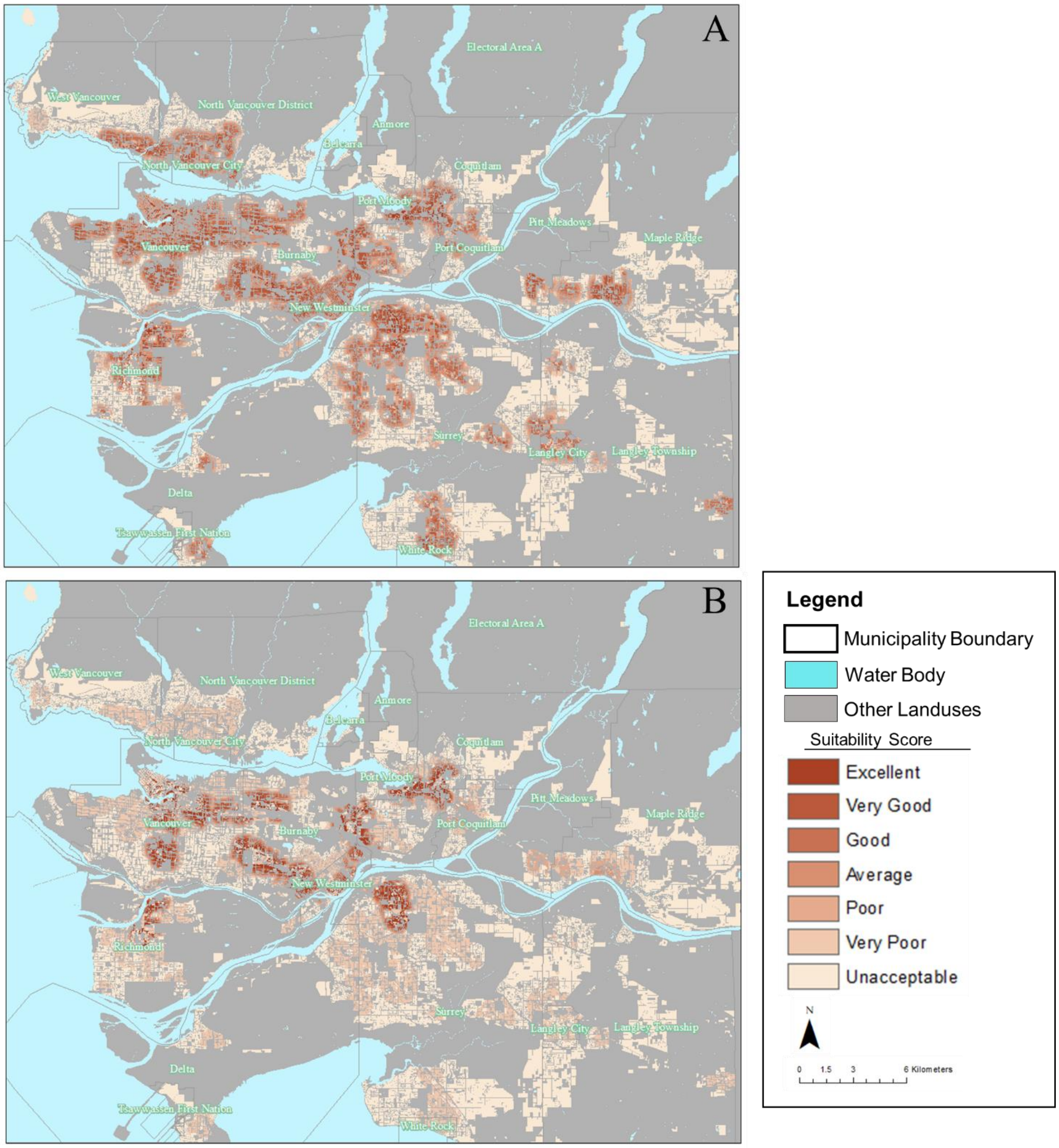

Figure 2.6. The obtained LSP suitability values for Metro Vancouver Region representing (A) urban developer and (B) urban planner perspectives.

As presented in the output suitability maps for urban developer perspective, the highest suitability scores are mostly found in the Downtown Vancouver, Brentwood Town Centre, Coquitlam Centre, Metrotown, Surrey Central and Richmond-Brighouse that are shown in Figure 2.7. By looking in the greater details, some of these high suitable areas have already built-up high-rise building as shown in 2018 Google Map's model, and moreover, those areas identified by LSP method are mostly located in open space such as parking lots, or undeveloped open green land, to name a few. At the same time, some commercial area that are not built up in high dense form could be razed down and served as potential lands for high-rise building. For example, some low-density commercial area as showing in the Metrotown and Port Moody region can be transformed into high-density area. This is demonstrating the effectiveness of the GIS-based LSP method and confirming our LSP attributes tree and logic aggregation process.

From urban planner perspective, the suitability map has a rather large suitable area compared to the urban developer's since they put more emphasis on proximity to recreational park and public transportation. Also, they would pay additional attention to the low-rise buildings which can be converted to high-rise buildings and augmenting the property tax revenues for municpalites. Hence, the LSP output map presents a greater amount of high suitability area around Oakridge SkyTrain station, Metrotown, Burquitlam, Port Moody, and Coquitlam Centre. In those places, some low-rise buildings near SkyTrain Stations and shopping malls, especially if old and in poor conditions, would be considered suitable land use to be converted for high-rise building development.

Figure 2.7. Selected areas for Metro Vancouver Region with high suitability scores from developer perspective within the Metro Vancouver Region and the obtained suitability map overlaid with Google Map's 3D model.

Furthermore, by comparing one of the selected regions among these different suitability maps shown in Figure 2.8, it can be seen that on both urban developer and urban planner suitability maps, the mid-rise, high-rise, shopping centre, recreational and protected area are not suitable for development. An Agree and Disagree Area map is created to reflect the overlaps (agree) and differences (disagree) of excellent suitability area for urban developer and urban planner (bottom right in Figure 2.8). Based on that map, both stakeholders during decision-making process could discuss and agree on some areas such as open spaces, parking lots, to be suitable locations for urban densification. However, the single-detached and townhouse residential area remain as unsuitable for development of high-rise buildings in urban developer perspective due to the high cost of conversion. In contrary, those low-density residential area performs a higher suitability for development in urban planner perspective due to the reason that they would consider retrofitting existing built-up areas, for example, a very old low density residential area in poor building conditions closed to the high density region can be transformed into high density area. At the same time, those area closer to the recreational facilities have higher suitability values from urban planner perspective since they focus on better living environment but also on already existing infrastructure.

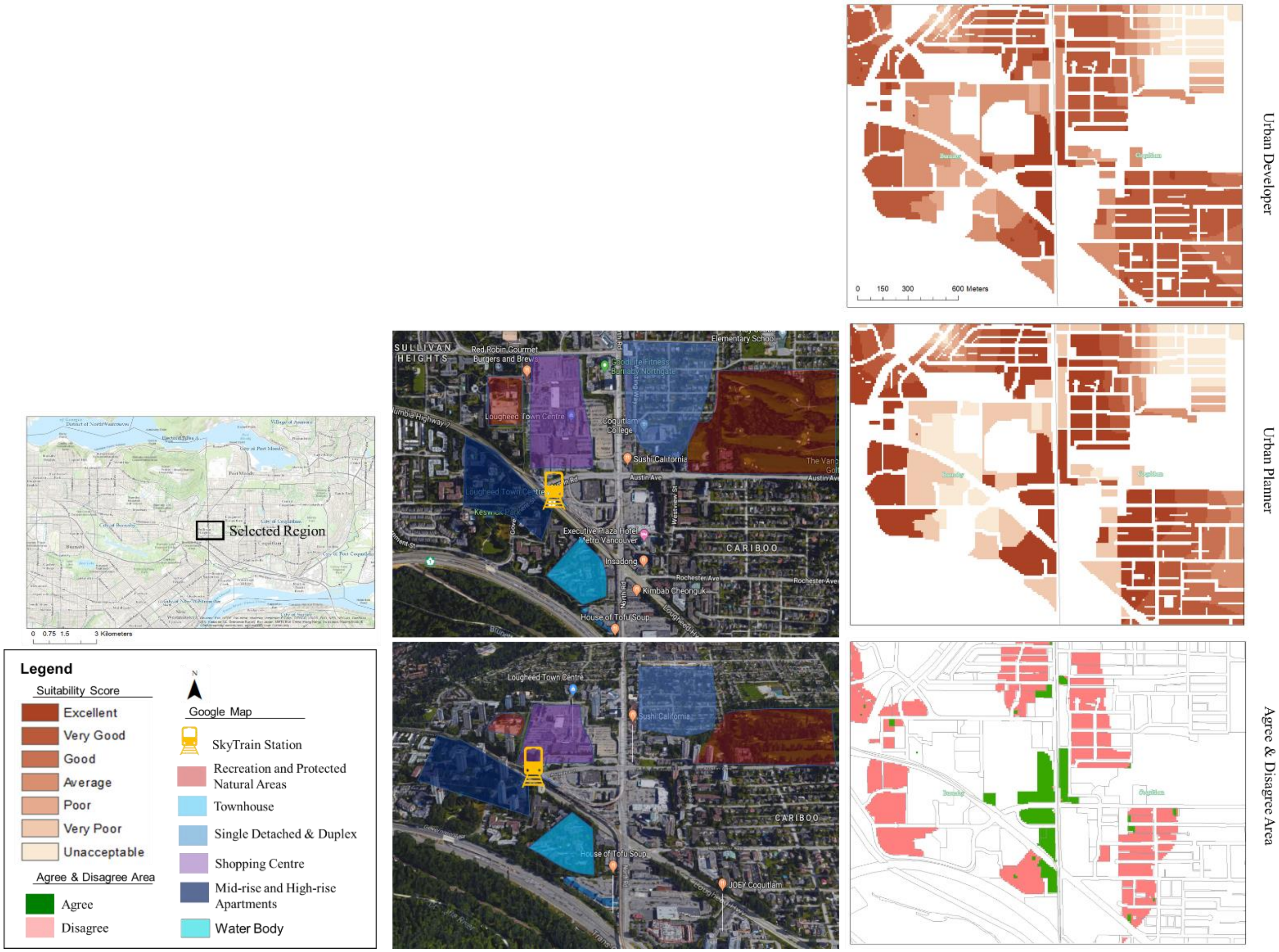

Figure 2.8. **Selected suitability maps with comparison of urban developer and urban planner perspectives and the corresponding Google Map 3D model (overlook view and side view).**

2.6. Conclusions

The main purpose of this study is to examine the capability of GIS-based LSP methodology for evaluating suitability locations for urban densification and has been implemented on the Metro Vancouver Region. Results indicate the LSP method is an effective tool for creating justifiable logic criteria for high density urban development. In addition, the outcomes of this study are aiming at guiding future regional urban development in Metro Vancouver Region and facilitating the decision-making process of regional land use planning for municipal and regional government use. However, refinement of the outcome can be conducted by consulting specialists or interviewing the urban developer and urban planner for better understanding of their reasoning in respect to building and adding more attributes or improving aggregation structure. Moreover, additional attributes such as land price, age of buildings or addition of new transportation corridors would be beneficial for the improvement of the LSP aggregation structures that can be modified accordingly for re-evaluation of attributes and final suitability outcomes. With the consideration of more refined or coarser spatial scale can also create a different map to assist different needs in the suitability evaluation and decision-making process. Future research can focus on the sensitivity analysis of individual criterion and examination of the sensitivity of LSP method in cases of different aggregator groups such as GGCD or WPM.

In conclusion, the GIS-based LSP method is successfully used for evaluating suitable area for high density urban development, indicating that it possesses the capability of integrating large number of attribute criteria and the stepwise gradual process of quantitative modeling of reasoning logic that is necessary in the urban planning and land management decision making processes.

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Chapter 3.

Calculation of Overall Integrated Suitability[2]

3.1. Introduction

As the process of urbanization continues rapidly, the natural environments and human society are being challenged with its long-term impacts (Hennicke, 2005; Liao, Chang, Su, & Chiueh, 2013). Therefore, in order to accommodate the challenges such as deforestation or climate change, and alleviate its negative impacts, the sustainable urban development is proposed as a solution for better urban planning (Hamin & Gurran, 2009; Wheeler & Beatley, 2014). The sustainable urban development can be achieved through urban policies that protect the environment while facilitate economic growth (OECD, 2012). High-density urban development is a type of urban spatial form that mitigate the effect from rapid urbanization and urban sprawl (Ibrahim, 2007; Turkington, van Kempen, & Wassenberg, 2004). In contrast to urban sprawl with typical pattern of low-density development, urban densification is characterized by construction of high-rise buildings and implementation of mixed land use on a smaller surface area (Burton, 2002), which can provide a greater accessibility to nearby urban facilities.

Although there are different stakeholders such as government agents, real estate agents, environmentalists and conservationists involved and affected by the urban development process, urban developer and urban planner are the two stakeholders that predominate in the decision making process and construction of new high-rise buildings and are usually mutually by each other (Haque & Asami, 2014; Peiser, 1990a).

The initiatives of urban developer and urban planner are contradictive. Planners aim to regulate the zoning and land use in the urban area, in which they try to create a more functional and effective housing or shopping place within city (Calavita & Caves, 1994; Peiser, 1990a). In contrast, developers are driven by the objectives of maximizing their profits (Almagor, Benenson, & Alfasi, 2018; Coiacetto, 2000; Peiser, 1990b). Therefore, some urban planners are in confrontation with the perspectives of developers

[2] The version of this chapter co-authored with S. Dragicevic and J. Dujmovic will be submitted to the scientific journal for peer review.

as they consider the motivation of developers will affect the social systems, while some developers consider planners as neither responsible for nor understand process of the urban development (Peiser, 1990a). As a result, their perspectives need to be considered conjunctively in this situation.

However, the objectives of urban developer and urban planner can also be complementary with each other. Although their starting points are different, they both aim to achieve a more efficient and effective urban development (Dueker & Delacy, 1990). For example, as planners taking charge of the development approvals, developers would therefore depend on planner to guide the development process (Peiser, 1990a). Urban planner can not only provide information to developer for guiding development away from hazardous area and reducing the development risks (Stevens, Berke, & Song, 2008), but also lead the construction of new buildings in order to achieve more efficient land use (Mohamed, 2006, 2009), which is essential for high-density urban development. Moreover, planners can assist in developers' decision-making process by offering the information of urban growth trends (Mohamed, 2006). Therefore, their perspectives can also be considered disjunctively.

Furthermore, urban developer can sometimes partially rely on urban developers for providing direction on zoning, while they still follow their objectives of profit maximization. In this situation, a tradeoffs of the perspectives of urban developer and planner must be considered. Hence, in order to effectively address the evaluation of perspectives from both stakeholders involved in urban densification process, a multiple criteria evaluation (MCE) approach is necessary for integration of different objectives to satisfy different goals as it can employ various criteria in a decision-making problem.

MCE is a group of evaluation methods that allow decision maker to choose from various alternatives according to their perspectives (Malczewski, 2006). It has been widely used in different spatial applications such as agriculture (Ceballos-Silva & López-Blanco, 2003; Sánchez-Lozano, Teruel-Solano, Soto-Elvira, & Socorro García-Cascales, 2013), forest management (Phua & Minowa, 2005), while it is also applied in land use suitability (Malczewski, 1999, 2004). Therefore, the spatial decision support system (SDSS) (Malczewski, 1999, 2006) is proposed to implement MCE in GIS environment. In a GIS-based MCE application, GIS prepares the spatially referenced data that are used later by MCE to extract information for decision-making process (Malczewski, 1999). Therefore, by using GIS-based MCE method for urban development planning, land information can be captured in a more consistent and accurate way with the use of spatial database, which can in turn improve the understanding of relationships between perspectives from different stakeholders (Dueker & Delacy, 1990).

However, by using the common GIS-based MCE method such as AHP or OWA, the decision-making logic is hard to capture (Dujmovic, De Tré, & Dragicevic, 2009; Montgomery & Dragićević, 2016). The LSP method is based on soft computing and can represent the human reasoning logic by using stepwise aggregation. It can capture the information of selected criteria from simultaneity to substitutability with the use of logic aggregators (Dujmovic, 2007; Dujmović, 1975; Dujmović & Tré, 2011). Furthermore, the granulation of aggregators provide possibility for analyzing tradeoff of alternatives from different perspectives. Therefore, LSP remains as a necessary method for full spectrum of integrations of larger number of criteria and for obtaining suitability values of urban developer and urban planner.

The main objective of this research study is to integrate the perspectives of urban developer and urban planner by using GIS-based LSP method. Their perspectives of high-density urban development are represented by the suitability scores and maps generated in Chapter two. This proposed approach aims to provide a solution for integrating the suitability outputs of two stakeholders when considering different scenarios.

3.2. Methods

3.2.1. Study Area and Datasets

Metro Vancouver Region is located in the south-western British Columbia, Canada. It is the largest metropolitan area in Canada that experience a continuous population growth in recent years (Government of Canada, 2017). Therefore, a sustainable urban development strategy is necessary for accommodate the large population. Metro Vancouver authorities are pushing forward the Region Growth Strategy in order to provide the framework for sustainable growth (Metro Vancouver, 2019). Moreover, City of Vancouver has proposed the Eco-density Chapter and Greenest City Action Plan that aim to achieve higher density in built-up area in a sustainable approach

(City of Vancouver, 2016; Toderian, 2008). The GIS datasets are obtained through Chapter one in 10 meters resolution.

3.2.2. Overall Integrated Suitability

The LSP suitability maps show the densification suitability in each *(x,y)* point of the analyzed urban area. There are two different maps: *D(x,y)* denotes the suitability for urban developer and *P(x,y)* denotes the suitability for urban planner. Obviously, the areas of consensus or disagreement between the developer and the planner have to be investigated. If both the planner and the developer think that an area is highly suitable, then this is the best candidate for urban densification. Therefore, a justifiable logic aggregation of *P(x,y)* and *D(x,y)* maps yields the overall integrated suitability analysis and shows the most convenient order of urban densification development.

Three scenarios for combining the suitability values from two stakeholders were developed: (A) concurrent stakeholder scenario, (B) alternative stakeholder scenario and (C) tradeoffs stakeholder scenario. They can represent different solutions for modeling logic relationship between urban developer and urban planner and overall quantification of tradeoffs between their perspectives.

For the concurrent stakeholder scenario (A), a soft conjunctive (SC) and a hard conjunctive (HC) aggregators are used to combine the suitability values. This scenario represents the case when urban developer needs the approvals from urban planner in order to construct new building, and vice versa, the urban planner needs an interested developer to construct new buildings. A hard conjunctive (HC) aggregator represents a higher simultaneity than a soft conjunctive (SC) aggregator. In this case, the objectives of urban developer are stronger restricted by urban planner, and vice versa. For alternative stakeholder scenario (B), a soft disjunctive (SD) and a hard disjunctive (HD) aggregator are used to aggregate the values. It indicates a less frequent situation where urban developer is collaborating with urban planner for the selection of new construction sites. A hard disjunctive (HD) aggregator represents a more substitutable situation than a soft disjunctive (SD) aggregator. In this case, the two stakeholders' objectives are mutually accepted. For tradeoff stakeholder scenario (C), the arithmetic mean (A) with different weight values are used to integrate the suitability values. Three groups of weight values (25, 75), (50, 50), (75, 25) are used to represent the additional sub-scenarios when one of the stakeholders is dominant, or when they are equally affected by each other. The best overall integrated suitability is based on simultaneity, the suitability consensus of urban developer and urban planner.

3.3. Results

The overall integrated suitability maps are presented in Figure 3.1. The results represent the combination of suitability values for Metro Vancouver Region, and in more detailed spatial scale for Downtown Vancouver known as already being an urban high-density area. By comparing the overall results, more areas with higher suitability values are found in Alternative Scenario (B) than Concurrent Scenario (A). One possible explanation is that if two stakeholders collaborate with each other rather than conflict from each other, there will be more agreement between their perspectives and thus, generating more satisfying results in the choice of suitable locations for urban densification. The statistic of seven satisfaction levels in these three scenarios are provided in Table 3.1.

Table 3.1. The distribution of overall levels for integrated suitability.

	Alternative Scenario		**Concurrent Scenario**		**Tradeoff Scenario**		
	HD	SD	HC	SC	Developer=25%, Planner=75%	Developer=50%, Planner=50%	Developer=75%, Planner=25%
Excellent	67.82	65.54	64.84	64.46	66.11	64.89	63.53
Very Good	14.51	9.83	8.77	8.55	13.39	9.01	8.48
Good	9.98	15.48	10.09	8.50	12.70	12.29	8.70
Average	1.75	2.95	9.43	7.55	1.92	7.43	9.35
Poor	1.67	1.88	2.44	5.97	1.55	2.04	5.37
Very Poor	2.76	2.73	2.66	2.92	2.21	2.72	3.44
Unacceptable	1.51	1.59	1.76	2.05	2.11	1.62	1.13

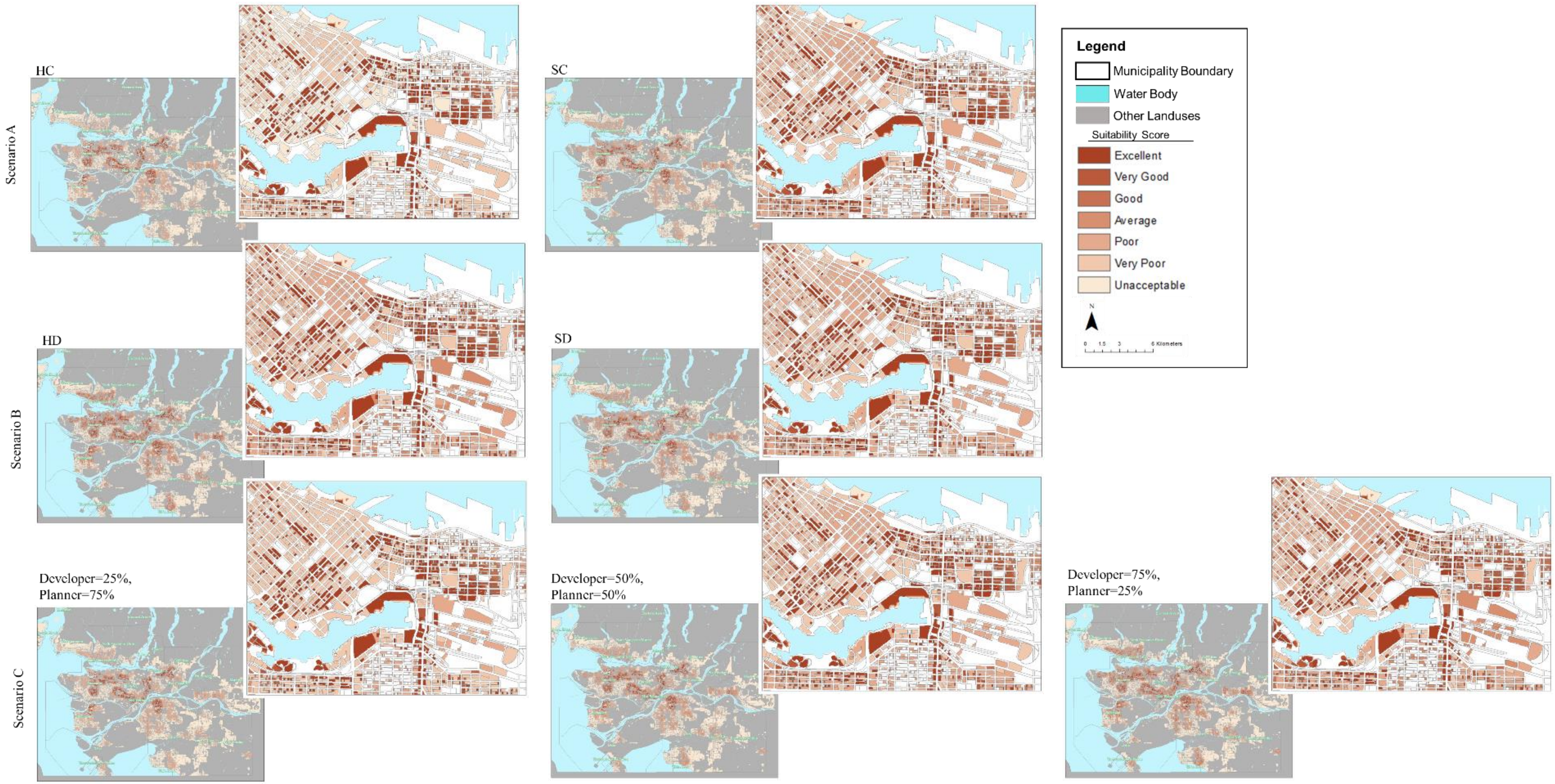

Figure 3.1. The obtained integrated suitability map representing three scenarios.

Figure 3.2 represents the fluctuation of seven satisfaction levels from substitutability to simultaneity with the increasing orness for aggregators that used to integrate suitability values. The absolute frequency of higher satisfaction (Excellent, Very good, Good) are increasing while that of lower satisfaction (Poor, Very poor, Unacceptable) are decreasing. This can be justified by the fact that when switching from concurrent scenario (A) to alternative scenario (B), with more collaboration and agreements occur between the two stakeholders and then more locations are considered suitable for high-rise building development as their perspectives are close to each other.

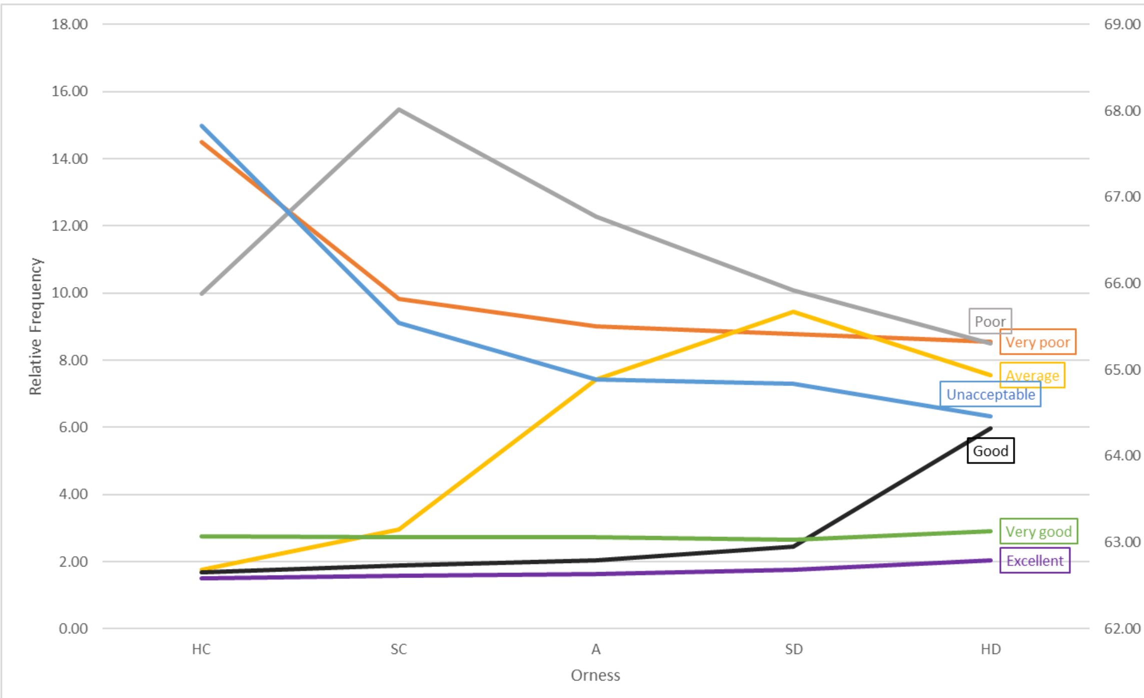

Figure 3.2. The line chart representing absolute frequency of overall levels according increasing orness.

3.4. Conclusions

The GIS-based LSP method provides a solution for integration of different perspectives of various stakeholders including urban developer and urban planner as for this case study. With the use of logic aggregators, three scenarios can be developed that represent different cooperation approaches and interaction between two stakeholders. The GIS-based LSP method overcome the limitations of previous GIS-based MCE methods for offering the crisp granulation of aggregators. Therefore, it is an effective method for providing flexible integration of perspectives of two stakeholders, urban developer and urban planner in the context of urban densification process.

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Chapter 4.

Exploratory Analysis of the LSP method for geospatial suitability analysis in GIS.LSP software environment[3]

4.1. Abstract

The Logic Scoring of Preference (LSP) is a multicriteria evaluation (MCE) method based on soft computing and realistic capturing of human logic reasoning for the decision-making process. The main objective of this study is the exploratory analysis of different LSP aggregator groups and the sensitivity of the method in geospatial application using a new GIS.LSP software tool. The LSP structures and aggregator groups have been used from the perspective of urban developers as stakeholders who play the key roles in the process of urban densification. The methodology has been applied on the datasets from Metro Vancouver Region, Canada. The GIS.LSP software tool was developed in Python 2.7 and interfaced with the ArcGIS software environment to facilitate the use and evaluation of the LSP method. In this case study, two main LSP aggregators groups, UGCD15 and UGCD7, are applied to build the selected criteria and create and compare the resulting LSP output suitability maps. Moreover, the sensitivity and cost/suitability analysis were conducted to further explore the GIS-based LSP method in the context of high-density urban development. The results indicate that the GIS-LSP method is an effective method providing a flexible and sensitive approach for creating realistic and justifiable complex criteria based on stakeholder's goals and requirements.

4.2. Introduction

Geographical Information Systems (GIS) are powerful tools that are used for solving various environmental and spatial problems, and therefore can be used as a part of spatial decision support systems (SDSS) (Densham, 1991). At the same time, Multi-Criteria Decision Analysis (MCDA), or also known as Multi-Criteria Evaluation (MCE), are

[3] The version of this chapter co-authored with S. Dragicevic and J. Dujmovic will be submitted to the scientific journal for peer review.

widely applied in SDSS for geospatial applications (Malczewski, 1999, 2006). There are already a number of MCE methods that combined with GIS devoted for spatial decision support to decision makers and stakeholders (Carver, 1991; Church, Loban, & Lombard, 1992; Eastman, Jin, Kyem, & Toledano, 1995). The use of GIS-based MCE is primarily aimed to find solutions for spatial decision-making problems with the integration between geospatial data, GIS software and multiple criteria (Jankowski, Andrienko, & Andrienko, 2001).

Logic Scoring of Preference (LSP) is a general MCE decision-making method that is based on modern concepts of soft computing and logic aggregation and used for suitability evaluation (Dujmović, 1975). By introducing a spectrum of logic operators and stepwise aggregation structure, the stakeholder's decision-making perspective with its goals and interests can be evaluated in a comprehensive way (Dujmović, Tré, & Weghe, 2008). The integration of GIS and LSP method can exert the efficiency of GIS in spatial analysis and the effectiveness of LSP in logic evaluation. As a result, GIS-based LSP method can provide a more flexible logic conditions than other common MCE (Dujmović et al., 2008) and especially those used in current GIS software environment. Moreover, it can further generate the suitability maps for a specific use to satisfy a particular decision maker's requirement. Therefore, comparing to common GIS-based MCE method that is frequently based on simple additive models and oversimplifying the intuitive human reasoning (Malczewski, 2006), the GIS.LSP approach has capability to better characterize decision making process and make it an effective tool for land use suitability analysis (Dujmović & Scheer, 2010).

Although MCE methods are available in the commonly used GIS software such as the Weight Overlay and Raster Calculator in ArcGIS (2019), the MCE module in TerrSet (IDRISI) (2019), the GeoFormula tool in MicroImages (TNT-GIS) (2019) and the r.mcda function in GRASS GIS (2019), they do not provide a module of LSP method. In TerrSet or ArcGIS GIS software environment, the 'Map Algebra' tool is the only way to incorporate LSP in GIS, which is limiting and time-consuming. The existing GIS-based MCE methods are using only the simple additive weighting (SAW), Boolean overlay, Analytical Hierarchy Process (AHP) and Outranking methods (Malczewski, 2006). They are usually capable to analyze the geospatial dataset with rather limited number of input suitability attributes (up to maximum of 10-12). The LSP MCE method is designed to overcomes these limitations and shortcomings.

GIS-based LSP method was previously used for suitability analysis in agriculture (Montgomery, Dragićević, Dujmović, & Schmidt, 2016), groundwater vulnerability (Rebolledo, Gil, Flotats, & Sánchez, 2016), urban residential development (Dragićević, Dujmović, & Minardi, 2018; Hatch, Dragićević, & Dujmović, 2014) and home location selection (Dujmović & Scheer, 2010). The GIS-based LSP method is compared with commonly available MCE ones in GIS software (Dujmovic, De Tré, & Dragicevic, 2009; Montgomery & Dragićević, 2016). Furthermore, the sensitivity analysis of the LSP method was perform for a computer system evaluation (Su, Dujmovic, Batory, Navathe, & Elnicki, 1987). However, there are still no research exploring how the GIS-based LSP method perform and how sensitive are the results when using different LSP aggregator groups for geospatial applications. Therefore, the main objectives of this study are to evaluate GIS-based LSP method by (1) comparing the two LSP aggregators groups and (2) performing the sensitivity analysis and cost/suitability analysis using the LSP method. These evaluations are performed using a typical case study of urban densification process based on geospatial data for Metro Vancouver, British Columbia, Canada as study area.

4.3. The LSP method

The LSP method is based on the soft computing, which offers a full spectrum of aggregators ranging from the extreme simultaneity (parameterized using the conjunction degree called andness) to substitutability (parameterized using the disjunction degree called orness) (Dujmović, 2018). It is originally used for evaluating computer systems and is further introduced into spatial application for land suitability analysis (Dujmović, 1975, 1996; Dujmović & Scheer, 2010). There are five steps to follow in order to use the GIS-based LSP method: (1) specify decision problem and stakeholder, (2) construct the LSP attributes tree, (3) define the elementary attribute criteria, (4) develop the LSP aggregation structure and (5) obtain the LSP suitability scores and map. The sensitivity analysis and cost/suitability analysis can also be applied for the purpose of examination of selected criteria and comparison of generated LSP suitability map (Dujmović, 2018). These main steps of LSP method can be briefly described as follows:

The Decision Problem and Stakeholder is a person or group of people that will utilize and make decision based on the final LSP suitability map. They need to be identified in order to specify the requirement of evaluation criteria. For this research study, the urban developer as stakeholder has been used as an example for the implementation of the proposed methodology. Mainly because sustainable urban development is encompassing urban densification and vertical urban growth with high-rise building as a part of the planning strategies that would alleviate the adverse effects of urban sprawl (Fallah, Partridge, & Olfert, 2011; Nakamura, 2012). Urban developers influence urban densification process (Fincher, 2004, 2007; Turkington, van Kempen, & Wassenberg, 2004) and carry one of the key roles (Mohamed, 2006; Peiser, 1990) in the urban planning process.

LSP Attributes Tree is constructed as a hierarchical structure with a list of criteria that are of the stakeholder concern. They will be further grouped to reflect the stakeholder's goals and interests. A few main criteria will be formed on the top, following by more detailed criteria appended after them. For this study, urban developer can specify two main criteria 'livability' and 'accessibility', livability can be refined by distance to an amenity such as recreational park and distance to shopping centre, while accessibility can be refined by distance to major road and distance to bus stop. Then, each of the criterion is further classified into mandatory, optional, or sufficient based on their importance and effect of the evaluation process. A mandatory criterion must be satisfied in order to achieve a high overall satisfaction for the evaluation. In contrast, a highly satisfied sufficient criterion can lead to an overall satisfactory of evaluation no matter how much satisfaction other criteria can reach. An optional criterion is desired but not mandatory, in other words, it can affect but is not decisive for the final satisfactory.

The Elementary Attribute Criteria provide further specification of individual attributes or criteria according to stakeholder's requirements. Each attribute will be regenerated into value ranging from totally unsatisfied (0) to completely satisfied (1 or 100%) in order to quantify the stakeholder's satisfaction level. The elementary attribute criteria is usually denoted by "vertex notation": $\mathrm{Crit(a)} = \{(a_0, s_0), \dots, (a_k, s_k)\}$, in which the attribute a is represented by a list of increasing key value a_0…a_k where the satisfaction level of stakeholder will change, and the corresponding satisfaction level (suitability score) $s_0 \dots s_k$. Between the key value $a_0 \dots a_k$, a simple linear interpolation is always assumed for creation of a continuous satisfaction level (Dujmović, 2018).

The LSP Aggregation Structure permits more detailed elaboration of attributes tree consisting all the criteria, weights and aggregators that necessary to represent a wide spectrum of human logic reasoning for chosen stakeholder.

Type of Aggregators – two types of aggregators are typically used to combine criteria such as the Graded Conjunction/Disjunction (GCD) and the Partial Absorption (PA) (Dujmović, 2018). The GCD aggregator is used when combining similar criteria like two mandatory criteria, two optional criteria, or two sufficient criteria. Otherwise, the PA aggregator is used when combining different types of criteria. For example, aggregating a mandatory criterion with an optional criterion, or a sufficient criterion with an optional criterion.

4.3.1. LSP Aggregator Groups

When using a GCD aggregator for aggregating two or more criteria, a specific aggregator is chosen from a certain aggregator group. The LSP method provides a total of seven GCD aggregators groups (Figure 4.1). A GCD aggregators group is characterized by its threshold andness and level of precision. Precision is determined by the crisp granulation of andness and orness for aggregators, which is further represented by the number of aggregators in the group (Dujmović, 2018). More aggregators in a group, more variations for decision-making logic can be represented by that group. Three uniform aggregators groups range from low precision to high precision: UGCD7, UGCD15, UGCD23. Three general aggregators groups from low to high precision: GGCD9, GGCD17, GGCD25 while WPM17 is for the medium precision aggregators group using weighted power mean (Dujmović, 2018). Different aggregators group is chosen according to the need and proficiency of stakeholder and the type of the application for the evaluation, however when dealing with single evaluation only one GCD aggregators group should be chosen.

The only difference between the UGCD, GGCD and WPM aggregators group is the threshold andness. Both UGCD and WPM uses a fixed threshold andness ($a_{\theta UGCD} = 0.75,\ a_{\theta WPM} \approx 0.67$), while GGCD uses an adjustable threshold andness. Threshold andness is one of the decisive elements in the logic aggregation form (Dujmović, 2018). It determines the exponent of a logic function and the range of aggregator categories. Therefore, GGCD is flexible and suitable for experienced user, while UGCD is more introductory and simpler to use.

Given their characteristic, the UGCD15 and UGCD7 aggregators groups have been used in this research study for exploration and comparison of LSP method. The visual and statistical comparisons of suitability maps as well as sensitivity analysis were conducted for these two aggregators groups in the context of geospatial suitability evaluation.

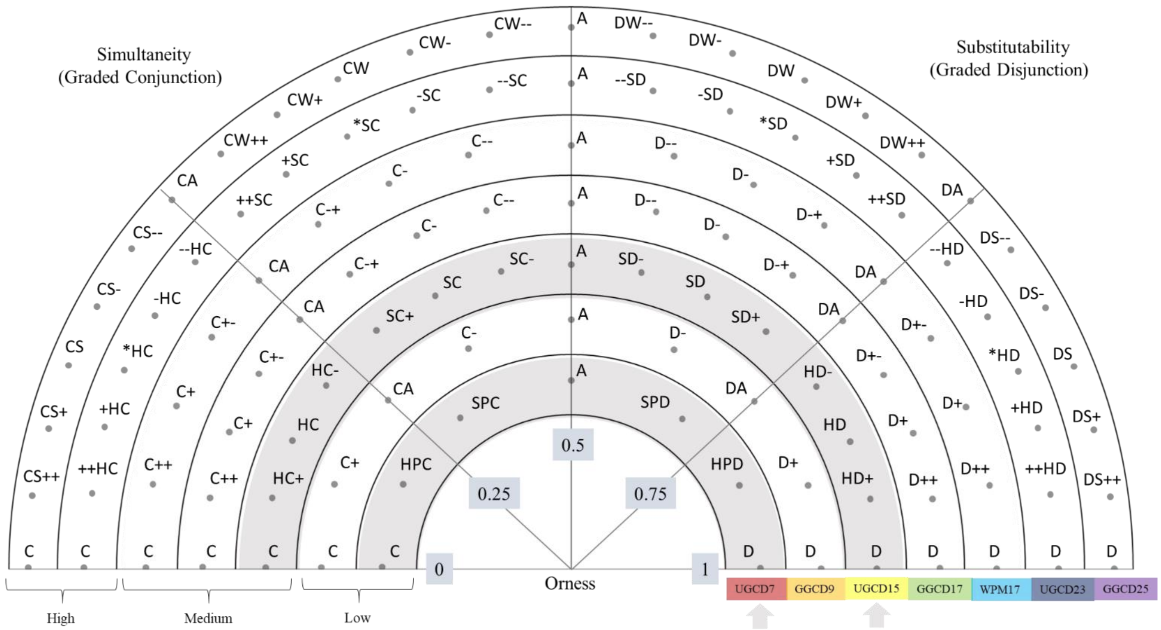


Figure 4.1. Seven GCD aggregators groups with their detailed aggregators, where two highlighted, UGCD15 and UGCD7, are used in this study.

4.3.2. Sensitivity Analysis

As LSP is a decision-making method, a sensitivity analysis is important for verifying relationship between input criteria and evaluation output. The sensitivity analysis represents how output is sensitive on the variation of input parameters (Dujmovic & Elnicki, 1981; Su et al., 1987). It provides more insight on the justification between selected criteria and the interpretation of output suitability value. For this research, the local sensitivity analysis was implemented by varying input parameter in a one-at-a-time (OAT) approach (Saltelli, Tarantola, Campolongo, & Ratto, 2004).

For this research study, the local sensitivity analysis is applied to the variations of the three LSP method components: (1) input suitability values of individual criterion, (2) input attributes of individual criterion, and (3) aggregators. For the GIS-based LSP method, the sensitivity analysis can be performed according to a specific location or criterion. The sensitivity analysis will indicate how much an input criterion at a specific location can affect the output suitability value, or how much impact will have on the output suitability value if an aggregator is changed. In particular, even for the exact same criterion and aggregation structure, the sensitivity analysis result will vary by locations as the surrounding geographical and attribute elementary properties are distinct in different locations.

4.3.3. Cost/Suitability Analysis

At the end of an evaluation, after the stakeholder has obtained the LSP suitability scores and maps representing the suitability level for every location of the study area according to their goals and interests, an overall LSP suitability map can be further created by combining the suitability map with a cost map. The overall suitability map reflects a further step of reasoning and tradeoffs behind the financial negotiations between high suitability and low cost. More precisely, the cost map is showing the total cost of a location that the stakeholder must pay in order to develop urban contents at that location. In the geospatial context, the cost value can be the land price of that location. For example, the cost map can be also called a land price map.

4.4. The GIS.LSP tool

For the purpose of the implementation of the LSP method in GIS software environment, the GIS.LSP tool is developed. It supports all steps in the development and documentation of LSP criteria: the specification of the attribute trees, elementary attribute criteria, design of LSP aggregation structures, and generation of LSP suitability maps. It also capable of performing component analysis, sensitivity analysis, cost/suitability analysis and suitability map statistics. Figure 4.2 shows the LSP application in GIS raster data environment. For each of the raster cell ij, there is a value $x_{ij}^{(n)}$ generated by the elementary attribute criteria of attribute *n*, indicating the satisfaction level of certain property at this raster cell. Then, based on the function $L\left(x_{ij}^{(1)}, x_{ij}^{(2)}, \ldots, x_{ij}^{(n)}\right)$, the overall suitability of cell ij can be calculated.

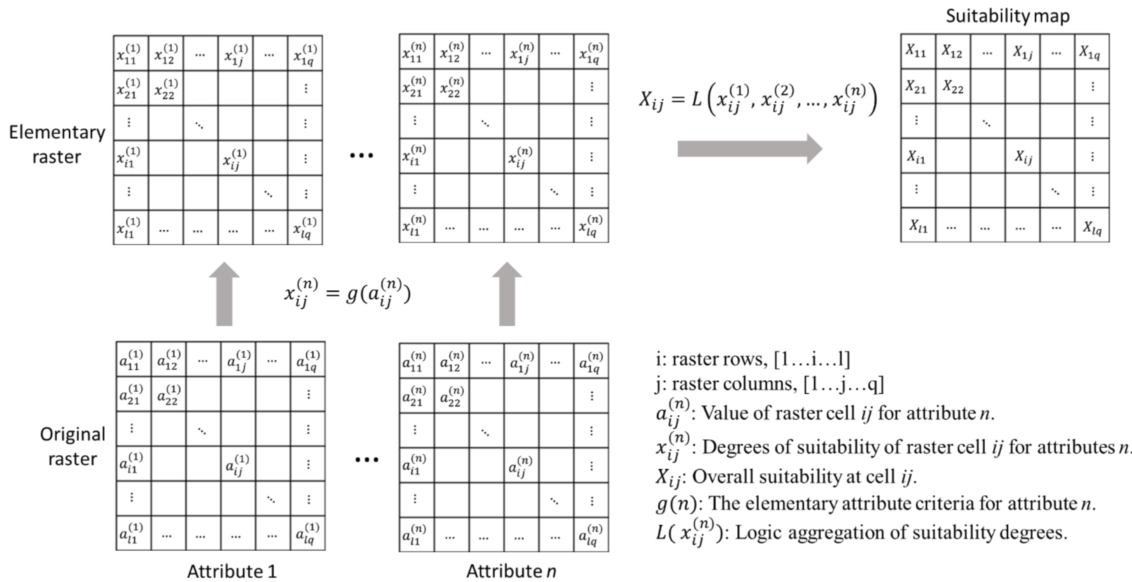


Figure 4.2. LSP method suitability aggregation in raster GIS environment.

4.4.1. Programing Environment and Framework

With the development of Software Development Kits (SDK) and Application Programming Interface (API), a standalone software is allowing for add-on functions development and in-between application communication. For example, varying in flexibility, there are ArcGIS API for JavaScript, ArcGIS Runtime SDK for Java and ArcGIS Runtime SDK for .NET (ESRI, 2019a). At the same time, ArcGIS software also offers the customization based on one of the popular and easy-to-use general-purpose programming languages – Python (2019). This allows for less flexible customization in Python such as ModelBuilder or loading Python script as a custom toolbox. Furthermore, it provides a more comprehensive customization of tool by using Python add-in (ESRI, 2019b).

The GIS.LSP tool is developed by Python add-in (ESRI, 2019b) and it is presented as an ArcMap 10.5 toolbar once the add-in is installed. The tool programed in Python environment with the use of ArcPy (ESRI, 2019c) and wxPython (Precord, 2010) package. ArcPy provides the access to classes and modules in ArcGIS, including functions of spatial data analysis, data management and conversions. The wxPython is the cross-platform toolkit that helps to create graphical user interface (GUI) in Python environment. Therefore, the GIS.LSP module is accomplished by using wxPython to create user interfaces that facilitate the development of LSP aggregation structure and using ArcPy to perform raster calculation that generate the suitability map. The flow chart of the processing approach implemented in GIS.LSP is presented in Figure 4.3. The detail descriptions of several suitability map analysis modules, and operation of changing aggregators group and threshold andness are shown in Table 4.1.

Table 4.1. Descriptions and applications of suitability map analysis and aggregators group modification in GIS.LSP.

Function	Descriptions
Component Analysis	X_{ij} is compared with x_{ij} of every single criterion. If $x_{ij} < X_{ij}$, then this criterion needs to be improved in order to increase the X_{ij}.
Sensitivity Analysis	Given a list $\boldsymbol{x_{ij}} = x_{ij}^{(0)},\ x_{ij}^{(1)}, x_{ij}^{(2)}, \ldots, x_{ij}^{(n)}$ of perturbations or changes in the a range of the suitability values for selected criterion or an aggregator, and the evaluation parameters $\boldsymbol{p_{ij}} = p_{ij}^{(0)},\ p_{ij}^{(1)}, p_{ij}^{(2)}, \ldots, p_{ij}^{(n)}$, the corresponding suitability values list $\boldsymbol{X_{ij}} = F(\boldsymbol{x_{ij}}; \boldsymbol{p_{ij}}) = X_{ij}^{(0)},\ X_{ij}^{(1)}, X_{ij}^{(2)}, \ldots, X_{ij}^{(n)}$ is generated. The Absolute Influence Range is also calculated by using formula: $\max(\boldsymbol{X_{ij}}) - \min(\boldsymbol{X_{ij}})$.
Cost/Suitability Analysis	In LSP method, the cost/suitability analysis can be achieved by using soft computing and graded logic (Dujmović, 2018): $X_{ij}(Cost) = \left(Cost_{min}/Cost_{ij}\right)^{W} * \left(X_{ij}/X_{ijmax}\right)^{1-W}$.
Statistics	The absolute frequency of suitability scores is counted by the user-defined range of value.
Change Aggregator Group	Change the aggregator group of a project to another aggregators group. Every single aggregator in the original aggregators group is changed to the aggregators in the targeted aggregators group according to the closeness of two aggregators' andness value.
Change Threshold Andness	Change the threshold andness value of a GGCD aggregators group. Threshold andness must in the range of (0.5, 1).

*In above formula:
x_{ij}: The suitability score generated by elementary attribute criteria of a certain attribute at location ij; p_{ij}: The evaluation parameters; X_{ij}: The overall suitability score at location ij; X_{max}: The maximum overall suitability score in the study area; $Cost_{ij}$: The cost value at location ij; $Cost_{min}$: The minimum cost value in the study area; $X_{ij}(Cost)$: The weighted hard partial conjunction of the relative suitability of cost and the relative suitability of evaluated location at location ij; W: The relative importance of low cost for a given stakeholder (0 < W < 1, ranges from totally not important to extreme important).

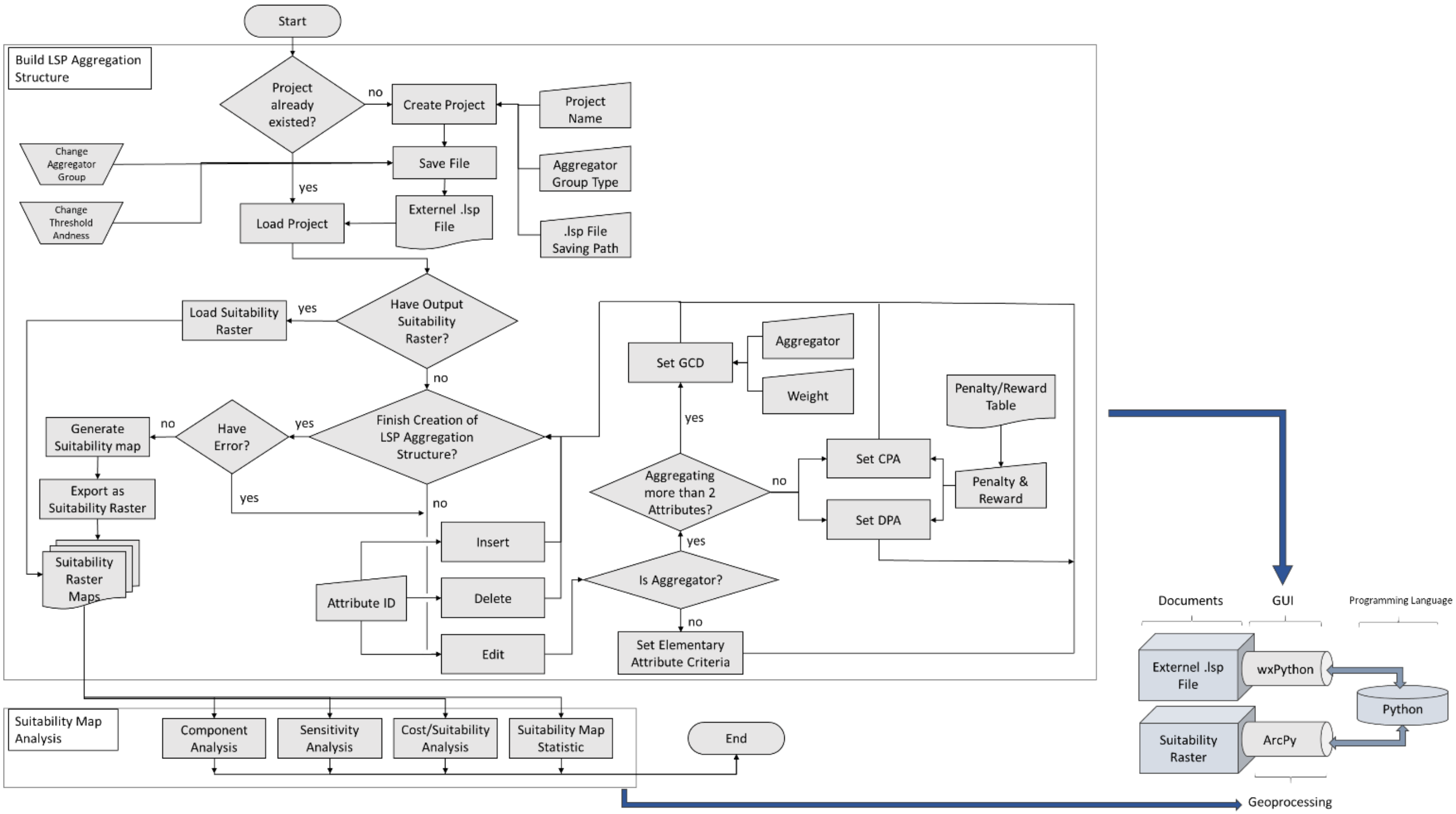


Figure 4.3. Flow chart of the geoprocessing approach for GIS.LSP method and tool.

The .lsp file is created to store the LSP aggregation structure and all the information related to the evaluation. It will be created under the user-defined path and automatically saved every time when the user modifies the elementary attribute criteria and the aggregation structure. The .lsp file is loaded into GIS.LSP as a project file and it can be decomposed into a hierarchical structure in Figure 4.4. The project is a root object class containing all the necessary information for a chosen suitability evaluation. The aggregator group under project is an object class including all the aggregators of a certain aggregator group ranging from full conjunction to full disjunction. The attribute object in the attributes list is a universal object class that represents the element in LSP attributes tree. In another words, an attribute object is a node in the overall attributes tree, which can be a criterion or an aggregator. It is the major component of GIS.LSP that store the information related to the elementary attribute criteria, weights and penalty/reward values. At the lower level, the aggregator object is the representation of a single aggregator including the andness value that used for computation of LSP suitability scores and creation of LSP suitability map.

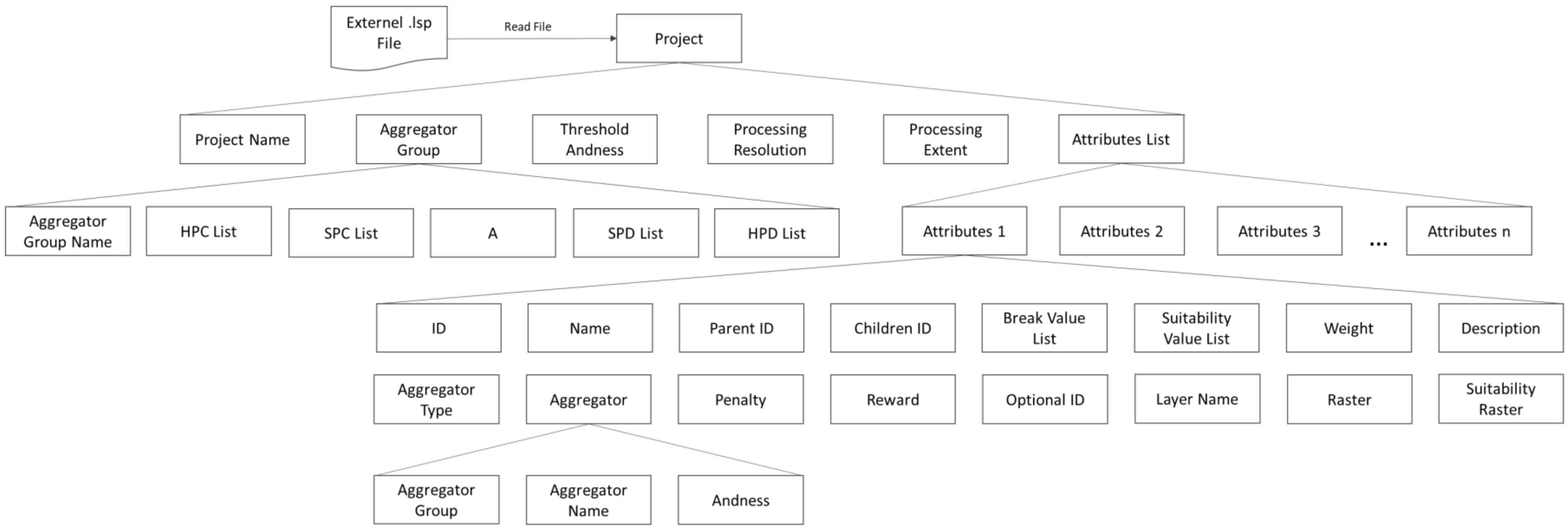
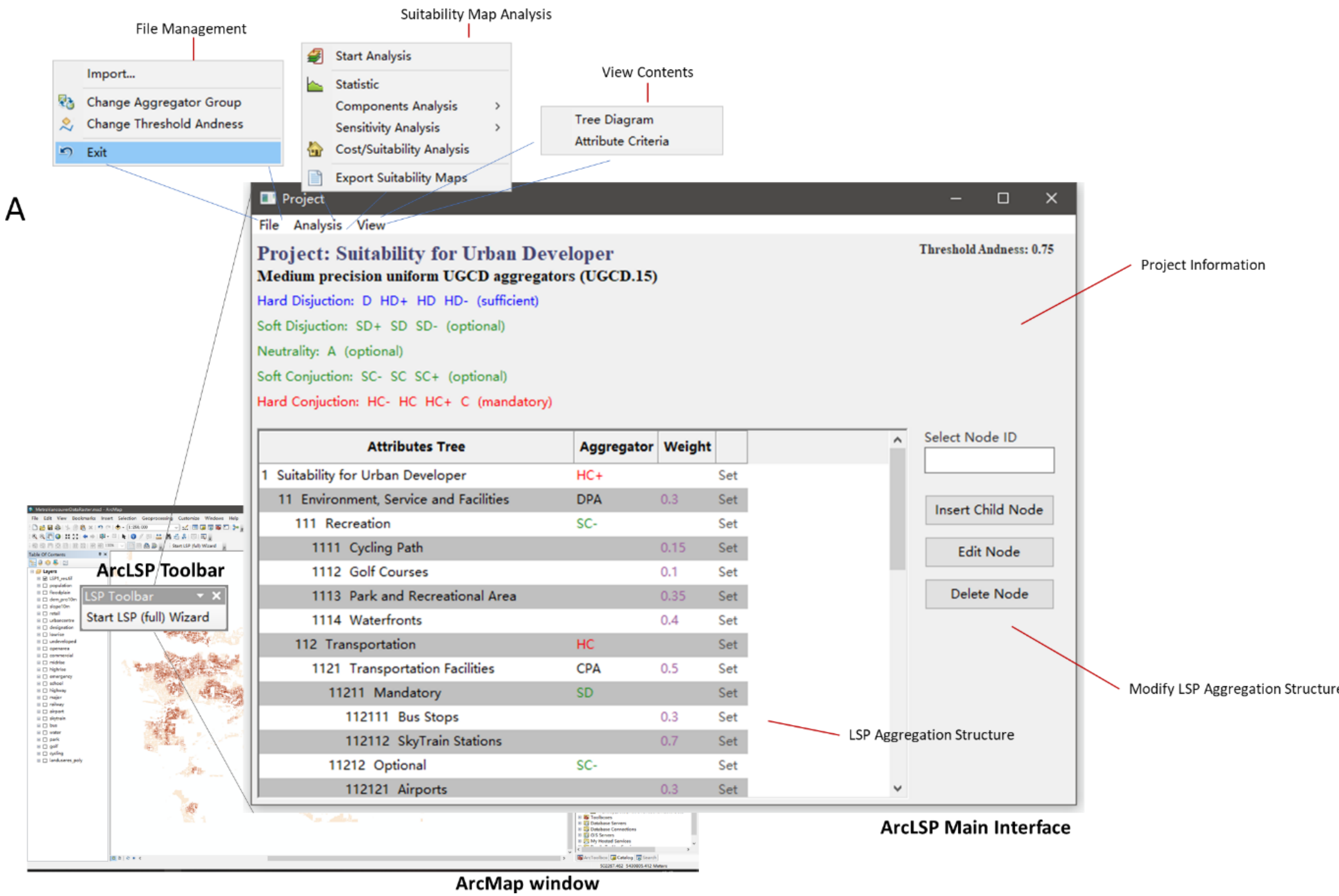


Figure 4.4. GIS.LSP tool .lsp file structure.

4.4.2. User Interface

The GIS.LSP tool main user interface is presented in Figure 4.5A. It will show up once the project is created or the project file is loaded. Interfaces for several main GIS.LSP function are presented in Figure 4.5B.

There are three benefits of building the framework in this way. First, by using object class, the gap between developer and user is lessened and the object is easier to locate and maintain. Second, the attributes are organizing hierarchically, but not linearly, which facilitate the modification of LSP aggregation structure and generation of suitability map. Third, instead of being a standalone program, GIS.LSP is coupled with ArcMap as a toolbar. This provide the user more flexibility of utilizing a large group of geoprocessing tool offered by ArcMap, which giving the opportunity to conduct a further step of spatial information analyzing, modeling and visualizing within the same environment.


A
File Management
Import...
Change Aggregator Group
Change Threshold Andness
Exit
Suitability Map Analysis
Start Analysis
Statistic
Components Analysis
Sensitivity Analysis
Cost/Suitability Analysis
Export Suitability Maps
View Contents
Tree Diagram
Attribute Criteria
Project
File Analysis View
Project: Suitability for Urban Developer
Threshold Andness: 0.75
Medium precision uniform UGCD aggregators (UGCD.15)
Hard Disjuction: D HD+ HD HD- (sufficient)
Soft Disjuction: SD+ SD SD- (optional)
Neutrality: A (optional)
Soft Conjuction: SC- SC SC+ (optional)
Hard Conjuction: HC- HC HC+ C (mandatory)
Project Information
Attributes Tree
Aggregator
Weight
1 Suitability for Urban Developer HC+ Set
11 Environment, Service and Facilities DPA 0.3 Set
111 Recreation SC- Set
1111 Cycling Path 0.15 Set
1112 Golf Courses 0.1 Set
1113 Park and Recreational Area 0.35 Set
1114 Waterfronts 0.4 Set
112 Transportation HC Set
1121 Transportation Facilities CPA 0.5 Set
11211 Mandatory SD Set
112111 Bus Stops 0.3 Set
112112 SkyTrain Stations 0.7 Set
11212 Optional SC- Set
112121 Airports 0.3 Set
Select Node ID
Insert Child Node
Edit Node
Delete Node
Modify LSP Aggregation Structure
LSP Aggregation Structure
ArcLSP Toolbar
LSP Toolbar
Start LSP (full) Wizard
ArcLSP Main Interface
ArcMap window

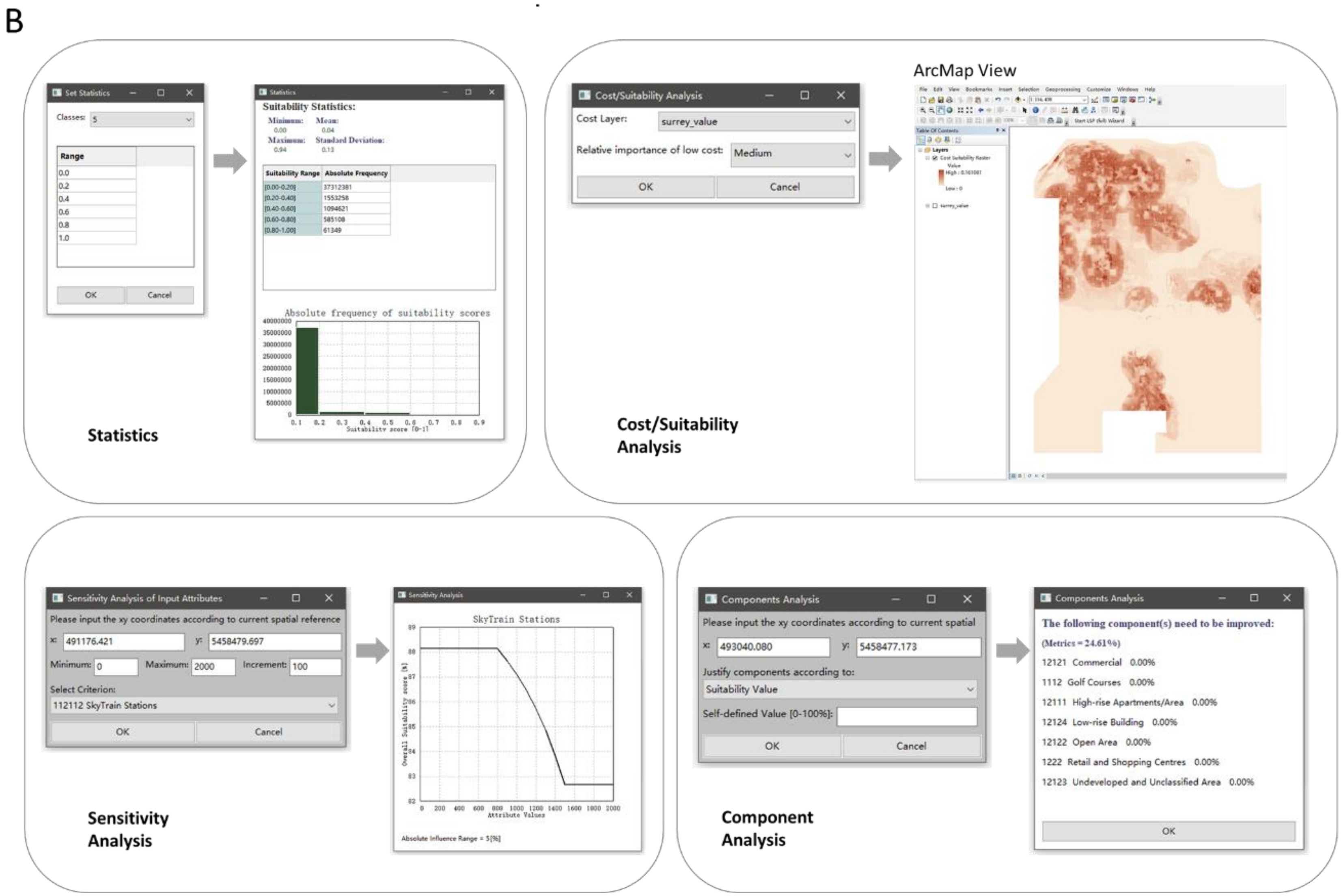


Figure 4.5. GIS.LSP tool user interface with (A) main functions and (B) various analytical subfunctions.

4.5. Case Study of Urban Densification suitability evaluation

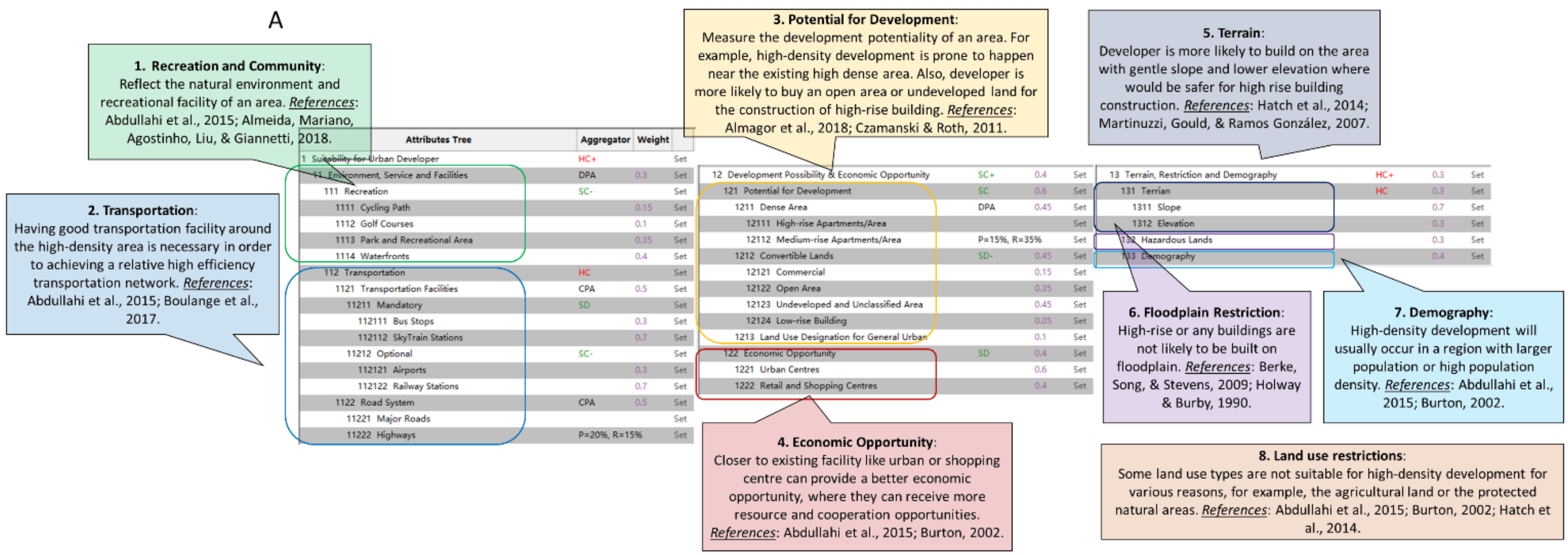
4.5.1. Context and Datasets

Metro Vancouver Region is well known for its rapid growth in terms of population that entails fast urban development (Metro Vancouver, 2011). The sustainable development of the region is being proposed through regional plans and initiatives (Metro Vancouver, 2010), in which a planning encourage the urban densification process in order to mitigate the negative impact of urban sprawl on natural environment. Data for Metro Vancouver is accessed through City of Surrey Open Data Catalogue (2019), DMTI Spatial, Inc (2016), DataBC (2018), Metro Vancouver Open Data (2016), Statistics Canada (2012), TransLink General Transit Feed Specification Data (2018) and Digital Elevation Model Dataset (2018). All the GIS datasets are converted into ArcGIS raster format in 10m spatial resolution. Slope and elevation data are processed based on the assumption that the high-rise building is always built on a flat ground.

4.5.2. GIS.LSP Method Implementation

Creation of LSP Attributes Tree - the perspectives of urban developer are complex, and they are directly implicated to the rapid high-rise building development (Almagor, Benenson, & Czamanski, 2018; Czamanski & Roth, 2011). Eight groups of criteria are selected to best describe the urban developer’s reasoning and they are presented on Figure 4.6A with justifications and related references. Then, each group is decomposed into sub-criteria that justify the criteria from further aspects. They are reorganized according to their relationships and formed the attributes tree.

Elementary Attribute Criteria - the elementary attribute criteria as suitability functions are linked to GIS raster layer for every criterion. The GIS raster values are ranging from 0 to 1 that stand for the suitability of a certain criterion according to urban developer’s perspectives. The list of elementary attribute criteria used in this study are shown by the GIS.LSP interface in vertex notation (Figure 4.6B).


A
1. Recreation and Community: Reflect the natural environment and recreational facility of an area. References: Abdullahi et al., 2015; Almeida, Mariano, Agostinho, Liu, & Giannetti, 2018.
2. Transportation: Having good transportation facility around the high-density area is necessary in order to achieving a relative high efficiency transportation network. References: Abdullahi et al., 2015; Boulange et al., 2017.
3. Potential for Development: Measure the development potentiality of an area. For example, high-density development is prone to happen near the existing high dense area. Also, developer is more likely to buy an open area or undeveloped land for the construction of high-rise building. References: Almagor et al., 2018; Czamanski & Roth, 2011.
4. Economic Opportunity: Closer to existing facility like urban or shopping centre can provide a better economic opportunity, where they can receive more resource and cooperation opportunities. References: Abdullahi et al., 2015; Burton, 2002.
5. Terrain: Developer is more likely to build on the area with gentle slope and lower elevation where would be safer for high rise building construction. References: Hatch et al., 2014; Martinuzzi, Gould, & Ramos González, 2007.
6. Floodplain Restriction: High-rise or any buildings are not likely to be built on floodplain. References: Berke, Song, & Stevens, 2009; Holway & Burby, 1990.
7. Demography: High-density development will usually occur in a region with larger population or high population density. References: Abdullahi et al., 2015; Burton, 2002.
8. Land use restrictions: Some land use types are not suitable for high-density development for various reasons, for example, the agricultural land or the protected natural areas. References: Abdullahi et al., 2015; Burton, 2002; Hatch et al., 2014.
Attributes Tree | Aggregator | Weight
1 Suitability for Urban Developer | HC+ | | Set
11 Environment, Service and Facilities | DPA | 0.3 | Set
111 Recreation | SC- | | Set
1111 Cycling Path | | 0.15 | Set
1112 Golf Courses | | 0.1 | Set
1113 Park and Recreational Area | | 0.35 | Set
1114 Waterfronts | | 0.4 | Set
112 Transportation | HC | | Set
1121 Transportation Facilities | CPA | 0.5 | Set
11211 Mandatory | SD | | Set
112111 Bus Stops | | 0.3 | Set
112112 SkyTrain Stations | | 0.7 | Set
11212 Optional | SC- | | Set
112121 Airports | | 0.3 | Set
112122 Railway Stations | | 0.7 | Set
1122 Road System | CPA | 0.5 | Set
11221 Major Roads | | | Set
11222 Highways | P=20%, R=15% | | Set
12 Development Possibility & Economic Opportunity | SC+ | 0.4 | Set
121 Potential for Development | SC | 0.6 | Set
1211 Dense Area | DPA | 0.45 | Set
12111 High-rise Apartments/Area | | | Set
12112 Medium-rise Apartments/Area | P=15%, R=35% | | Set
1212 Convertible Lands | SD- | 0.45 | Set
12121 Commercial | | 0.15 | Set
12122 Open Area | | 0.35 | Set
12123 Undeveloped and Unclassified Area | | 0.45 | Set
12124 Low-rise Building | | 0.05 | Set
1213 Land Use Designation for General Urban | | 0.1 | Set
122 Economic Opportunity | SD | 0.4 | Set
1221 Urban Centres | | 0.6 | Set
1222 Retail and Shopping Centres | | 0.4 | Set
13 Terrain, Restriction and Demography | HC+ | 0.3 | Set
131 Terrian | HC | 0.3 | Set
1311 Slope | | 0.7 | Set
1312 Elevation | | 0.3 | Set
132 Hazardous Lands | | 0.3 | Set
133 Demography | | 0.4 | Set

B

Attribute Criteria

Criterion	Attribute Criteria: {(value1, suitability1), . . . , (value_n, suitability_n)}
Cycling Path	{(0.0, 0.0), (15.0, 1.0), (200.0, 1.0), (350.0, 0.0)}
Golf Courses	{(10.0, 0.0), (200.0, 1.0), (1500.0, 1.0), (3000.0, 0.0)}
Park and Recreational Area	{(0.0, 1.0), (300.0, 1.0), (900.0, 0.0)}
Waterfronts	{(0.0, 0.0), (30.0, 1.0), (600.0, 1.0), (1000.0, 0.0)}
Bus Stops	{(0.0, 0.0), (20.0, 1.0), (300.0, 1.0), (600.0, 0.0)}
SkyTrain Stations	{(0.0, 1.0), (800.0, 1.0), (1500.0, 0.0)}
Airports	{(1500.0, 0.0), (2000.0, 1.0), (10000.0, 1.0), (15000.0, 0.0)}
Railway Stations	{(0.0, 0.0), (100.0, 1.0), (800.0, 1.0), (1500.0, 0.0)}
Major Roads	{(0.0, 1.0), (150.0, 1.0), (600.0, 0.0)}
Highways	{(0.0, 1.0), (500.0, 1.0), (1000.0, 0.0)}
High-rise Apartments/Area	{(10.0, 1.0), (500.0, 1.0), (1500.0, 0.0)}
Medium-rise Apartments/Area	{(5.0, 1.0), (450.0, 1.0), (1000.0, 0.0)}
Commercial	{(0.0, 0.0), (1.0, 1.0)}
Open Area	{(0.0, 0.0), (1.0, 1.0)}
Undeveloped and Unclassified Area	{(0.0, 0.0), (1.0, 1.0)}
Low-rise Building	{(0.0, 0.0), (1.0, 1.0)}
Land Use Designation for General Urban	{(0.0, 0.0), (1.0, 1.0)}
Urban Centres	{(0.0, 1.0), (500.0, 1.0), (1200.0, 0.0)}
Retail and Shopping Centres	{(0.0, 1.0), (600.0, 1.0), (1200.0, 0.0)}
Slope	{(0.0, 1.0), (20.0, 1.0), (60.0, 0.0)}
Elevation	{(0.0, 1.0), (300.0, 1.0), (1000.0, 0.0)}
Hazardous Lands	{(10.0, 0.0), (50.0, 1.0)}
Demography	{(0.0, 1.0), (350.0, 1.0), (1000.0, 0.0)}

Figure 4.6. High-density urban development suitability analysis for urban developer's perspectives executed in the GIS.LSP tool with (A) attributes tree with justifications, and (B) elementary attribute criteria.

LSP Aggregation Structure - contains aggregators that describe the developer's reasoning logic of the trade-off between different criteria, while the weight represents the relative importance of criteria. When developing the LSP aggregation structure, a canonical aggregation structures (CAS) is the design rules and must be followed in order to make the structure justifiable (Dujmović, 2018). For example, when aggregating from leaves to root of the attributes tree, the andness of aggregator must be increasing in the case of conjunctive CAS, or decreasing following disjunctive CAS.

The LSP aggregation structure is presented on Figure 4.7 by GIS.LSP interface using UGCD15 aggregators group, however they can be made in other aggregator groups as well such as UGCD7. Weight and Penalty/Reward values remain unchanged for all these two aggregators groups. Each criterion is corresponding to a raster generated by the dataset and further serves as the input in aggregation structure.

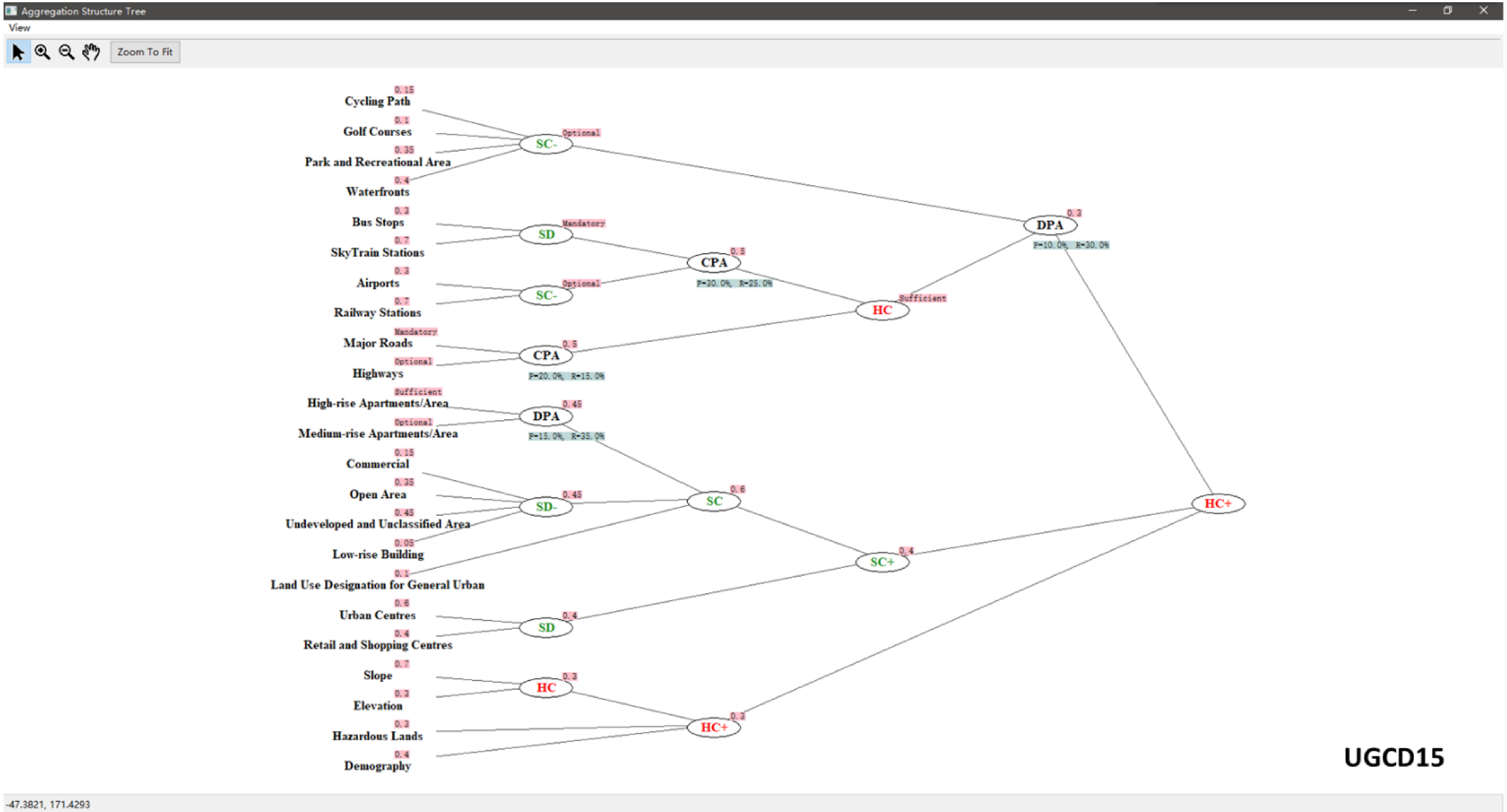


Figure 4.7. The LSP aggregation structure for urban developer's stakeholder using UGCD15 aggregators groups in GIS.LSP user interface.

4.6. Results

The suitability scores and maps were obtained for UGCD15 and UGCD7 with datasets for Metro Vancouver Region are provided on Figure 4.8 with the area in Downtown Vancouver, known as already highly densified, for greater detail. As in Chapters 2 and 3, the obtained suitability values are subdivided in seven satisfaction levels for the generated suitability maps: excellent [1.00–0.80], very good (0.80–0.66], good (0.66–0.52], average (0.52–0.38], poor (0.38–0.24], very poor (0.24–0.10], unacceptable (0.10–0.00]. If an area is in excellent satisfaction level, it is therefore a highly suitable location for new high-rise building construction based on the defined urban developer's preferences and goals. In contrast, a very poor or unacceptable satisfaction level indicates a contradiction to the urban developer's reasoning process, which means that area is not suitable for a developer to conduct high-rise building process.

4.6.1. Comparison of Aggregators Groups

The tables comparing two aggregator groups for obtained values of suitability scores are presented in Table 4.2. The results indicate that, although UGCD15 and UGCD7 are similar to each other, there are still some differences in the mid satisfaction area (average), while there is less difference in the low and high satisfaction area (excellent and unacceptable suitability). Furthermore, the suitability scores for different area in UGCD7 are rather similar, comparing to the more distinction of suitability score in UGCD15. There are two reasons responsible for these phenomena. First, the same attributes tree and weight and penalty/reward value are applied to these two aggregators groups can cause a rather similar result. Second, there are less aggregators in UGCD7 than in UGCD15 to distinguish the different reasoning patterns of stakeholder. For example, the two different aggregators, HC and HC+ in UGCD15, are both represented by HPC in UGCD7, while the SC- and SD- in UGCD15 are both represented by A in UGCD7.

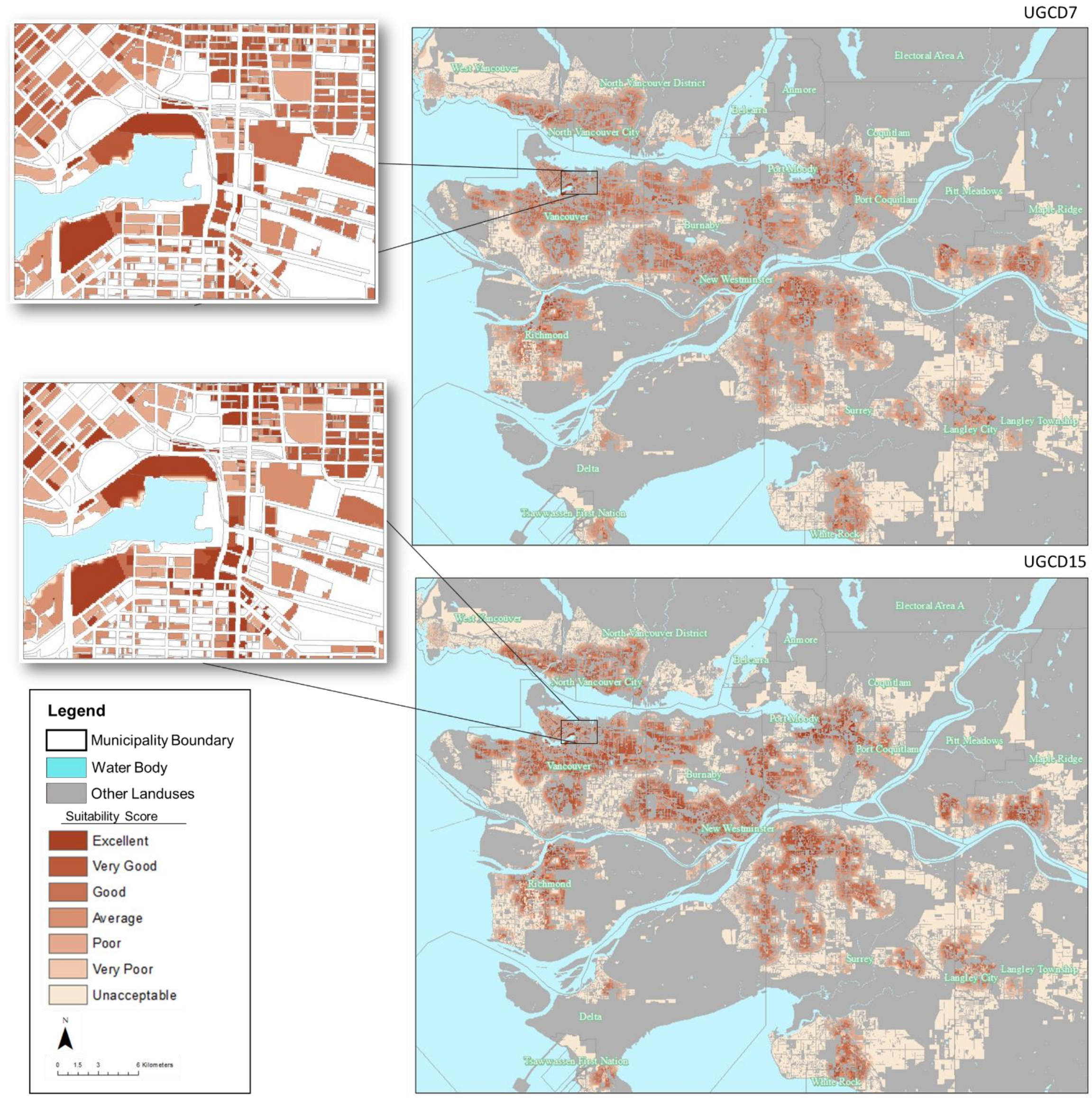


Figure 4.8. The LSP suitability maps obtained for UGCD15 and UGCD7 aggregators groups for Metro Vancouver Region and in detail for Vancouver Downtown area.

Table 4.2. The distribution of satisfaction levels for UGCD15 and UGCD7 aggregator groups.

	Relative Frequency (%)						
	Excellent	Very good	Good	Average	Poor	Very poor	Unacceptable
UGCD15	0.76	6.10	8.80	7.83	6.81	6.83	62.88
UGCD7	0.43	1.58	8.44	12.41	9.53	7.79	59.82

4.6.2. Sensitivity Analysis of UGCD15 aggregators

The sensitivity analysis is performed for UGCD15 aggregators group with two attributes ‘Major Roads’ and ‘SkyTrain Stations’, and two aggregators ‘Transportation (HC)’ and ‘Potential for Development (SC)’ at two location (Figure 4.9).

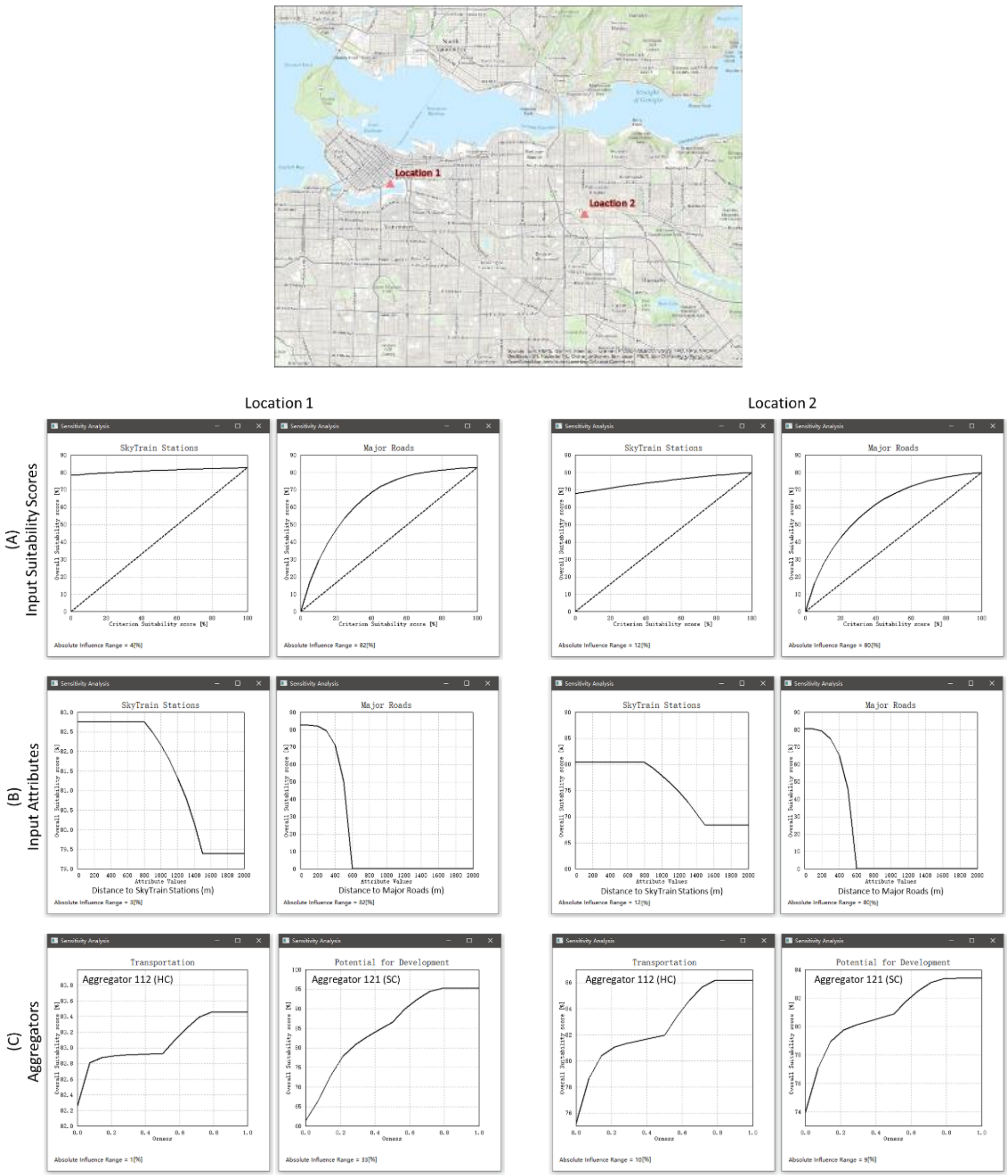


Figure 4.9. Sensitivity analysis conducted for two locations using UGCD15 aggregators group with varying (A) input suitability scores, (B) input attributes and (C) aggregators on overall suitability value for two attribute: SkyTrain Stations and Major Roads, and two aggregators: Transportation (HC) and Potential for Development (SC).

Variation of Input Suitability Values

The suitability values of criteria are changing from a list of values between 0 and 100% while remaining the rest of aggregation structure unchanged. The sensitivity curve is mapped by the list of suitability values of criteria at a certain location and the corresponding list of overall suitability value at this location. Although the increment is various, the curve is overall increasing for all the criteria.

Two observations can be draw in the sensitivity curve (Figure 4.9A). First, the 'Major Roads' is a mandatory criterion, therefore, having a large effect on both location 1 and 2. In the contrary, the 'SkyTrain Stations' is an optional criterion that aggregated by an SPD aggregator, which can be partially substituted by other criteria, and thus, not having much impact on the overall suitability value at these locations. This is also given to the fact that at these locations, there are other criteria reaching the suitability value of 100% such as 'Urban Centres' or 'Demography', and therefore, reducing the impact of 'SkyTrain Stations'. Second, the sensitivity curve will go through a zero value and presented to be a concave form. The main cause of this concave shape is the strong limiting effects from the use of conjunctive aggregator have on the suitability score of criteria (Dujmović, 2018). As the suitability score of criteria increased, its effects on the overall suitability value is in turn declining in the conjunctive aggregation structure.

Variation of Input Attributes

The suitability score of targeted criteria is changing with different input attributes, in this example, which is the distance to SkyTrain Stations (or distance to Major Roads) according to the elementary attribute criteria (Figure 4.9B). Thus, it will impact on the overall suitability value at certain location. By observing the sensitivity curve of SkyTrain Stations, the overall suitability value has a significant decline when the distance increases from 800m to 1500m. The real-world justification can be when a new SkyTrain station is built within 800m to the location, the suitability of this location for constructing new high-rise will increase. Otherwise, if the SkyTrain station is built far beyond 1500m, the overall suitability decrease.

Variation of Aggregators

The overall suitability value will be affected by changes of certain aggregator in the LSP aggregation structure (Figure 4.9C). It is increasing when the orness of aggregator increase. This can be justified by the fact that with the increasing orness, the aggregator is switching from HPC to HPD, and thus, the substitutability of attribute criteria increases, making the improvement of overall suitability value.

4.6.3. Cost/Suitability Analysis

The cost/suitability analysis is conducted in City of Surrey. The land price raster is generated by the assessment data of 163,623 properties by using kriging interpolation. Three importance levels of low cost are implemented: high, medium and low importance. In the situation of high importance of low cost, developer would sacrifice some of the highly suitable area in order to pursue the maximization of profit. This is usually happened on the small or medium size developer firm, whose resource and knowledge on available land supply is limited (Almagor et al., 2018). In contrast, the situation of low importance of low cost will happen in larger developer firm with more accumulated wealth, in which the development and economic opportunity is considered as priority.

The difference between low importance and high importance can be clearly identified by observing the region A and B in Figure 4.10. The land price in region A is relatively high while in region B is relatively low. As the importance of low cost increased, the original highly suitable area in region A are gradually become unsuitable. On the other hand, region B is transforming from unsuitable to suitable. This can also be justified by the fact that, due to the extreme high land price in original urban centre, some of the high-density development will happen in the suburban area with lower land price, characterized by a leapfrogging developing pattern (Benguigui, Czamanski, & Marinov, 2001; Heimlich & Anderson, 2001; Newburn & Berck, 2006).

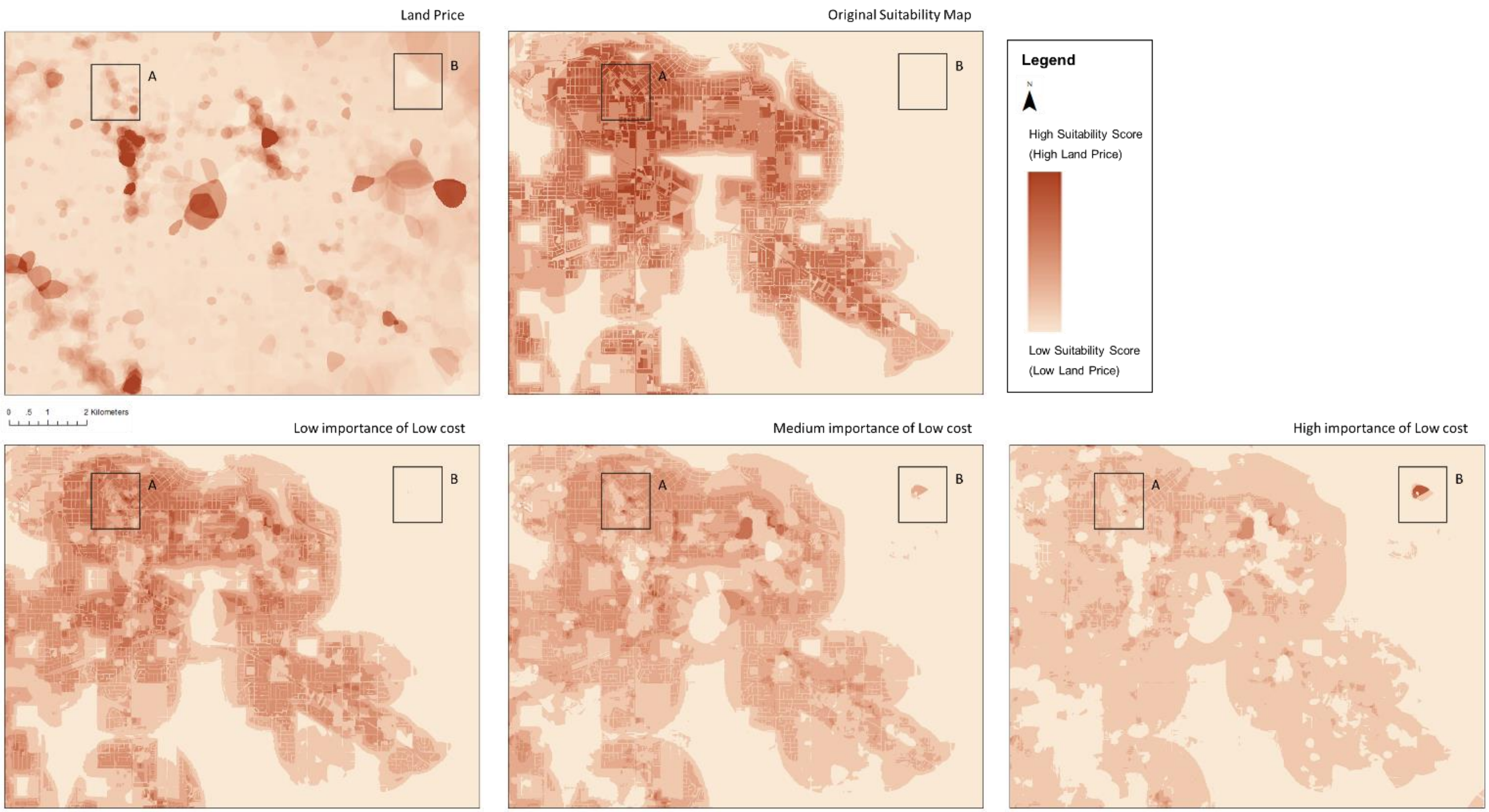


Figure 4.10. Output maps for the cost/suitability analysis for UGCD15 aggregators group for City of Surrey, Metro Vancouver Region and for two locations A and B.

4.7. Discussion

For the suitability analysis of high-density development, even with the same aggregators group and LSP aggregation structure, the suitability map will still vary for different spatial resolutions. By processing with a data at lower spatial resolution, differences between two closer location would sometime be ignored and generated an unjustifiable result. For example, a huge variation of the slope between two adjacent location will not be captured in low spatial resolution. The suitability map result will also be affected by different classification methods. For instances, if five satisfaction level are used for the suitability map instead of seven with the equal interval classification method, some of the original 'very good' area will be now identified as 'excellent' and generated a different output.

When conducting the cost/suitability analysis in two different regions, the cost/suitability maps could not be directly used for comparison. Because according to the formula in Table 1, the cost/suitability value is subject to the minimum of cost value and maximum of suitability value, which can be varied in two different regions. Therefore, the original cost/suitability output is only reflecting the relative result in this region. Therefore, a normalization of cost/suitability value need to be performed before proceeding to the comparison for different regions.

The LSP aggregation structure in this case study can be further refined in order to capture a wider range of urban developer's perspectives. Instead of defining the elementary attribute criteria and aggregation structure based on existing literatures, a survey about developer's perspectives in new building construction in Metro Vancouver Region can be carried out to make the elementary attribute criteria and LSP aggregation structure more justifiable. On the other hand, a further step of building up the online community that share GIS.LSP project file is feasible. Users can therefore have access to the reliable resources and LSP aggregation structure that created by professionals.

Except for using GIS.LSP in the area of high-density development, it can draw on other research area such as the suitability analysis of housing location or agriculture land. For the LSP method, it can even be implemented in Cellular Automata as a method for defining the transition rule, in which a neighborhood cell with higher suitability will more likely to transform into targeted land use.

4.8. Conclusions

With the implementation of LSP method in the area of high-density development, it is justified to be an effective tool for capturing the urban developer's reasoning process by integrating their goals and interests in the attributes tree and LSP aggregation structure. Beside generating the suitability map, it can not only provide more insight on the relationship between criteria by conducting the sensitivity analysis, but also combine a further cost/suitability analysis, which is useful for land suitability analysis due to land price is usually an important factor affecting the choice of developer. Therefore, it is proved to be flexible and sensitive for combining human reasoning logic into evaluation process.

The GIS.LSP tool has fully embedded the LSP method in the GIS software environment, significantly extending the capability of existing GIS-based MCE modules for suitability analysis. With its user-friendly interface and wide choice of aggregators group, the GIS.LSP can be used in different research area and is suitable for most application. The chosen file format facilitates the storing and sharing of project information and LSP aggregation structure. In addition, by employing the same raster data format with ArcGIS, user can further reprocess the output suitability map according to their needs of use in ArcMap, which provides a complete group of built-in geoprocessing and cartographic tools.

Further exploration of different aggregators groups such as GGCD9 and GGCD25 can be performed in order to investigate their effectiveness and sensitivity for land suitability analysis. The GIS.LSP tool can be further enhanced to employ the 3D files in ArcGIS in order to capture the variation of human reasoning logic in 3-dimentional space. Instead of performing the LSP method in a horizontal way that generate a single layer of suitability map, multiple layers of suitability maps can be achieved by considering the different vertical properties in the study area. In summary, the LSP and the proposed GIS.LSP tool method with spectrum of aggregators and aggregator groups can be used for spatial decision making, planning and management in various geospatial applications ranging from urban, agricultural, forestry to ecological.

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Chapter 5.

Conclusion

5.1. Overall Conclusions

High-density urban development is a complex process that involves urban developers and planners as the main actors capable to advance this process. Therefore, the main objective of this thesis was to utilize the LSP method for identifying suitable areas for high-density development in the perspectives of both urban developer and urban planner as two stakeholders. Furthermore, an ArcGIS-based module was developed to facilitate the use of LSP method in GIS environment. Two different stakeholders' perspectives and various LSP aggregators groups were used to elaborate the efficiency of LSP method in capturing the stakeholders' decision-making logic. The overall results demonstrate that GIS-based LSP method is effective in the suitability analysis of high-density development. Moreover, proposed method is flexible and can be applied to various suitability evaluation case studies and possess the ability to represent closely the human reasoning process.

The first objective of this thesis research was addressed by using the LSP method for urban land suitability analysis of high-density development in both developers and planner's perspectives. Then, the GIS-based LSP method was implemented in the ArcGIS software environment using the raster datasets in 10 meters resolution. The obtained suitability values were classified based on seven satisfaction levels ranging from high to low: excellent, very good, good, average, poor, very poor and unacceptable. Results show that LSP has the advantages of capturing the more detailed human reasoning process with the use of aggregation structure and incorporating a larger number of criteria without losing the individual significance.

Based on the perspective of urban developer, they are not only focusing more on the proximity to shopping areas, urban centers, major roads and public transportation, but also the availability of developable lands. Therefore, six regions were identified to consist of more suitable lands for high-density development, namely Downtown Vancouver, Brentwood Town Centre, Coquitlam Centre, Metrotown, Surrey Central and Richmond-Brighouse. In those regions, the suitable lands are usually located in open space and undeveloped land. Furthermore, some suitable area is also located in low-density commercial and residential land. Because following the developers' goal of maximizing their profit, they would sometimes acquire the low-density commercial land and use for the construction of new high-rise building. On the other hand, urban planners are focusing more on the preservation of the natural environment and proximity of public service facilities. Therefore, based on their perspectives, more suitable areas are located around Oakridge SkyTrain station, Metrotown, Burquitlam, Port Moody, and Coquitlam Centre. The obtained suitability values of these two perspectives aim to give directions where would be better to construct new high-rise in Metro Vancouver and assist the decision-making process of urban planning for sustainable policy makers. The difference of 23.01% between the output suitability maps of urban developer and urban planner show that they are rather having similar goals and criteria. Above all, the LSP method is justified to be effective for combining a great amount of multi-aspects criteria and integrating more detailed decision-making logic into evaluation of high-density development suitability analysis.

However, the two different stakeholders' perspectives provide different sizes of high suitable areas for constructing high-rise buildings which will not accommodate the same amount of new and incoming inhabitants in the city for next 4-5 years. For example, based on Table 2.6, the excellent suitable areas for development are only 4.23 km2 in urban developer perspective and 13.86 km2 in urban planner perspective. Therefore, the combination of two output maps is needed in order to generate an integrated overall suitability map by combining the perspectives from both stakeholders.

The second objective of this thesis was related to the analysis of combination of various output suitability values obtained for urban developer and urban planner. Three scenarios were created to represent the different collaboration pattern of urban developer and planner. Results show that the suitability map generated by alternative scenario are having more satisfied area than the concurrent scenario. Furthermore, the different weight values of developer and planner in the tradeoff scenario can represent the situation when one of the stakeholders is dominating the development process. As a result, the GIS-based LSP method is proved to be an effective method for offering more flexible integration of developer and planner's perspectives.

For the purpose of exploring how the differences between various LSP aggregators groups can impact the resulting suitability map were addressed with the third objective of this thesis. This part of the research study was designed to incorporate two different aggregators groups into the suitability analysis of high-density urban development by using the GIS.LSP module. Particularly, two aggregators groups (UGCD15 and UGCD7) were implemented using the same aggregation structure and datasets as the first part in Metro Vancouver Region. The resulting suitability maps were classified into seven satisfaction levels. A great similarity was found on the suitability maps of UGCD15 and UGCD7 aggregators groups. The reason behind this is the use of same attributes tree and weight and penalty/reward value. Furthermore, a similar granulation of andness and orness between UGCD15 and UGCD7 is also the reason that they generate the rather similar result. However, the suitability scores for different area in UGCD7 are rather similar, comparing to the more distinction of suitability scores in UGCD15. There is one possible explanation that there are less aggregators in UGCD7 than in UGCD15 to distinguish the different reasoning patterns of a stakeholder.

The sensitivity analysis was performed for the UGCD15 aggregators group and the sensitivity curves were compared for two attributes and two aggregators at two different locations. Three observations could be derived from the results. First, the variation of suitability score of a mandatory criterion would affect the result more than the optional criterion. Because if the hard requirements are not satisfied, the overall result is not satisfied, while the soft requirements are not necessary for obtaining a satisfied result; Second, in the conjunctive aggregation structure, the low suitability score of other mandatory criteria could limit the impacts of a high suitability score mandatory criterion on the overall result. This means due to the low suitability score of other mandatory criteria, even a 100% satisfied mandatory criterion could not lead to a high suitability score of the overall result. Third, when the orness of aggregator increase, the overall suitability value will also increase.

In addition, the cost/suitability analysis was implemented for the UGCD15 aggregators group by using the land price data from City of Surrey. The cost of a project is an important factor that affecting the developer's decision-making process. Three scenarios were specified to represent the developer's consideration of importance of low cost. As the result indicated, when the importance of low cost changes from low to high, the original highly suitable area with high land price are gradually changing to not suitable area.

In order to implement the GIS-based LSP methodology and respond to the last objective of this thesis, the comparisons of different stakeholders and LSP aggregator groups, the GIS.LSP tool has been developed. It is a self-developed module using Python language and ArcGIS Python add-in that can be installed in the ArcGIS software environment. In particular, the wxPython package applied in the module is aimed to create the user interfaces that can handle the interactive operations and facilitate the development of LSP aggregation structure. The project document (.lsp file) was used to store the project information and LSP aggregation structure once it is developed. On the other hand, the ArcPy package in GIS.LSP was used to achieve the spatial data analysis and management in the Python language environment. The developed tool aims to facilitate the calculation of raster data and generate the final suitability map based on LSP aggregation structure.

In summary, the obtained thesis results indicate that the LSP method tightly incorporated in the GIS environment is an effective approach, possessing flexible variations that are based on several aggregators group providing various suitability analysis options. Furthermore, by using different aggregators group and threshold andness, LSP method can be adjusted according to the need of stakeholders. It is proved to be effective and sensitive in capturing the variation of human reasoning logic. The sensitivity and cost/suitability analysis provided in the GIS.LSP can be used for further exploration after generating the suitability map.

5.2. Limitations and Future Research Work

Beside the successful implementation of the GIS-based LSP methodology following the outlined research objectives, there are still limitations that need to be addressed on future work and extend the research. First, the way how urban developer and planner's perspectives were derived from previous literature and governmental documentation could cause biases upon the selection of criteria and aggregation structure. Since the result of LSP method is sensitive and subjective to the perspective of stakeholder, the method for determining the key factors affecting the decision-making process of stakeholder can be improved. For example, a behavioral survey based on questionnaire can be used to investigate the developer's reasoning process (Nappi-Choulet, 2006; Winarso, 2002). During the survey, the background information and practices of developer can be inquired firstly. Then, the questionnaire can involve the opinion and reaction of developer about the policy of high-density development in Metro Vancouver Region. Finally, the questionnaire can focus on the motivation and determination of developer for constructing new high-rise building.

The criteria calibration and suitability maps validation were not fully incorporated in this study. Although a sensitivity analysis was implemented to explore the impact of a mandatory and an optional criterion in this study, a more complete sensitivity analysis of all the criteria and aggregators can be applied to determine their usefulness for the LSP method evaluation (Dujmović, 2018). As a result, the attributes tree, elementary attribute criteria and LSP aggregation structure can be refined. For example, to examine whether the suitability score is sensitive to the improvement of the mandatory criteria across the overall study region (Dujmovic, 2007). As for the validation of the result of this study, the 2016 land use data can be used to extract the high-rise building, and further used to compare with the high suitability area.

Furthermore, the dynamic nature of the urban development process can demand that LSP suitability analysis should be performed in spatio-temporal context. For example, the obtained suitability maps used for high-rise developments that will occur in next 4-5 years will possibly be invalid due to the changes of urban environment. The fluctuation of population growth or population distribution in the future will also affect the usefulness of output suitability maps. The aged buildings with higher deterioration level would have higher priority for redevelopment (Ma, Cooper, Daly, & Ledo, 2012). Therefore, the time factor or the attributes for future projection can be considered in the future research work by taking into account (1) more detailed future urban designation area that can be incorporated to reflect the possible changes of urban environment; (2) the projection of population growth and distribution as this can become one of the attributes in the LSP structure, and (3) the criteria reflecting building age and deterioration level can be incorporated into the evaluation process as some aged or deteriorated commercial and residential buildings can be retrofitted and regenerated into high-density areas. Moreover, the factor of future floodplain area can be incorporated. For example, the area that in lower elevation are susceptible to be affected by the raise of sea level in the future. The spatio-temporal LSP suitability analysis can be performed to address the in temporal context similar to the approach proposed by Koziatek & Dragićević (2017). In each time interval, the evaluation will be reconsidered by incorporating the new developed areas from the previous time interval. And thus, making the generation of future LSP suitability maps become possible. Moreover, the LSP method can be incorporated to guide transition rules of Cellular Automata model of urban growth to generate the future high-density locations based on current high-density area.

The GIS-based LSP method can be further explored by using additional and different aggregators groups and threshold andness values presented in Chapter 2 to determine the LSP capability of representing human reasoning logic in multiple aspects. Because the use of different aggregators groups and threshold andness is subjective to the different professional level of user and research disciplines, the GIS-based LSP method can be implemented in other land suitability analysis such as forest management (Phua & Minowa, 2005; Store & Kangas, 2001), urban planning (Abdullahi, Pradhan, & Jebur, 2015; Aburas, Abdullah, Ramli, & Asha'ari, 2017; Marinoni, 2004; Mohammed, Elhadary, & Samat, 2016) and site selection (Gorsevski, Donevska, Mitrovski, & Frizado, 2012; Nas, Cay, Iscan, & Berktay, 2010).

Finally, the fully understanding of LSP method and the GIS.LSP tool can be challenging for the user in introductory level. However, for the actual application, if the user does not need high level of precision or the adjustable threshold andness, the UGCD15 is a suitable aggregator group that has a good balance of precision and simplicity, which is suitable for most of the application.

5.3. Thesis Contributions

The research work presented in this thesis is aiming to make contributions to the area of land suitability analysis for high-density urban development and the implementation of LSP method in GIS environment. The development of attributes tree, elementary attribute criteria and LSP aggregation structure for representing the urban developer and planner's perspectives of constructing new high-rise building or high-density building form offers a basic scheme of representing their reasoning. By integrating the LSP method with GIS, this study contributes to the advancement of the decision-making methods explicitly using geospatial data. The three aggregators groups and five different threshold andness used in this study provides an insight upon the flexibility of the

LSP method to represent the suitability level of high-density development. In summary, the overall thesis research contributes in the advancement of more complex GIS-based MCE methods, the fields of GIScience and spatial decision making as well as urban planning and land use management.

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Appendix.

The GIS-based LSP method for multicriteria suitability evaluation in ArcGIS software: GIS.LSP User Manual

Introduction

The LSP method is based on soft computing that aims to provide a more accurate evaluation of human logic reasoning and assist in the decision-making process (Dujmović, 2018). It was firstly introduced in 1970s for the purpose of computer system evaluation (Dujmovic, 2007; Dujmović, 1975, 1996). Then, it was utilized with GIS to facilitate spatial decision making by calculating land use suitability and developing the suitability map (Dujmović & Scheer, 2010; Dujmović & Tré, 2011; Dujmović, Tré, & Weghe, 2008). The conjunction and disjunction aggregators used in the LSP method make it capable of capturing continuous human logic and integrating a larger number of input criteria.

GIS.LSP has been developed following the implementation of LSP.NT (Dujmović, 2018) to make the use of the LSP method in ArcGIS software possible. The GIS.LSP tool is installed by a Python add-in and it is presented as an ArcMap toolbar once the add-in is installed. It is programmed in Python mainly using the ArcPy and wxPython site packages (ESRI, 2019; wxPython, 2017). It aims to facilitate the use of LSP method in ArcGIS 10.4, 10.5 and 10.6 environments. It has integrated the creation, development and documentation of attributes tree, elementary attribute criteria, LSP aggregation structure, score calculation and suitability map generation, component analysis, sensitivity analysis, cost/suitability analysis and suitability map statistics into one single module. The module is user-friendly and easy to use and understand, therefore increasing the accessibility and usability of the LSP method in GIS-based software environment.

The mathematical functionality and soft computing logic are described in Dujmovic (1975, 1996, 2007 and 2018) and referred to in the Thesis Chapters 2, 3 and 4. GIS.LSP provides three Uniform Graded Conjunction/Disjunction (UGCD) aggregators groups, three General Graded Conjunction/Disjunction (GGCD) aggregators groups and a Weighted Power Mean (WPM) aggregators group. Details of seven aggregators groups

(UGCD.7, UGCD.15, UGCD.23, GGCD.9, GGCD.17, GGCD.25, and WPM.17) are shown as follows:

Low precision uniform UGCD aggregators (UGCD.7)

Hard Disjuction: D HPD (sufficient)

Soft Disjuction: SPD (optional)

Neutrality: A (optional)

Soft Conjuction: SPC (optional)

Hard Conjuction: HPC C (mandatory)

Medium precision uniform UGCD aggregators (UGCD.15)

Hard Disjuction: D HD+ HD HD- (sufficient)

Soft Disjuction: SD+ SD SD- (optional)

Neutrality: A (optional)

Soft Conjuction: SC- SC SC+ (optional)

Hard Conjuction: HC- HC HC+ C (mandatory)

High precision uniform UGCD aggregators (UGCD.23)

Hard Disjuction: D ++HD +HD *HD -HD --HD (sufficient)

Soft Disjuction: ++SD +SD *SD -SD --SD (optional)

Neutrality: A (optional)

Soft Conjuction: --SC -SC *SC +SC ++SC (optional)

Hard Conjuction: --HC -HC *HC +HC ++HC C (mandatory)

Low precision non-uniform GGCD aggregators (GGCD.9)

Hard Disjuction: D D+ (sufficient)

Soft Disjuction: DA D- (optional)

Neutrality: A (optional)

Soft Conjuction: C- CA (optional)

Hard Conjuction: C+ C (mandatory)

Medium precision non-uniform GGCD aggregators (GGCD.17)

Hard Disjuction: D D++ D+ D+- DA (sufficient)

Soft Disjuction: D-+ D- D-- (optional)

Neutrality: A (optional)

Soft Conjuction: C-- C- C-+ (optional)

Hard Conjuction: CA C+- C+ C++ C (mandatory)

High precision non-uniform GGCD aggregators (GGCD.25)

Hard Disjuction: D DS++ DS+ DS DS- DS-- DA (sufficient)

Soft Disjuction: DW++ DW+ DW DW- DW-- (optional)

Neutrality: A (optional)

Soft Conjuction: CW-- CW- CW CW+ CW++ (optional)

Hard Conjuction: CA CS-- CS- CS CS+ CS++ C (mandatory)

Medium precision weighted power mean aggregators (WPM.17)

Hard Disjuction: D (sufficient)

Soft Disjuction: D++ D+ D+- DA D-+ D- D-- (optional)

Neutrality: A (optional)

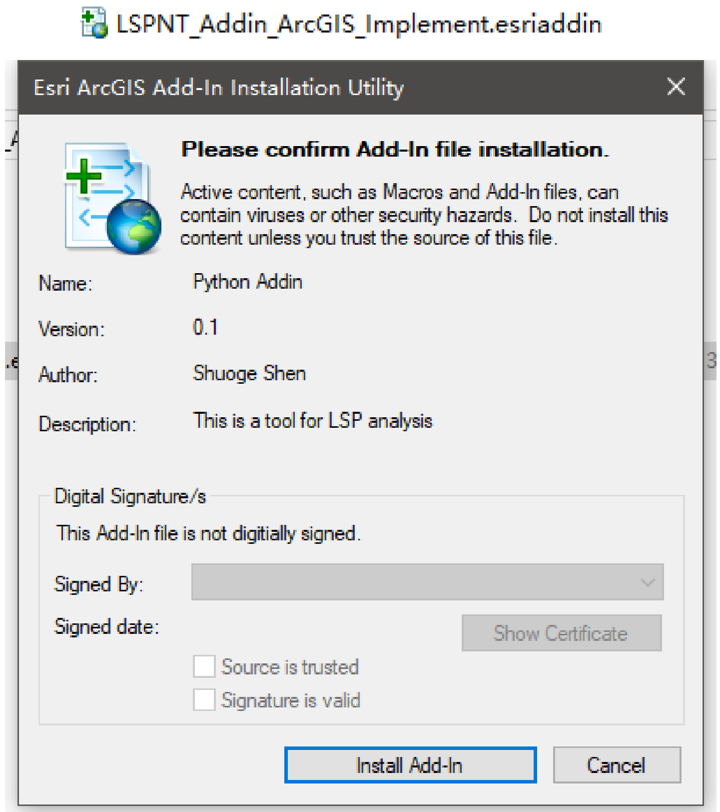
Soft Conjuction: C-- C- (optional)

Hard Conjuction: C-+ CA C+- C+ C++ C (mandatory)

Different levels of precision in determining overall suitability are represented by the number of aggregators in the group. The more aggregators a group has, the more different patterns of decision-making logic the GIS-based LSP method can capture. The low precision uniform aggregators group (UGCD.7) is suitable for beginners with no previous knowledge of LSP method and aggregation logic. The medium precision uniform aggregators group (UGCD.15) is suitable for general application of LSP method as it is simple to use while offering a sufficient number of aggregators. The high precision uniform aggregators group (UGCD.23) is suitable for more complex applications that require a higher discrimination of input criteria. Unlike uniform aggregators groups (UGCD) that use a fixed threshold andness, non-uniform aggregator groups (GGCD) apply the adjustable threshold andness which is more flexible for most applications but requires a higher level of knowledge for connecting logic aggregators to real world implementation. The WPM.17 uses a weighed power mean for calculation of score that is suitable for applications without need of hard partial disjunction aggregators.

Installing and accessing the GIS.LSP tool

The first step is to install the GIS.LSP tool into the ArcGIS environment. Currently, GIS.LSP can support ArcGIS 10.4, ArcGIS 10.5 and ArcGIS 10.6. The GIS.LSP tool is an ESRI add-in file that can be automatically installed in ArcGIS software by double clicking on the file:

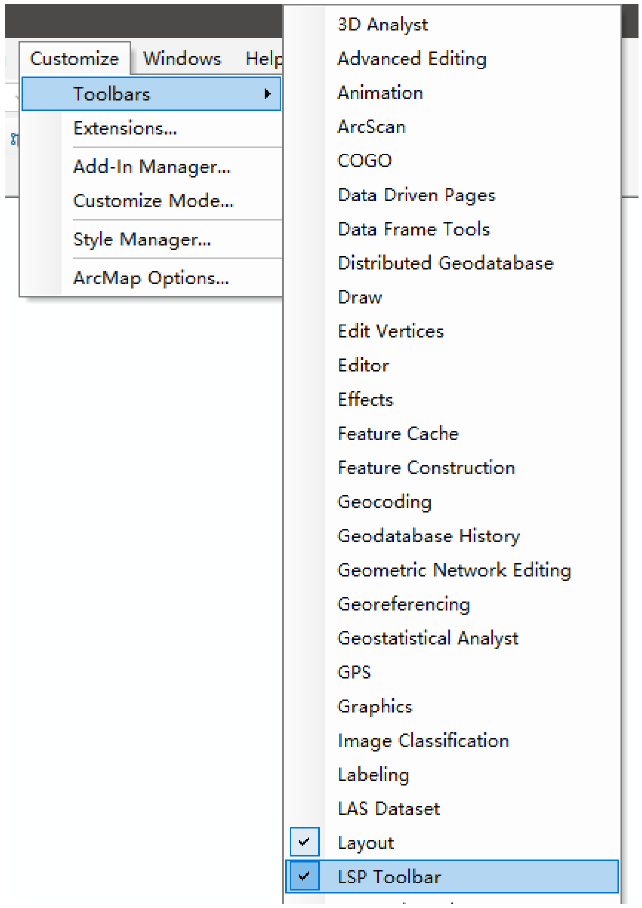


Click on **Install Add-In** in order to install the GIS.LSP.

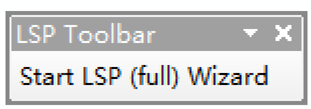
In order to successfully use GIS.LSP in the ArcGIS environment, the wxPython package also needs to be installed. The installation instructions for wxPython can be found at: https://wxpython.org/pages/downloads/.

The wxPython package should appear in the folder under the ArcGIS Python path:

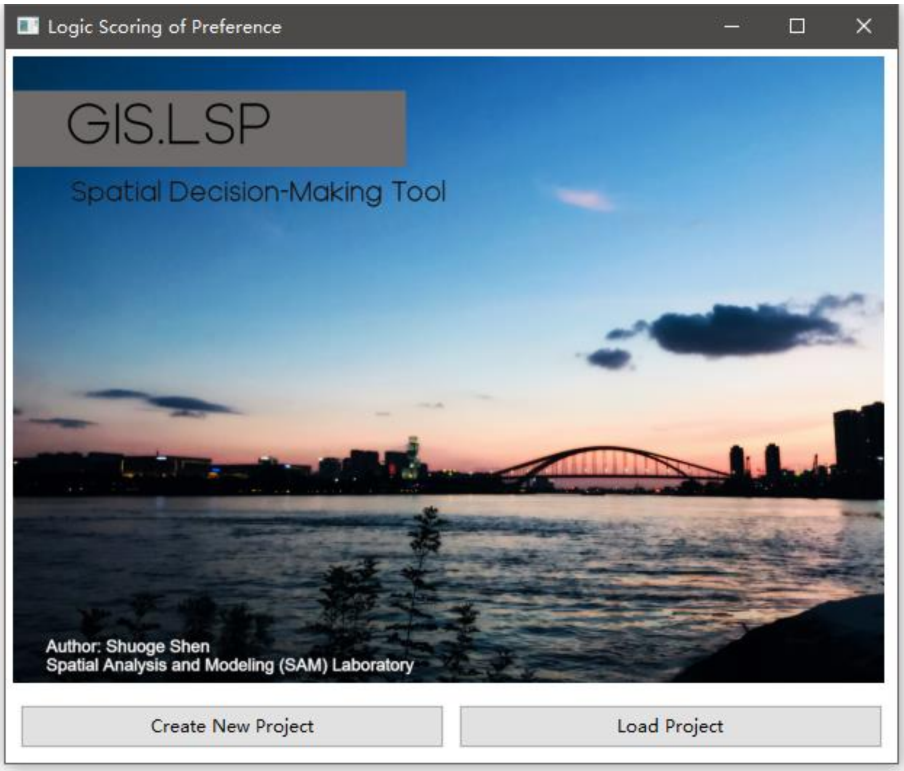
After finishing the installation of the GIS.LSP addin and wxPython package, the GIS.LSP tool will appear as an ArcMap toolbar:



After clicking on the **LSP Toolbar**, the GIS.LSP tool will show up:

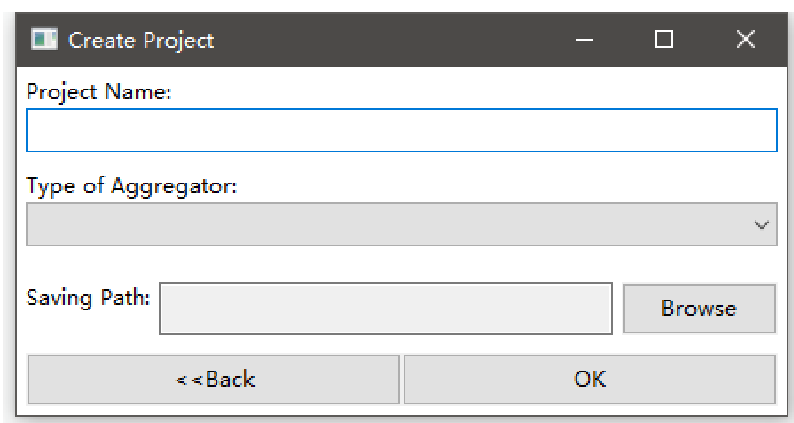


Simply click on **Start LSP Wizard**, and the GIS.LSP interface will appear:



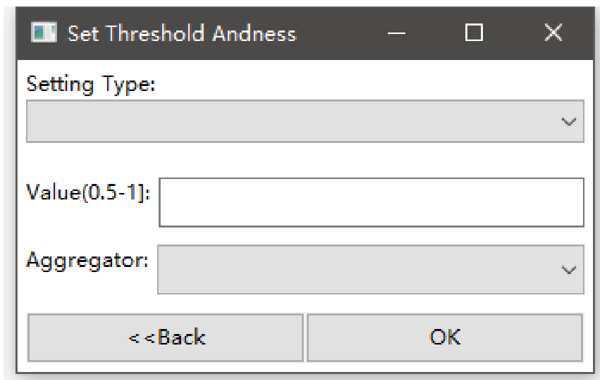
Creating or Loading an LSP suitability evaluation project

After gaining access to the GIS.LSP tool in ArcMap, a suitability evaluation project can be created or loaded. An evaluation project contains the project information and created LSP aggregation structure. If it is the first time using GIS.LSP module, it can be started by creating a project. The Project Name, Type of Aggregator and Saving Path should be specified when creating the project:



An aggregator group can be selected from a list of available aggregators groups: UGCD.7, UGCD.15, UGCD.23, GGCD.9, GGCD.17, GGCD.25, or WPM.17. Click on the **Browse** button to specify a saving path and a file name for the project file. After creating a project, a *.lsp* file can be found under the selected path:

If a GGCD aggregator group is selected for the evaluation project, a window will appear asking to specify the threshold andness of the project:

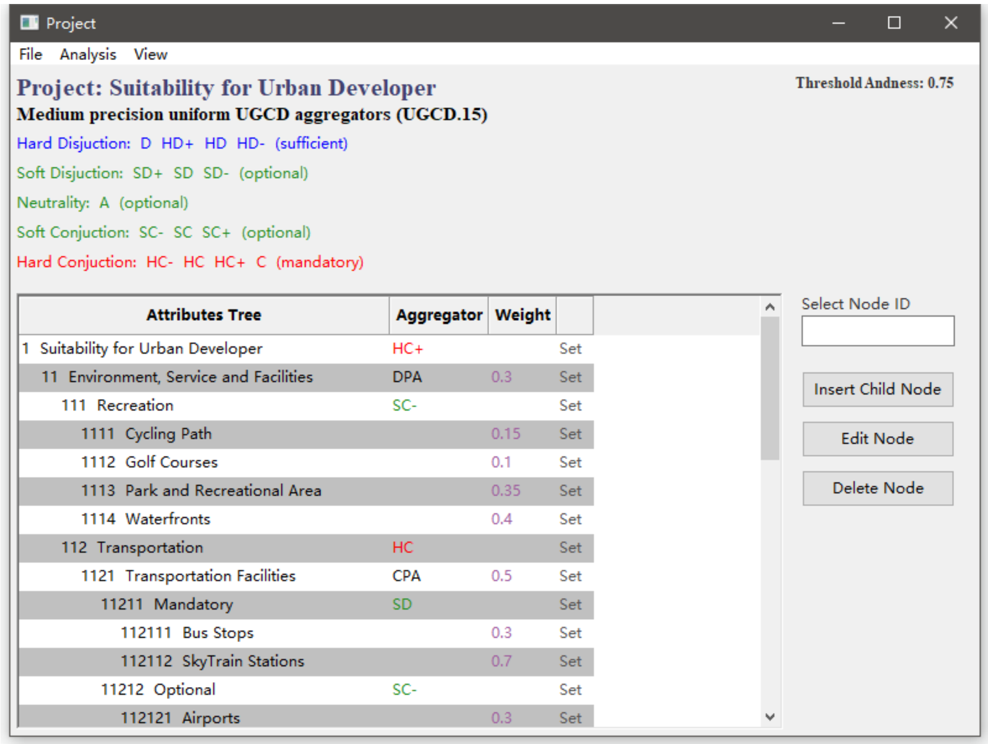


At this stage, the threshold andness value can be set by using a specified value or aggregator. The grouping of aggregators as Hard Disjunction (HD), Soft Disjunction (SD), Neutrality (A), Soft Conjunction (SC), or Hard Conjunction (HC) will be different according to the set threshold andness.

The evaluation project will be AUTOMATICALLY SAVED in this file every time we modify the project information or LSP aggregation structure, so there is no need to constantly save the file.

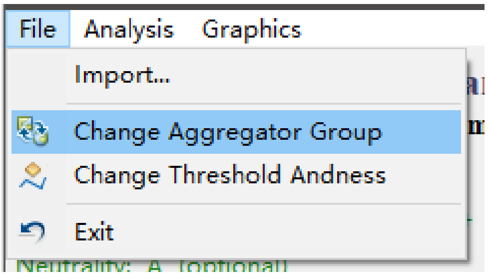
After the *.lsp* file is generated, this file can be loaded to restore this project by clicking on the **Load Project** button at the start interface.

The main interface of GIS.LSP will show up once creating the project or loading the project is finished:

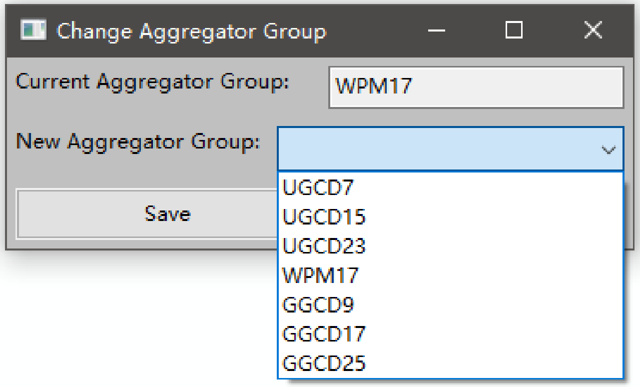


Changing aggregator group and threshold andness

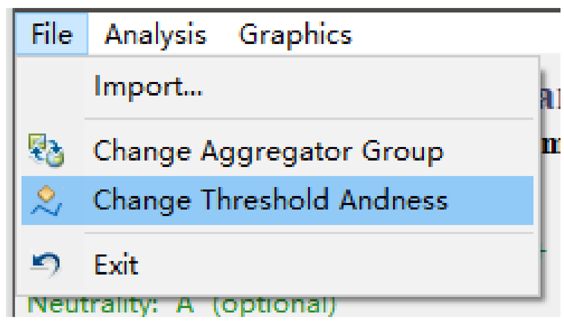
Using the main interface of GIS.LSP, the current aggregator group can be changed for a project by going to **File – Change Aggregator Group**:



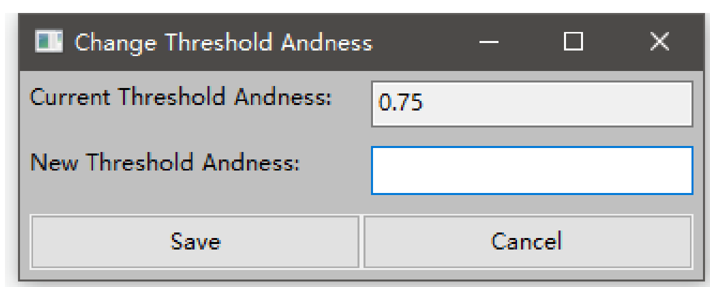
In the **Change Aggregator Group** window, the destination aggregator group can be selected:



If a GGCD aggregator group is used, the threshold andness can be changed by going to **File – Change Threshold Andness**:



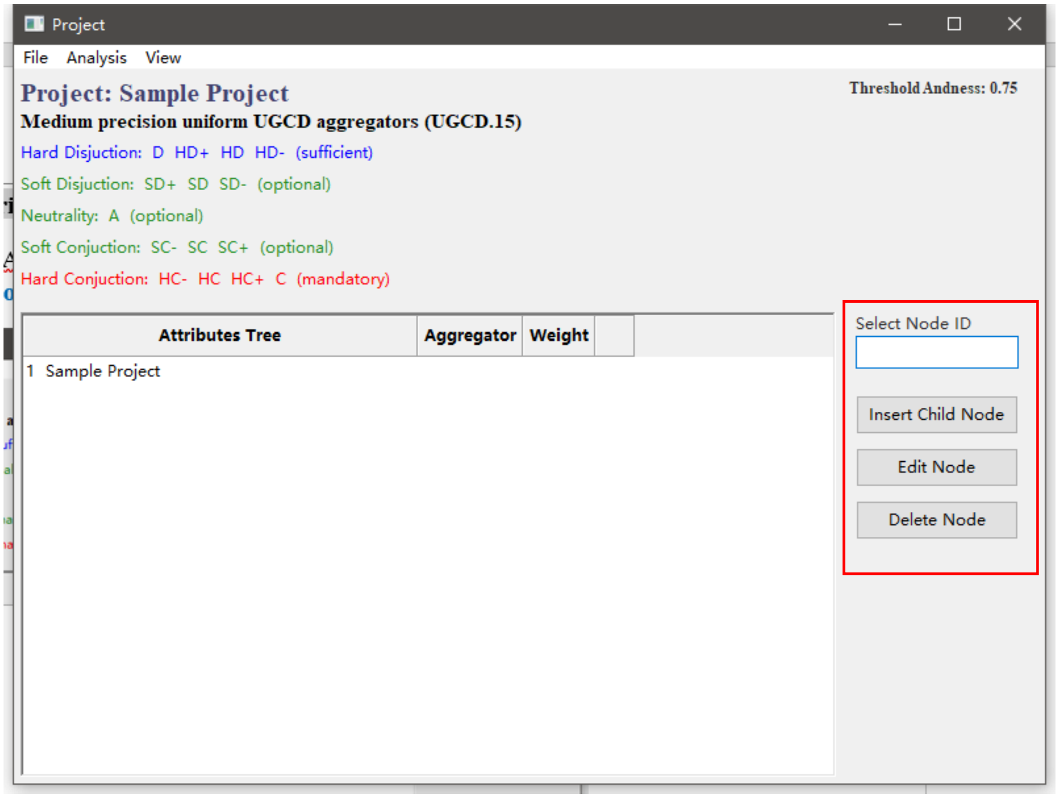
In the **Change Threshold Andness** window, a threshold andness value can be specified in the range of (0.5, 1):



Remember that the threshold andness of the UGCD aggregators groups and WPM.17 aggregators group are unchangeable since UGCD uses a fixed threshold andness of 0.75 and WPM.17 uses a fixed threshold andness of 0.67.

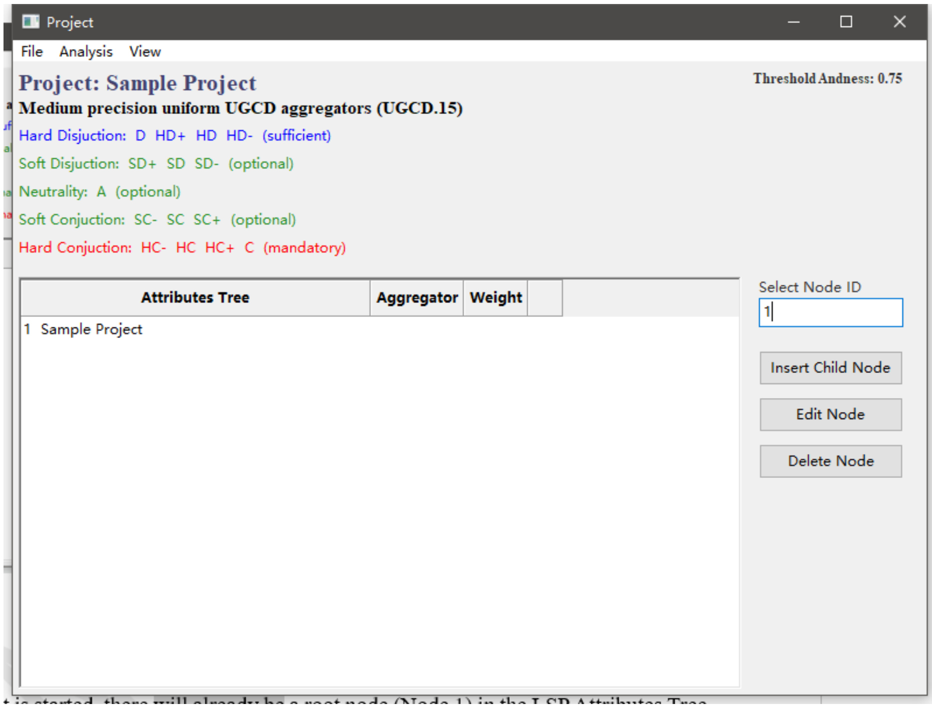
Editing the LSP Attributes Tree

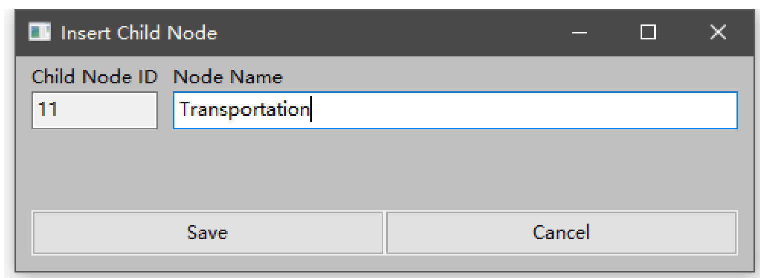
In the main interface of GIS.LSP, the LSP aggregation structure can be created and edited by using three buttons: **Insert Child Node**, **Edit Node** and **Delete Node**.



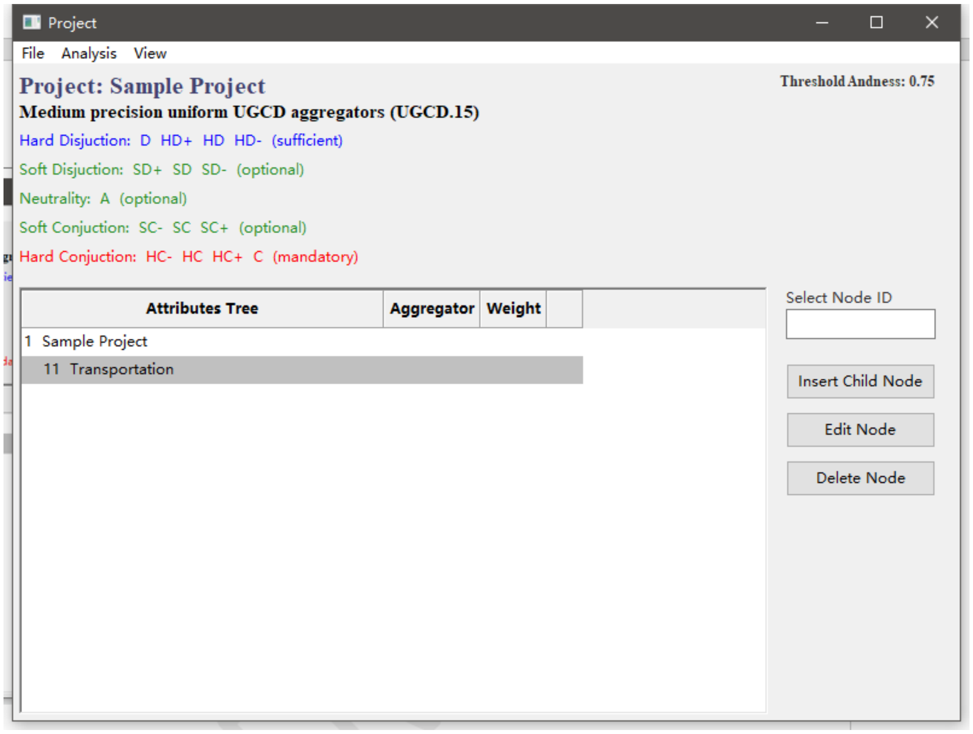
<u>Insert Child Node</u>

Every time a new project is started, there will already be a root node (Node 1) in the LSP Attributes Tree. In order to insert a new child node to an existing node, an existing node ID can be typed in the **Select Node ID** box. Then, click on **Insert Child Node**:





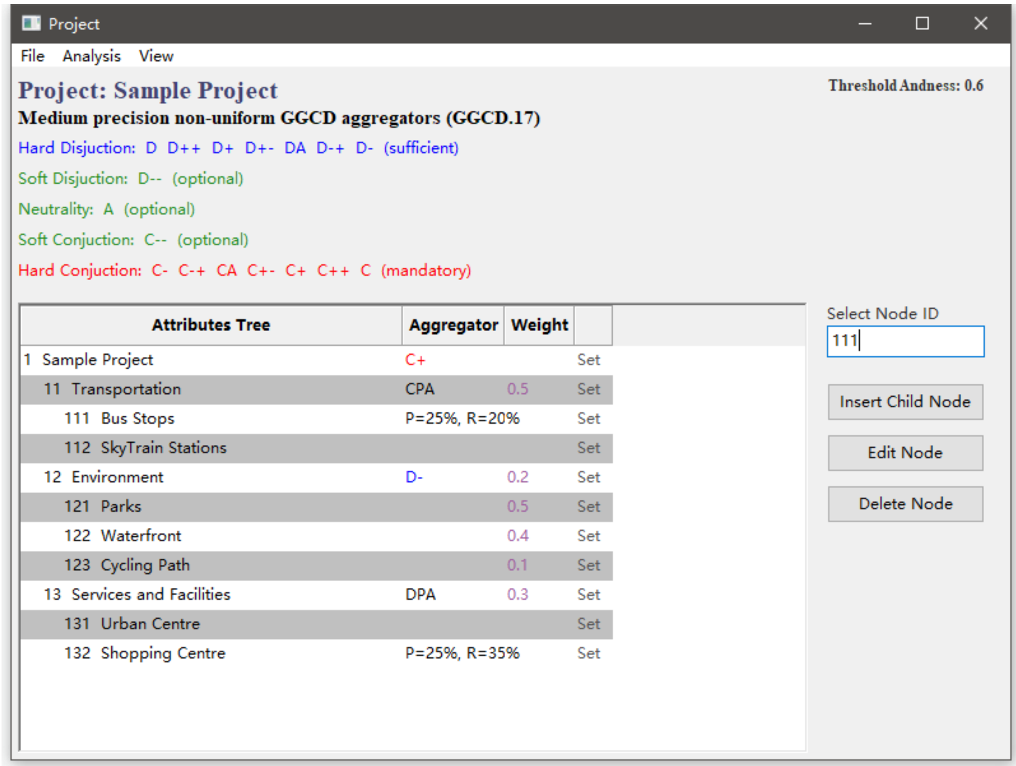
Specify a node name for this child node and click on **Save** to finish inserting. Then, a new child node will appear in the LSP attributes tree of the main interface:



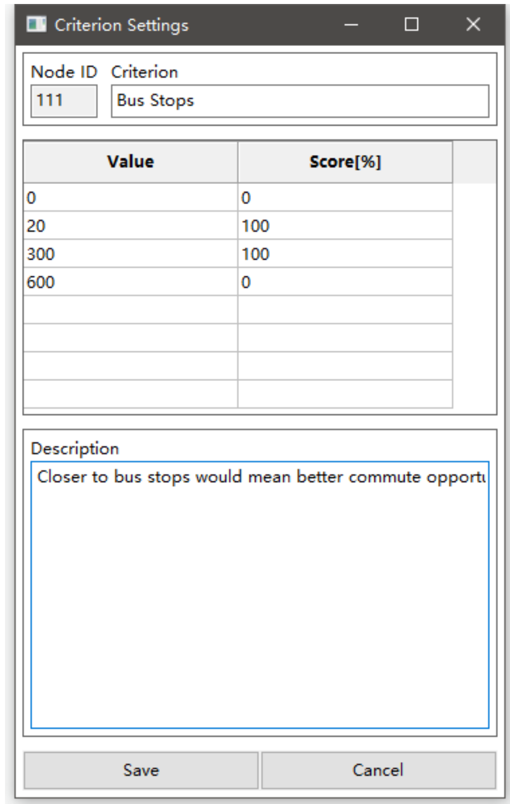
It is possible to continue inserting child nodes until the entire LSP Attributes Tree is completed.

Edit Node

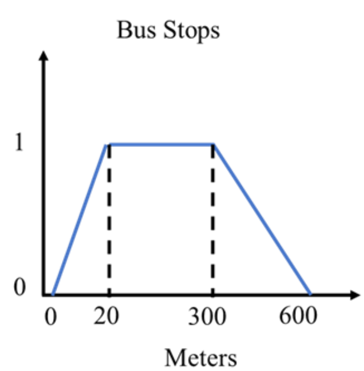
A node can be edited by typing the node ID into **Select Node ID** and clicking on **Edit Node**:



A node can be an input criterion or an aggregator. For example, in the above LSP Attributes Tree, the node 111 (Bus Stops) is an input criterion while the node 11 (Transportation) is an aggregator. For editing an input criterion node, a window will show up requiring the input of break values and corresponding suitability scores:

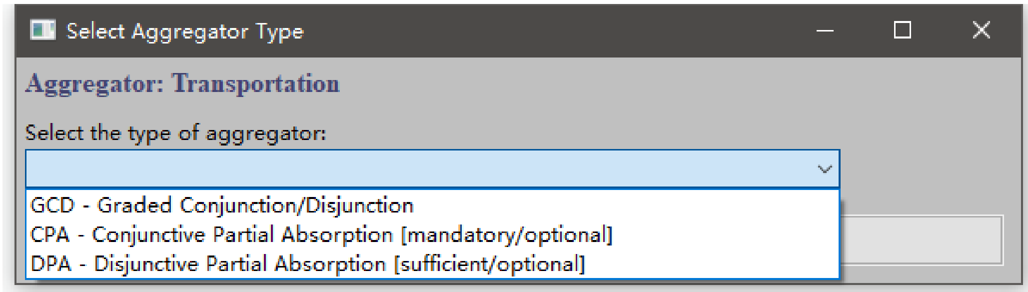


Note that the break values should be increasing. The break values and suitability scores in **the Criterion Settings** can be represented by a suitability function. For the example presented, the corresponding suitability function for *proximity to Bus Stops* is as follows:

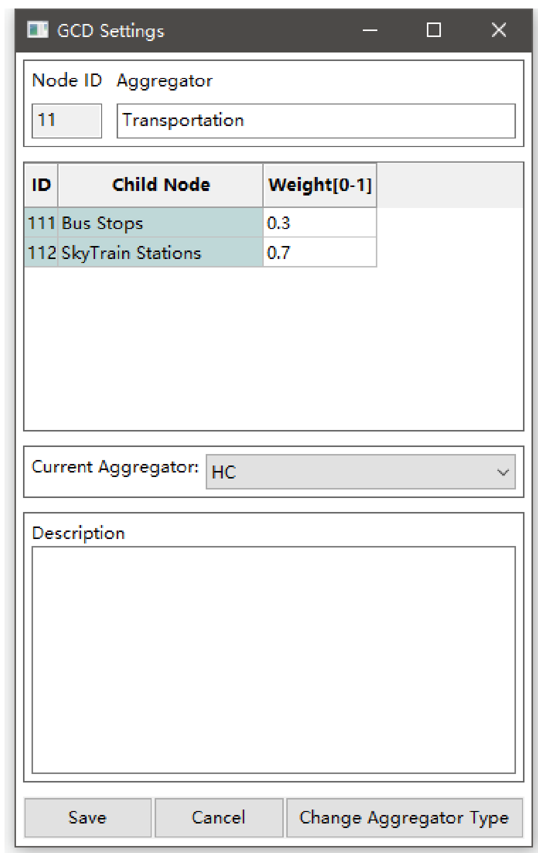


For editing an aggregator node, a window will show up requiring us to select from **Graded Conjunction/Disjunction (GCD), Conjunctive Partial Absorption (CPA)** or

Disjunctive Partial Absorption (DPA) if this node has only two children nodes. For nodes with 3 or more children, the CPA and DPA aggregators will not appear, and will go directly to the GCD settings.



In GCD Settings, the weight values need to be specified for its children nodes and the aggregator to be used must be chosen:

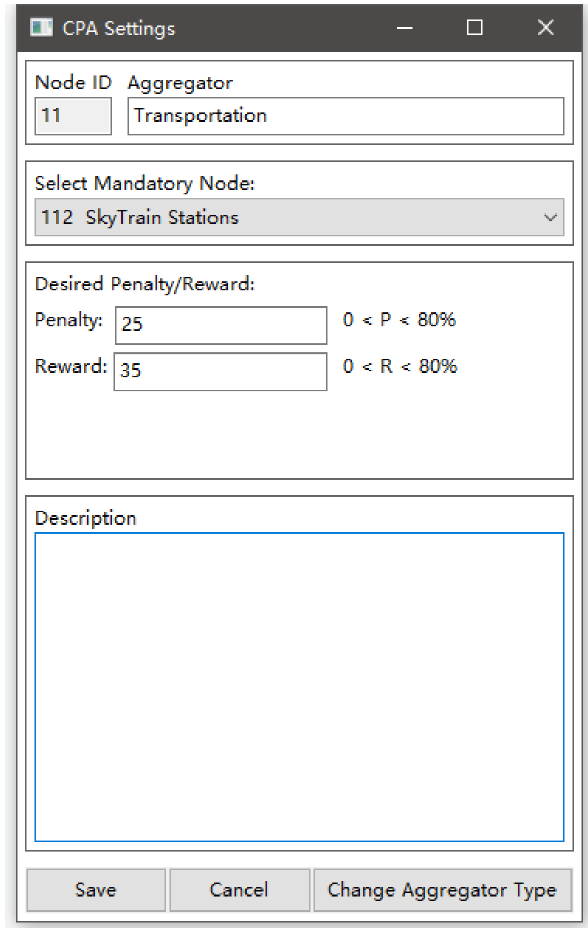


Then click on the **Save** button to confirm and return to the main interface:

Attributes Tree	Aggregator	Weight	
1 Sample Project			
11 Transportation	HC		Set
111 Bus Stops		0.3	Set
112 SkyTrain Stations		0.7	
12 Environment			
121 Parks			
122 Waterfront			
123 Cycling Path			
13 Services and Facilities			
131 Urban Centre			
132 Shopping Centre			

The selected aggregator and the weight values will be visible in the LSP Attributes Tree.

In CPA Settings, the mandatory node and the corresponding penalty and reward values for the optional node need to be specified:



Then click on the **Save** button to confirm and return to the main interface. The CPA aggregator and penalty/reward values will be shown in the LSP Attributes Tree:

Attributes Tree	Aggregator	Weight	
1 Sample Project			
11 Transportation	CPA		Set
111 Bus Stops	P=25%, R=20%		Set
112 SkyTrain Stations			
12 Environment			
121 Parks			
122 Waterfront			
123 Cycling Path			
13 Services and Facilities			
131 Urban Centre			
132 Shopping Centre			

The settings of DPA are similar to that of CPA.

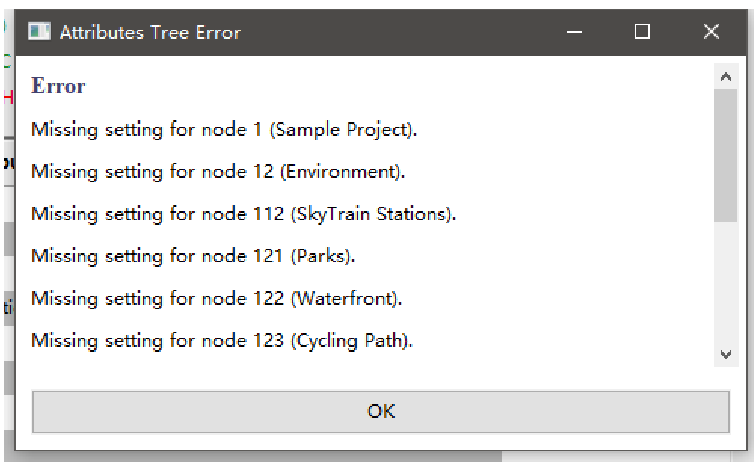
Note that the aggregator type can always be changed among GCD, CPA and DPA by using the **Change Aggregator Type** button if this aggregator only has two children nodes. If a node has more than two children nodes, it can only be set as GCD.

Delete Node

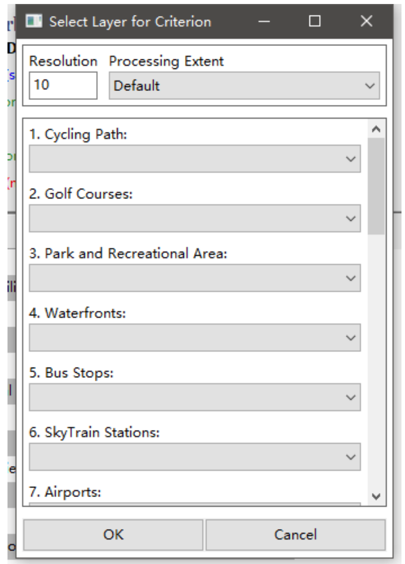
A node can be deleted by typing its node ID into **Select Node ID** and clicking on **Delete Node**. The node and all its children nodes will be deleted.

Calculating LSP suitability values and creating LSP suitability maps

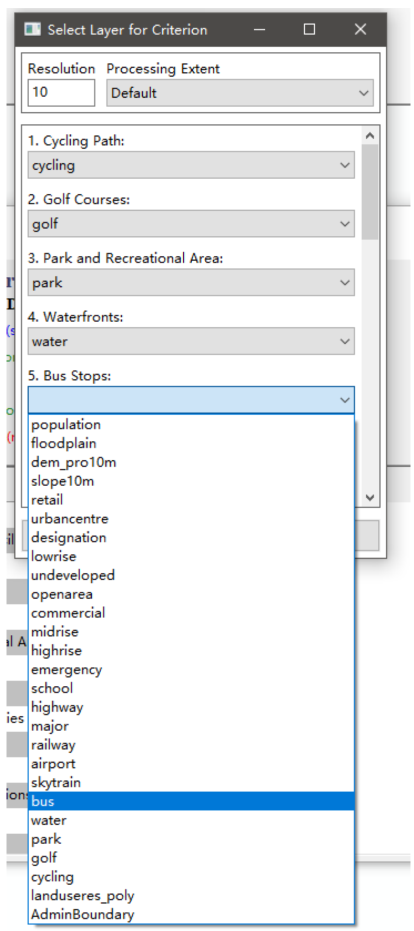
After creating the LSP Attributes Tree and setting up all the nodes, the LSP suitability map containing LSP suitability scores in each raster can be calculated by clicking on **Analysis – Start Analysis**. If there are errors in the LSP Attributes Tree, an Error window will show up:



If there is no Error, the **Select Layer for Criterion** window will show up:

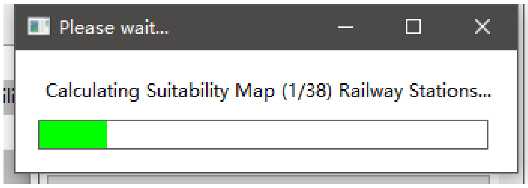


Then, the Resolution, Processing Extent and corresponding GIS raster layer need to be set for each criterion:

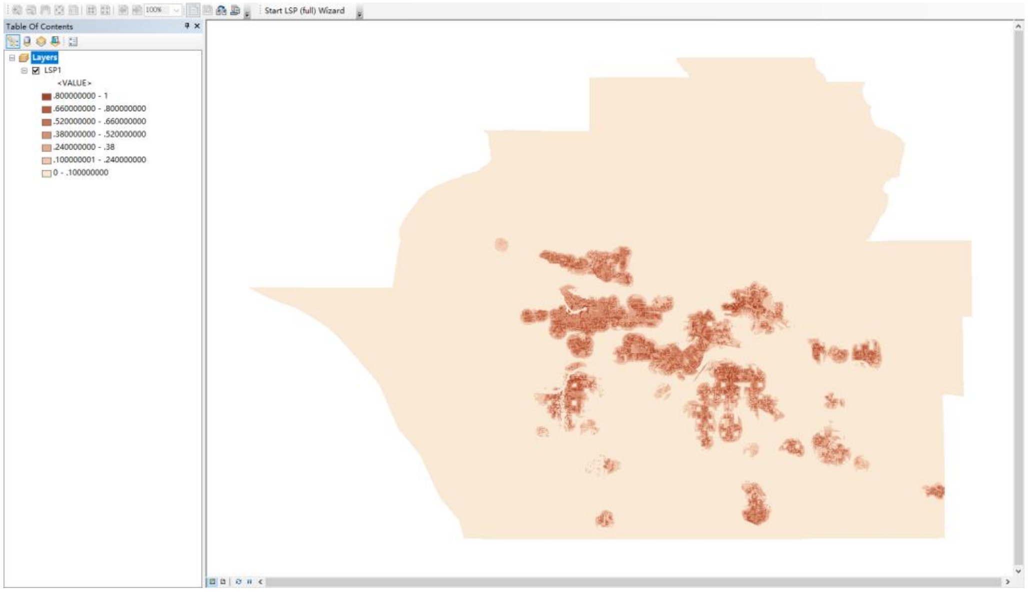


Note that a raster layer can only be selected if it is based on the raster GIS layer that appears in the **Table of Contents** in ArcMap. Ensure that you have all the layers in raster GIS data format necessary for the analysis in the TOC before going to the next step.

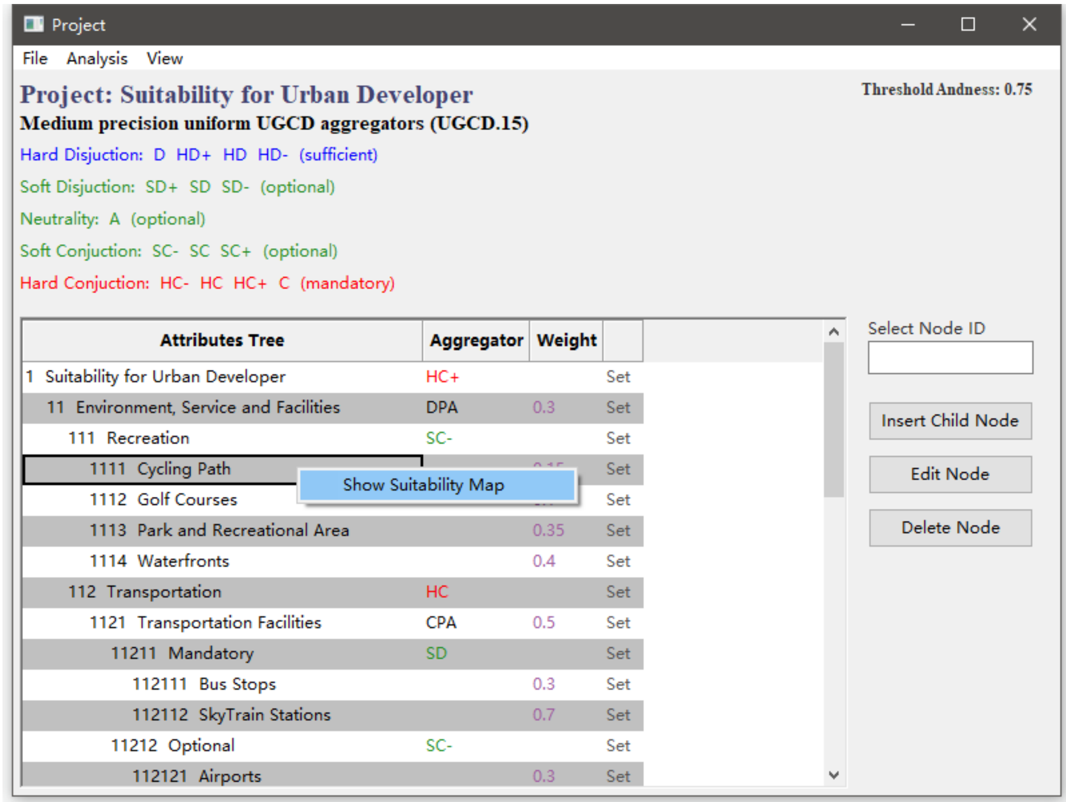
After setting up the raster GIS layers for all the criteria, click on **OK** so that the analysis process will start. A processing bar will show up:



Once the analysis process is completed, the output LSP suitability map will automatically show up in ArcMap as LSP1 layer:



The LSP suitability map can also be viewed for any criterion or aggregator by going to the LSP Attributes Tree and by right clicking on it, then clicking **Show Suitability Map**:



Exporting and Importing LSP suitability maps

After finishing the generation of LSP suitability maps, remember to go to **Analysis – Export Suitability Maps**. Specify an empty folder for saving the LSP suitability maps. In this way, the LSP suitability maps will be saved as ESRI GRID files, which can be imported directly when the LSP suitability maps are to be viewed or analysed without going back to recalculate them.

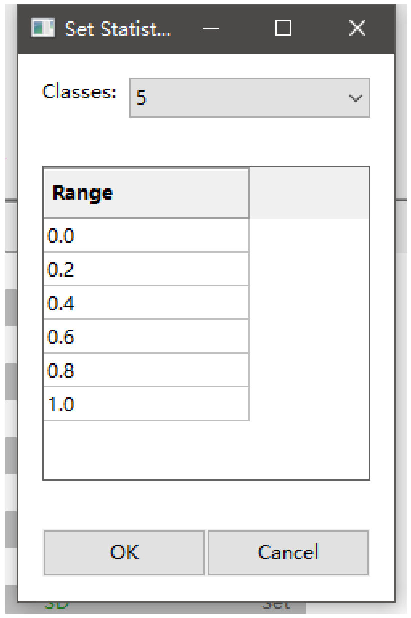
Therefore, if the suitability maps have already been exported to an empty folder, when the project file is loaded the next time and the suitability maps will be viewed or analysed, they can be imported by clicking on **File – Import**.

Analysing the output LSP suitability map

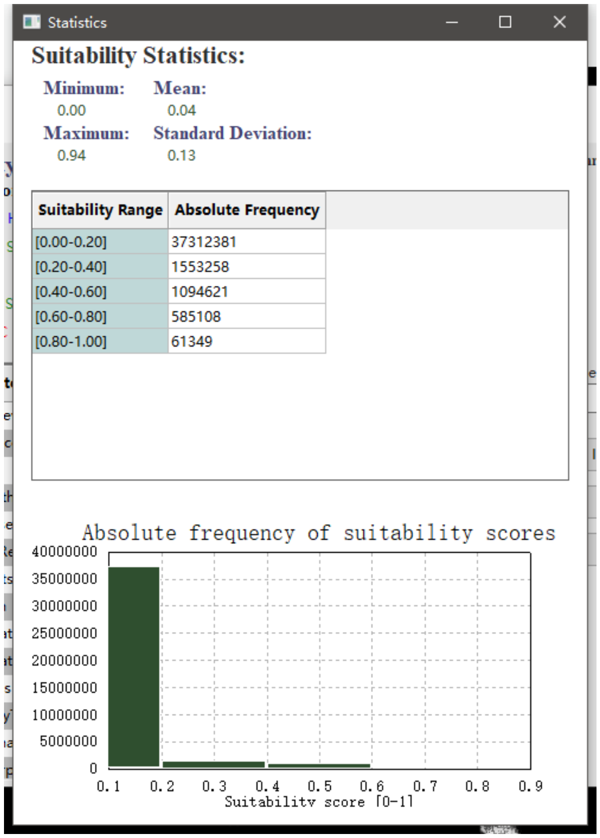
Whenever finishing the calculation of LSP suitability maps or importing LSP suitability maps, the LSP suitability scores presented on the map can be further analysed to gain more information for the decision-making process. The LSP suitability map can be analysed through **Analysis – Statistics**, **Components Analysis**, **Sensitivity Analysis**, and **Cost/Suitability Analysis**.

Statistics

Statistics of a suitability map can be calculated through **Analysis – Statistics**:

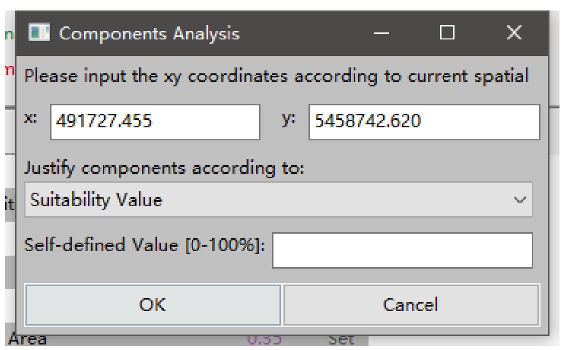


The number of classes and range values need to be specified in order to calculate the minimum, maximum, mean, standard deviation and distribution of absolute frequency of the LSP suitability map:

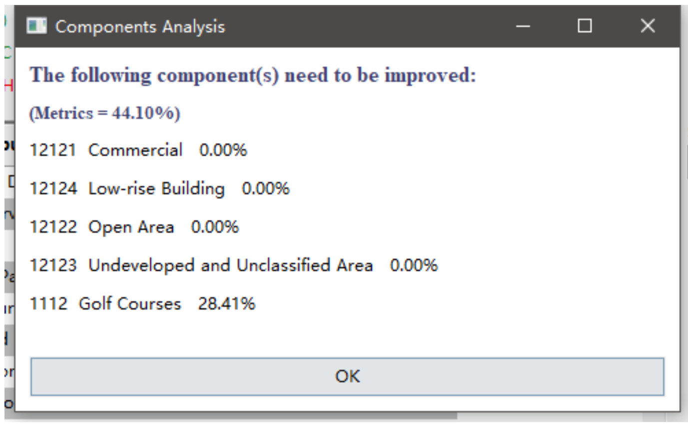


Components Analysis by Location

The components analysis by location can represent the insufficiency for criteria scores of a certain location by indicating which criteria needed to be improved in order to enhance the overall suitability for a particular location. Click on **Analysis – Components Analysis – By Location** to access this function:

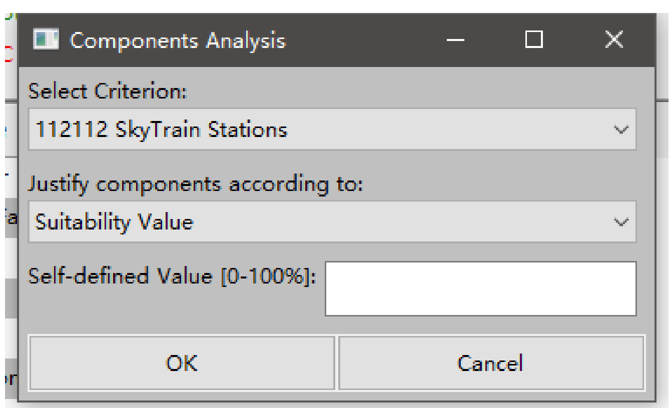


The coordinates *x* and *y* should be an input to pinpoint the location to be examined. The components can be justified according to Suitability Value or Self-defined Value. If the Suitability Value is chosen, then the overall LSP suitability score value at this particular location (*x,y*) will be used to compare with the LSP suitability value that is computed for each criterion. On the other hand, the selection of Self-defined Value will use the value to compare with the LSP suitability values of each criterion. The result window will show which criteria are below the chosen value at this particular location:

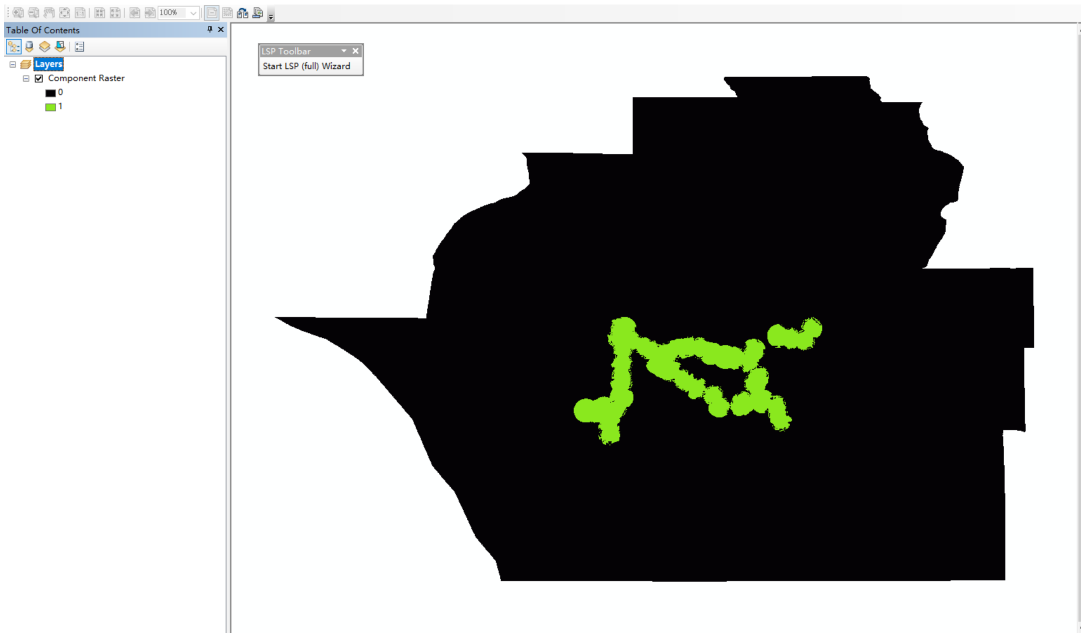


<u>Components Analysis by Criterion</u>

The components analysis by criterion is similar to components analysis by location, except that it is indicating which locations do not have satisfactory suitability scores based on the chosen criterion. Click on **Analysis – Components Analysis – By Criterion** to access this function:



A certain criterion needs to be specified to justify the components according to Suitability Value or Self-defined Value. In this example, the SkyTrain Stations criterion has been chosen for analysis, and the result will show which locations have suitability scores below the specified value:

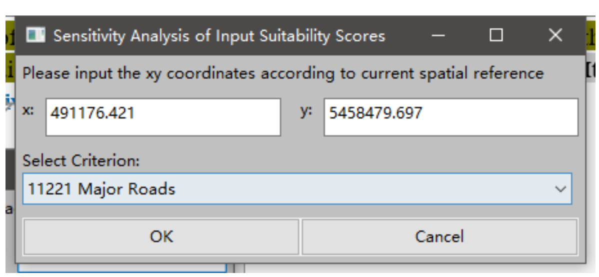


The component raster with value 0 indicates that the area needs to improve, while a value of 1 represents the satisfied areas.

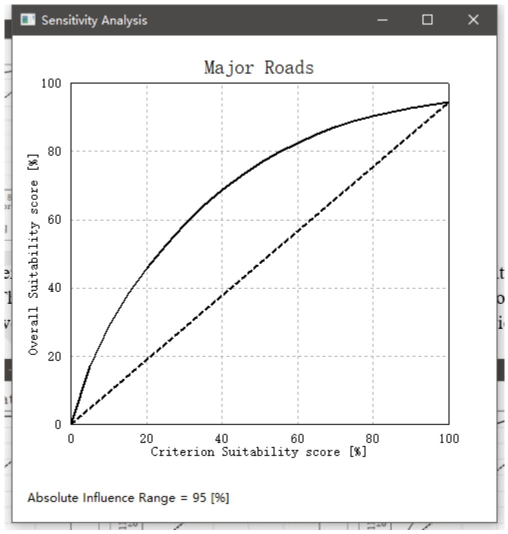
<u>Sensitivity Analysis</u>

Sensitivity Analysis of Input Suitability Scores

The sensitivity analysis of input suitability scores can provide insights on how the change of the suitability value of a certain criterion will affect the overall LSP suitability values. It can be accessed through **Analysis – Sensitivity Analysis – Input Suitability Scores**:



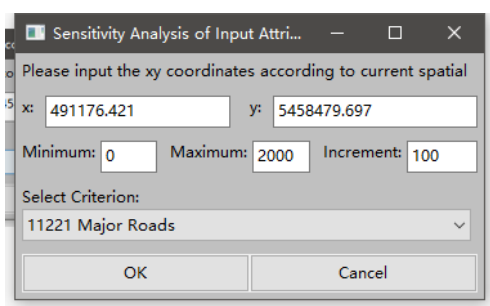
The coordinates *x* and *y* have to be input to specify a certain location. The criterion for examination should also be selected. In this example, the Major Roads criterion has been chosen. The result will show how the change of suitability value for Major Roads will affect the overall suitability value at this location:



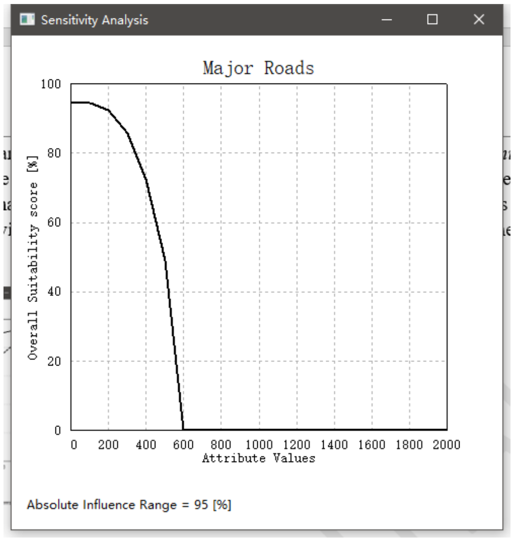
The absolute influence range will indicate the maximum influence range of this criterion on the overall suitability result. The result is affected by the mandatory, optional, or sufficient property of a criterion, its corresponding weight value and also the selected location. Different criteria can yield different results.

Sensitivity Analysis of Input Attributes

The sensitivity analysis of input attributes can provide insights on how the change of the input attributes (e.g. distance to facility) will affect the overall LSP suitability values. It can be accessed through **Analysis – Sensitivity Analysis – Input Attributes**:

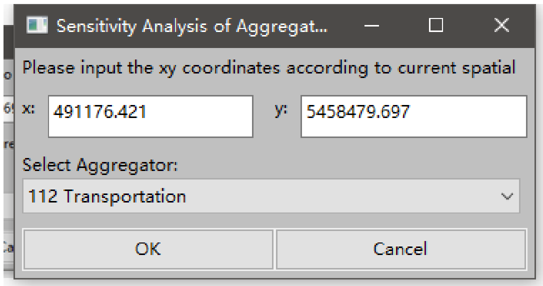


The coordinates *x* and *y* have to be input to specify a certain location. The *minimum*, *maximum* and *increment* have to be input in order to generate a list of input attributes that will be used for analysis. The criterion for examination should also be selected. In this example, the Major Roads criterion has been chosen. The result will show how the change of distance to Major Roads will affect the overall suitability value:

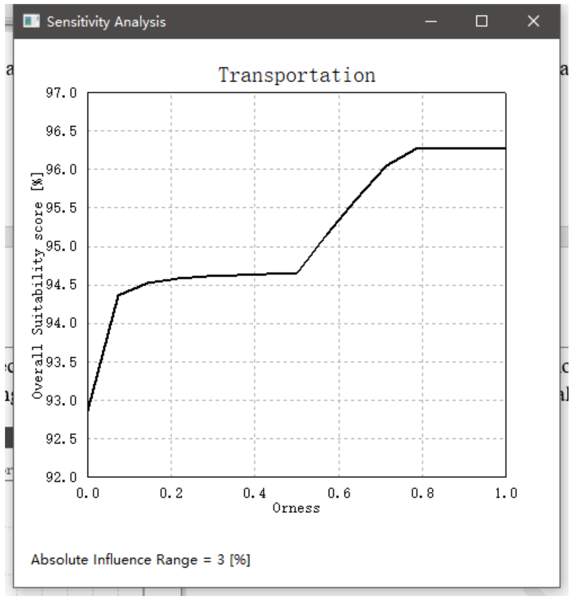


Sensitivity Analysis of Aggreagtors

The sensitivity analysis of aggregators can provide insights on how the change of a certain aggregator will affect the overall LSP suitability values. It can be accessed through **Analysis – Sensitivity Analysis – Aggregators**:

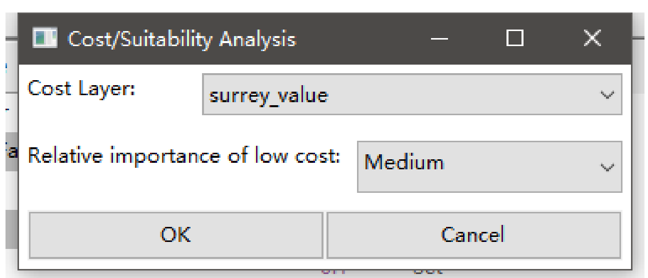


The coordinates *x* and *y* have to be input to specify a certain location. The aggregator for examination should also be selected. In this example, the Transportation aggregator has been chosen. The result will show how the change of this aggregator with increasing orness will affect the overall suitability value:



<u>Cost/Suitability Analysis</u>

The Cost/Suitability Analysis can offer a further LSP suitability analysis by considering the cost value. For example, the cost value could be the land price or the cost distance. This can be integrated with the overall LSP suitability map to generate a new LSP suitability map by considering cost as an additional factor in the decision-making process. It can be accessed through **Analysis – Cost/Suitability Analysis**:

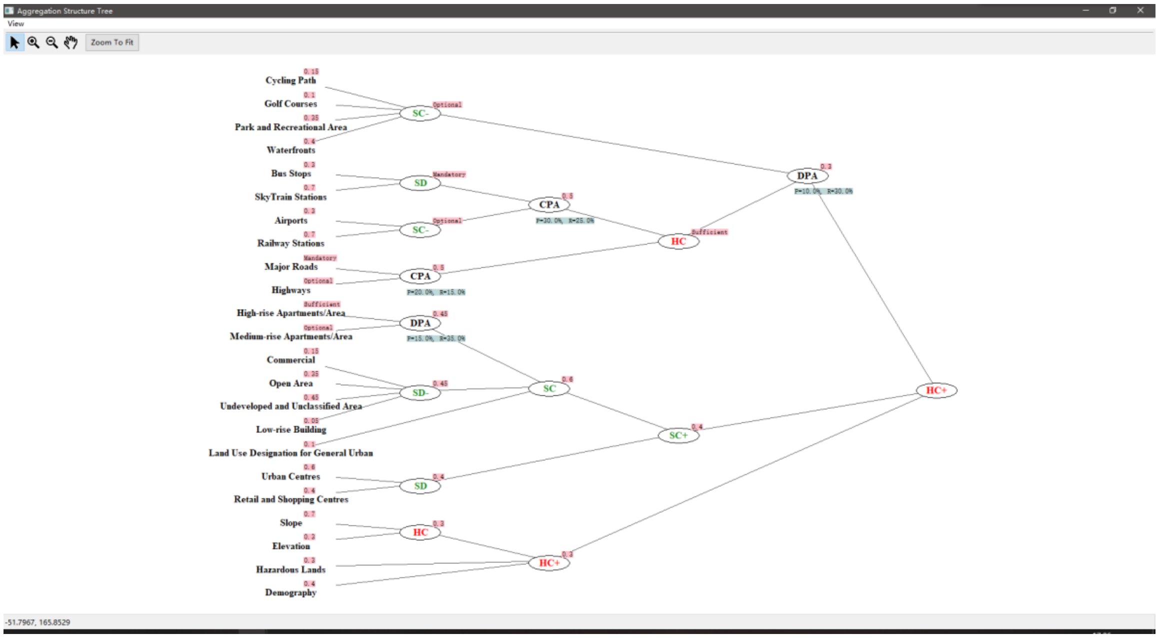


The cost layer should be specified in raster GIS format with the same resolution as the LSP suitability map. Then, the relative importance of low cost should be selected. For example, some will consider low cost of a location as very important when making decision while some will view low cost as unimportant. The result will provide an LSP suitability map that differs from the original LSP suitability map:

Views

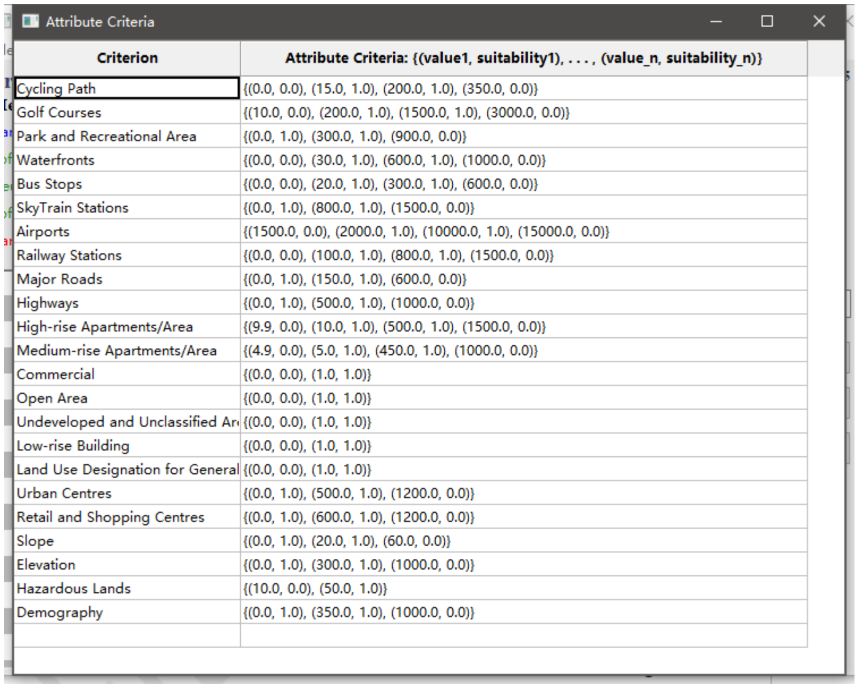
LSP Attribute Tree Diagram

GIS.LSP can generate the attribute tree diagram based on the chosen LSP Attributes Tree. This can be accessed through **View – Tree Diagram**. The tree diagram will show the criteria, aggregators and their corresponding weight value or penalty/reward value. The user can interact with the diagram by using the *Pointer* to move elements or using *Pan* to move the canvas. The color of diagram can also be changed by going to **View – Color Options**. An example generated Tree Diagram is shown as follows:



Elementary Attribute Criteria

GIS.LSP can generate the elementary attribute criteria for all the criteria in a report format. The elementary attribute criteria will be shown in vertex notation format. This can be accessed through **View – Attribute Criteria**. An example generated Attribute Criteria is shown as follows:



Criterion	Attribute Criteria: {(value1, suitability1), . . . , (value_n, suitability_n)}
Cycling Path	{(0.0, 0.0), (15.0, 1.0), (200.0, 1.0), (350.0, 0.0)}
Golf Courses	{(10.0, 0.0), (200.0, 1.0), (1500.0, 1.0), (3000.0, 0.0)}
Park and Recreational Area	{(0.0, 1.0), (300.0, 1.0), (900.0, 0.0)}
Waterfronts	{(0.0, 0.0), (30.0, 1.0), (600.0, 1.0), (1000.0, 0.0)}
Bus Stops	{(0.0, 0.0), (20.0, 1.0), (300.0, 1.0), (600.0, 0.0)}
SkyTrain Stations	{(0.0, 1.0), (800.0, 1.0), (1500.0, 0.0)}
Airports	{(1500.0, 0.0), (2000.0, 1.0), (10000.0, 1.0), (15000.0, 0.0)}
Railway Stations	{(0.0, 0.0), (100.0, 1.0), (800.0, 1.0), (1500.0, 0.0)}
Major Roads	{(0.0, 1.0), (150.0, 1.0), (600.0, 0.0)}
Highways	{(0.0, 1.0), (500.0, 1.0), (1000.0, 0.0)}
High-rise Apartments/Area	{(9.9, 0.0), (10.0, 1.0), (500.0, 1.0), (1500.0, 0.0)}
Medium-rise Apartments/Area	{(4.9, 0.0), (5.0, 1.0), (450.0, 1.0), (1000.0, 0.0)}
Commercial	{(0.0, 0.0), (1.0, 1.0)}
Open Area	{(0.0, 0.0), (1.0, 1.0)}
Undeveloped and Unclassified Ar	{(0.0, 0.0), (1.0, 1.0)}
Low-rise Building	{(0.0, 0.0), (1.0, 1.0)}
Land Use Designation for General	{(0.0, 0.0), (1.0, 1.0)}
Urban Centres	{(0.0, 1.0), (500.0, 1.0), (1200.0, 0.0)}
Retail and Shopping Centres	{(0.0, 1.0), (600.0, 1.0), (1200.0, 0.0)}
Slope	{(0.0, 1.0), (20.0, 1.0), (60.0, 0.0)}
Elevation	{(0.0, 1.0), (300.0, 1.0), (1000.0, 0.0)}
Hazardous Lands	{(10.0, 0.0), (50.0, 1.0)}
Demography	{(0.0, 1.0), (350.0, 1.0), (1000.0, 0.0)}

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