Multi-objective Land Use Optimization Using Genetic Algorithm

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ABSTRACT

Multi-objective Land Use Optimization Using Genetic Algorithm

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Land use optimization, a kind of resource allocation, can be defined as the process of allocating different land use categories (e.g., residential, commercial, and industrial, etc.) to specific units of area within a region. As one of the most popular words nowadays, sustainable development can be viewed as a process of change in which the exploitation of resources, the direction of investment, the orientation of technological development and institutional change are all harmonized. Sustainability is, hence, an important and imminent societal goal for land use planning. Land use optimization involves the active planning of land for future use by people to provide for their needs. In this thesis, the central goal is to develop a sustainable land use optimization prototype to enrich the field of planning support with regard to sustainability.

Land use optimization is a multifaceted process that entails complex decision-making which involves the selection of activities, the percentages to allocate, and where to allocate. It will also add a whole extra class of variables to the problem when combined with the inevitable consideration of spatial optimization. The related applications by linear programming (LP), "Pareto Front Optimal" based methods, heuristics methods and integration of GIS etc. for spatial multi-objective land use optimization are reviewed and analyzed on their advantages and disadvantages in this thesis. Accordingly, due to the nonlinearity and the complexity caused by the multiple objectives and increasing variables during the optimization process, the efficiency and effect would be the issues to be considered. The need for effective and efficient models for land use optimization is evident from the above discussion as the core content. In order to comprehensively fulfill all the requirements, the understanding of the sustainability of land use is translated into eight objectives to form the Multi-objective Optimization of Land Use (MOLU) model. Furthermore, an efficient model named Boundary based Fast Genetic Algorithm (BFGA) using goal programming is employed in the multi-objective optimization in Tongzhou Newtown. This algorithm is especially efficient for land use optimization problems derived from its special boundary based operators. Furthermore, considering the characteristics of planning support process and these two models mentioned above, the interactive spatial land use optimization prototype with a friendly interface and a simplified 3D visualization module could be established, thus yielding good effects and potential to support the planning process in the study area. Finally, in light of the study results and limitations, some directions are also provided for future research.

摘要

作爲資源配置的一種，土地利用優化可以定義爲在特定區域內，將不同的用地類型（如居住用地、商業用地、工業用地等等）分配至特定的區域單位的過程。作爲當今世界最流行的辭彙之一，可持續發展是資源的開發利用，投資方向，技術發展導向以及制度變革處在和諧狀態下的發展變化過程"。因此，可持續性同樣也是土地利用規劃的重要及迫切的社會目標。土地利用優化就是人們爲了滿足自身需求，協調各方面目標而做出的未來土地利用規劃。在本篇論文中，我們的核心的目標即是建立一種可持續發展的土地利用優化原型，從而可以促進輔助規劃決策模型的發展。

作爲一個複雜的決策制定過程，土地利用優化包含了土地利用類型的選擇，針對土地利用類型的特定的分配比率，以及分配的位置。 當不得不考慮其空間優化特性的時候，更多的變量會使優化的問題變得更爲複雜。在本篇論文中，相關的應用線性規劃方法，帕累托優化方法，啓發式演算法以及地理資訊系統結合的空間多目標土地利用優化的應用案例得到了詳細的回顧，同時，也分析了各自的方法的優缺點。從中，我們得知基於優化過程中由於多目標以及多變量帶來的非線性以及複雜性，優化的效果和效率是必須要考慮的關鍵問題。在以上的討論中，我們可以知道對於高效的土地利用優化模型的需要是非常明顯的。在本篇論文中，爲了綜合的滿足以上所有的要求，可持續性在土地利用層面被理解爲八個目標，基於這些目標，構成了土地利用多目標優化（MOLU）模型。除此以外，一個有效的名爲基於邊界的快速遺傳演算法（BFGA）結合目標規劃方法被成功的應用於通州新城的土地利用多目標優化中。利用一些特別的基於邊界的

運算元，BFGA 在土地利用優化問題中顯得非常有效。考慮到輔助規劃決策過程及以上兩種模型的特性，具有友好介面以及簡化 3D 視覺化功能的互動式土地利用空間優化原型被建立了起來，並在研究區域的輔助規劃過程中展示了其應用效果及潛力。最後，在分析研究結果的基礎上，本文提出了將來可能的研究方向。

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ABBREVIATIONS

Boundary based Fast Genetic Algorithm (**BFGA**)

Boundary based Mutation Operator (**MBO**)

Boundary based Crossover Operator (**CBO**)

Canada Geographical Information System (**CGIS**)

Carbon Dioxide (**CO_2**)

Cellular Automata (**CA**)

Chemical Oxygen Demand (**COD**)

Constraints Mutation Operator (**MCO**)

Decision Support Systems (**DSS**)

Dynamic Multi-Objective Evolutionary Algorithm (**DMOEA**)

Environmental Performance Index (**EPI**)

Environmental Sustainability Index (**ESI**)

European Environment Agency (**EEA**)

Evolutionary Algorithms (**EA**)

Fast Non-dominated Sorting Genetic Algorithm (**NSGA-II**)

Generation Gap (**GG**)

Genetic Algorithm (**GA**)

Geographical Information System (**GIS**),

Gross Domestic Income (**GDI**)

Gross Domestic Product (**GDP**)

Gross National Income (**GNI**)

Gross National Product (**GNP**)

Hop-Skip-Jump (**HSJ**)

Improved SPEA (**SPEA2**)

International Institute for Sustainable Development (**IISD**)

Level of Detail (**LOD**)

Linear Programming (**LP**)

Making Development More Sustainable (**MDMS**)

Management Information System (**MIS**)

Millennium Development Goals (**MDGs**)

Multi-Attribute Decision Analysis (**MADA**)

Multi-Criteria Decision Making (**MCDM**)

Multi-Objective Decision Analysis (**MODA**)

Multi-objective Evolutionary Algorithm Based on Decomposition (**MOEA/D**)

Multi-objective Genetic Algorithm (**MOGA**)

Multi-objective Optimization of Land Use (**MOLU**)

Multiple Criteria Decision Analysis (**MCDA**)

Niched Pareto Genetic Algorithm (**NPGA**)

Non-dominated Sorting Genetic Algorithm (**NSGA**)

Non-Governmental Organizations (**NGOs**)

Not In My Back Yard (**NIMBY**)

OpenSceneGraph (**OSG**)

Organization for Economic Cooperation and Development (**OECD**)

Pareto Envolope-based Selection Algorithm (**PESA**)

Pareto-Archived Evolution Strategy (**PAES**)

Patch based Mutation Operator (**MPO**)

Planning Support Systems (**PSS**)

Pressure-State-Impact-Response (**PSIR**)

Pressure-State-Response (**PSR**)

Random Weighted Genetic Algorithm (**RWGA**)

Region-based Selection in Evolutionary Multi-objective Optimization (**PESA-II**)

Rank-density Based Genetic Algorithm (**RDGA**)

Simulated Annealing (**SA**)

Spatial Decision Support Systems (**SDSS**)

Strength Pareto Evolutionary Algorithm (**SPEA**)

United Nations (**UN**)

United Nations Commission for Sustainable Development (UNCSD)

Virtual Reality (**VR**)

World Summit on Sustainable Development (**WSSD**)

World Wide Web (**WWW**)

CHAPTER 1: INTRODUCTION

1.1 Background

1.1.1 Sustainable development and land use planning

China has witnessed astonishing economic growth and urban development during the past three decades. This rapid urban expansion has been accompanied by numerous related problems, such as the loss of open space, increased traffic congestion, and environmental deterioration. Consequently, optimal land use planning is imperative to channelize the growth process in a sustainable manner.

Land use planning is a process of resource allocation that involves allotting different uses to specific units of area within a region, such as residential land, industrial area, recreational facility, green land etc. It can be divided to two main steps: land use structural and spatial planning. The well-known Brundtland Commission (WCED, 1987) defines sustainability as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (P.43). In more detail, sustainable development is understood as a process of change in which the exploitation of resources, the direction of investment, the orientation of technological development and institutional change all are in harmony by Brundtland Commission. Sustainability, thus defined, is of paramount significance in land use planning. Land use planning, hence, deals with the active allocation of land for future use by people to provide for their own needs.

Comprehensive sustainability in land use planning can be termed as a long-term and intricate balance between economic development, environmental protection, efficient resource use, and social equity. Leccese and Mc cormick (2000), in the "Charter of the New Urbanism", described a sustainable land-use planning agenda. Their manifesto emphasized infill development, environmental protection, compactness, and local geography as the main elements of balanced urban development.

However, there are too many uncertainties in these guides to realize land use sustainability during the planning process. Besides, effectively translating and reflecting these aspects in land use planning poses yet another problem. Thus, a series of comprehensive analysis leading to a set of factors representing the sustainable land use with more maneuverability is imminent. Furthermore, suitable and effective approaches are needed to integrate these requirements or objectives to yield sustainable land use planning scenarios.

1.1.2 Land use planning support

The primary objective of land use planning support is to facilitate the process of land use planning in accordance with specific objectives. It is a very complicated process, which covers the entire planning process, including the data management, suitability analysis, simulation, predication, optimization, interactive design support, visualization etc, which are all related to Spatial Decision Support Systems (SDSS), Geographical Information System (GIS), and Multiple Criteria Decision Analysis (MCDA).

Management Information System (MIS) came into existence towards the end of 1960s. Subsequently, DSS, which could combine database management systems, analytical models, and visualization to improve the decision making process were invented. The decision making process was further extended with the spatial dimension, thus leading to SDSS. In the field of planning, the corresponding SDSS could be regarded as Planning Support Systems (PSS). All these aspects that aid the planning process could be defined as planning support, thus planning support serves as an "umbrella" for a very broad concept. Planning support already encompasses the concept of "PSS". PSS consists of a wide diversity of geo-information tools that are dedicated to support public or private planning process (or parts thereof) at any particular spatial scale and within a specific planning context (Batty, 1995; Geertman & Stillwell, 2004).

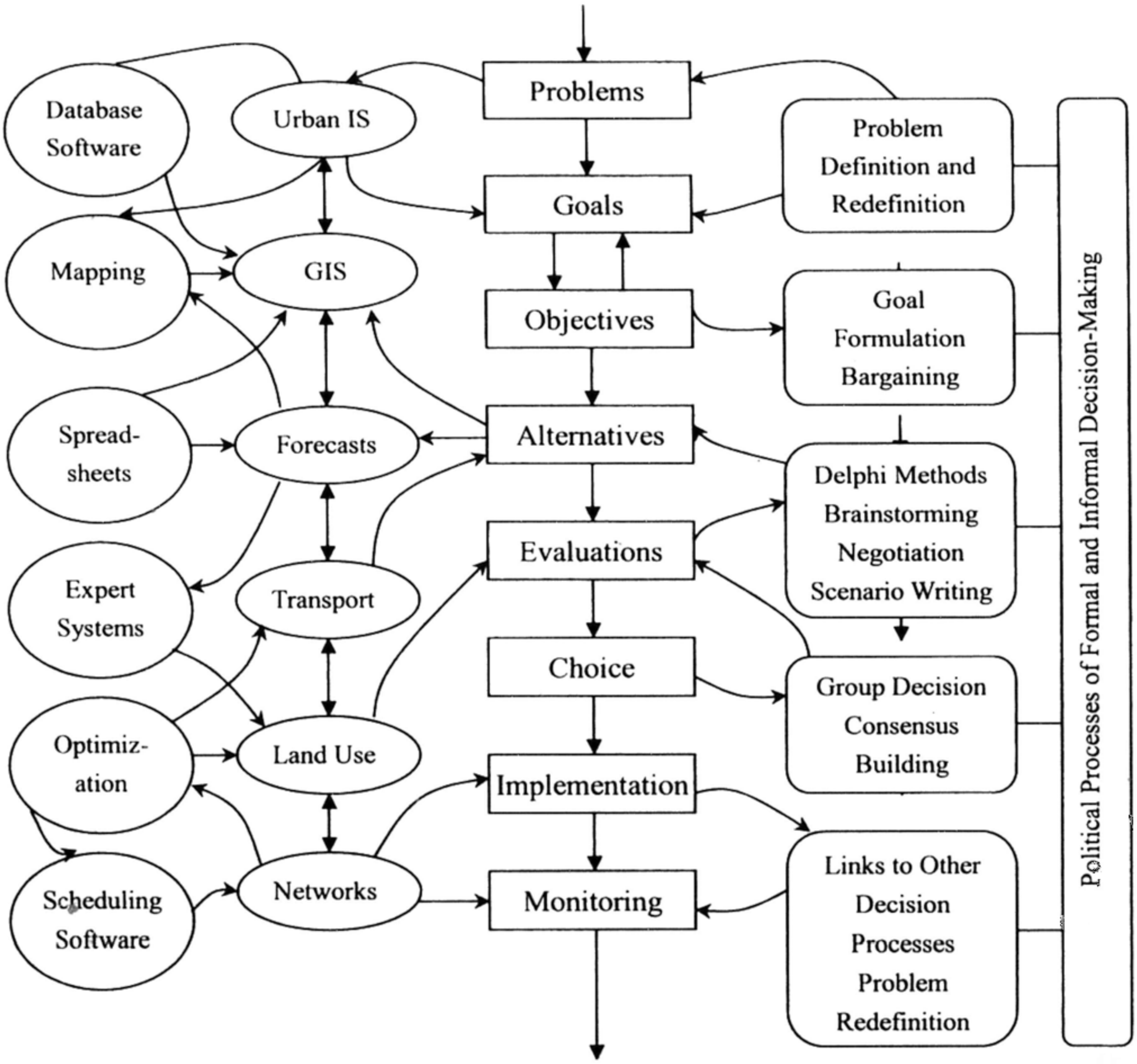

Figure 1-1 The Process of PSS and Urban Planning (Batty, 1995)

There are also some mature and successful general applications of PSS such as the "UrbanSim" "What If ?" and "CommunityViz" etc (Klosterman, 1999; Kwartler & Bernard, 2001; Waddell, 2002). Besides, other specific PSSs that are also very popular are present. These include the Planning System for Sustainable Development (PSSD), which is the area-specific system and System for Planning and Research in Towns and Cities for Urban Sustainability (SPARTACUS system), which is a task-specific system.

Among planning support process, GIS, is one simple and useful tool that can capture, store, analyze, manage, and present data that is linked to the location. Besides handling the spatial data and managing the spatial database, GIS can be used to supply the interface for interactive planning design and to provide 2D or 3D visualization(s) for planners or policy makers as well as to aid public participation. When integrated with other models, such as statistical or dynamic models such as Moran's I, Cellular Automata (CA), Agent based models, they can also help to provide the simulation and forecasting related to spatial data. Suitability analysis, a GIS-based process used to determine the appropriateness of a given area for a particular use, is based on some general GIS functions, supported by lots of commercial GIS products such as ARCGIS, Mapinfo, Idrisi etc. Continuing the discussion further on those lines, optimization can be defined as the process of satisfying all the objectives and searching for the optimal tradeoffs among these objectives from the context of the spatial problems. As for land use planning, which is the process of looking for the optimal tradeoffs from the perspective of all the stakeholders involved, both suitability analysis and spatial optimization could support the land use planning. Although there have been several studies in the field of land use planning optimization, a GIS tool that could supply the general function related is not available.

Viewed from a different perspective, MCDA techniques offer PSS a structured method to evaluate alternatives and select the most satisfactory one according to the decision maker's priorities across a number of relevant criteria (Malczewski, 1999). MCDA has been a popular approach for decision analysis in the GIS environment, especially to address geographical issues (Eastman, 1997; Jiang *et al.*, 1995; Malczewski, 1999). GIS-based MCDA could be considered as a process that transforms and combines geographical data and decision maker's value judgments (Malczewski, 2006). Accordingly, two critical aspects for spatial MCDA are: (1) the GIS capabilities of data acquisition, storage, retrieval, manipulation, and analysis, and (2) the capabilities for combining the geographical data and the decision maker's preferences into unidimensional values of alternative decisions. A number of multi-criteria decision rules have been implemented in the GIS environment for tackling land-use suitability problems. The decision rules can be classified into multi-objective and multi-attribute decision making methods, which respectively correspond to spatial optimization and suitability. The multi-objective approaches are mathematical programming oriented methods, while multi-attribute decision making methods are data oriented (Malczewski, 1999; Malczewski, 2004).

Considering the aforementioned concepts within the domain of sustainable land use planning, sustainable land use optimization would be the key issue in this research, Sustainable land use optimization could, in turn, be divided into structural optimization and spatial optimization and hence, directly address and satisfy the need of sustainable land use planning support.

1.1.3 Sustainable Land use optimization

During the sustainable land use planning process, land use optimization indicates the effective use of land use planning support tools to assist the planning process after comprehensively combining the objectives of sustainability from the land use planning perspective.

There are two key aspects to pursue sustainable and optimal land use planning. As mentioned earlier, the first one is the definition of sustainability on land use planning, which further includes the translation and evaluation of sustainability into the optimization model. Secondly, the effective and efficient model for spatial multi-objective optimization is also important. As the term suggests, the spatial optimization model should decide not only on what to do (selection of activities), how much to allocate, but also on where to allocate. With increased size of the region and enhanced spatial resolution requirements, an enormous increase in the number of variables as well as an increase in the number of objectives can result. All these aspects greatly increase the computational complexity of the optimization process, which will definitely influence the efficiency of the land use optimization significantly. This is especially true for the planning support process that requires response efficiency, accuracy, and resolution etc. Therefore, the need for a model that can solve or alleviate the conflicts between these requirements of sustainable land use optimization and planning support is obvious.

1.1.4 Approaches for land use optimization

The utility of optimization as a normative tool for spatial problem has widely been recognized (Church, 1999, 2002; Cromley & Hanink, 2003; Malczewski, 1999). In the past, Linear Programming (LP) approaches were employed to solve such land use optimization problems. The increasing sophistication of LP and faster computers has allowed such problems to be handled efficiently when dealing with a single objective. Even for multi-objectives problems, the LP approach can be employed to obtain tradeoffs by combining objectives together by setting the suitable weights. Even for multi-objectives problems, the LP approach can be employed to obtain tradeoffs by combining objectives together by setting the suitable weights. Some scholars have integrated LP with GIS for spatial land use planning (Aerts *et al.*, 2003a; Arthur & Nalle, 1997; Chuvieco, 1993; Stewart, 1991, 1993; Zimmermann, 1978). However, numerically quantify the relative weights for each objective is also a problem for planners. Besides, non-convex optimal solutions cannot be obtained by minimizing linear combinations of the objectives. Furthermore, the complexity of the problem increases with the inclusion of multiple objectives and these objectives may not always be linear or simple. The objectives within a spatial context must have to add spatial information to all the attributes, which again increases the complexity of the problem. Also, the grids or the neighboring features are also not independent. For general non-linear multi-objective optimization problems, combining all the objectives directly, such as single objective based methods is also an efficient way. However, the scale and weights of the objectives sometimes confuse the planners.

In order to avoid the lack of non-convex solutions and to obviate scale problems and setting weights, a method named "Pareto Front Optimal", derived from Pareto's original work, is employed. The beauty of the Pareto set is that it is independent of the relative importance of all the objectives. Thus far, it has been very popular in solving multi-objective problems, particularly spatial optimization problems such as land use optimization (Balling *et al.*, 1999; Chandramouli *et al.*, 2009; Xiao *et al.*, 2002). However, compared to the single objective based methods for multi-objective optimization, the Pareto front optimal method is less efficient and hard to achieve the special optimum according the needs of planners or policy makers.

All these aspects described above create a need for effective optimization methods for land use optimization. A gradual change from strict optimization to the use of heuristics is observed in the design of the optimal solutions. Aerts made use of "Simulated Annealing (SA)" to perform the land use planning in a multiple objective *LP* context (Aerts & Heuvelink, 2002). Duh used a knowledge-informed Pareto SA to perform the multi-objective spatial allocation (Duh & Brown, 2007). Besides, one density-based optimization model has also been created by Ligmann-Zielinska to obtain the sustainable land use patterns based on Hop-Skip-Jump (HSJ) method (Ligmann-Zielinska *et al.*, 2008). Furthermore, Genetic Algorithm (GA), introduced by Holland (1975) during his investigations of adaptive systems, is also an effective heuristic method. GAs have been successfully used to search complex solution spaces in a variety of application domains (Feng & Lin, 1999; Goldberg, 1989; Michalewicz, 1996) and have proved to be efficient optimizers across a range of applications. Stewart *et al.* (2004) have taken advantage of general GA to perform multi-objective land use planning in a small research area based on grid. Janssen et al. (2008) also have utilized GA for land use planning support using the interactive operation on a small area (20 by 20 cells) based on single objective multi-objective optimization method.

Besides the successful applications on single objective multi-objective optimization based GA models mentioned above, GA is also well suited to solve multi-objective optimization problems by searching the Pareto front based on "Pareto Front Optimal" method. The near-global optimum searching and convergence ability of GA makes it possible to find a diverse set of solutions for difficult problems with non-convex, discontinuous, and multi-modal solutions space (Zhang & Leung, 2000). The first multi-objective GA, called vector evaluated GA, was proposed by Schaffer (Schaffer, 1985), and subsequently, Multi-objective Genetic Algorithm (MOGA), Niched Pareto Genetic Algorithm (NPGA), Random Weighted Genetic Algorithm (RWGA), Non-dominated Sorting Genetic Algorithm (NSGA), Strength Pareto Evolutionary Algorithm (SPEA), Fast Non-dominated Sorting Genetic Algorithm (NSGA-II) etc. (Deb *et al.*, 2000; Fonseca & Fleming, 1993; Horn *et al.*, 1994; Murata & Ishibuchi, 1995; Srinivas & Deb, 1994; Zitzler & Thiele, 1999) were developed. Feng studied to the generation of alternative maps for urban planning using a GA (Feng & Lin, 1999). Balling used GA to solve vector based urban planning problems (Balling *et al.*, 1999). Matthews (Matthews, 2001) also used MOGA to help land use planning based on vector representation. Besides, there are also several other similar Pareto front based algorithms applications for land use optimization, however, those algorithms are far too time-consuming to support the planning process involving large amount of variables or objectives, especially when using the algorithm with too complicated mechanism.

Approaches should be problems based. As for sustainable land use optimization, the most important requirement of the approaches is the participation of the planners or policy makers in the planning optimization, as well as the efficiency to pursue the optimal land use planning scenarios. Consequently, the revised single objective multi-objective optimization based model with these characteristics is the one of the primary goals in this research.

1.2 Objectives

As discussed above, the goal of this study is to develop an optimization model with the purpose of sustainability to generate sustainable land use scenarios to support the land use planning process according to the planners or policy makers' preference. The study centers around two major issues in sustainability for land use optimization, the translation and evaluation of these objectives for sustainability; and the effect and efficiency of the spatial optimization model for land use planning support. In the context of Tongzhou Newtown, located in the east of Beijing, China, a Boundary based Fast GA for Multi-objective Optimization of Land Use (BFGA-MOLU) model has been established to implement and test the theoretical findings. The objectives of this study are as follows:

1. To analyze the considerations of sustainability on land use planning, and extract the objectives from the analysis for further optimization.
2. To design an effective multi-objective optimization model to fit the optimization process of sustainable land use planning support that requires the participation of the planners or policy makers.
3. To translate the objectives to the model that can guide the land use planning directly and build the suitable evaluation models of each objective according to specific situation including the research area and data limitation.
4. To build an efficient GA model with revised operators to implement the Multi-objective optimization model with the respect to the efficiency requirement of land use planning support.
5. To establish a friendly interface of the sustainable land use planning support prototype system to help the planning process as well as the 3D visualization that

could support planning and decision-making by the planners or policy makers and even facilitate public participation.

1.3 Significance

China has witnessed astonishing economic growth and urban development during the past three decades. This rapid urban expansion has been accompanied by numerous related problems, such as the loss of open space, increased traffic congestion, and environmental deterioration. Consequently, optimal land use planning is imperative to channelize the growth process in a sustainable manner. However, during the planning process, it is difficult for the planners or decision makers to analyze the research area and perform comprehensive planning using existing models or tools related to SDSS, GIS, and MCDA. This is particularly true when the research area is too large or there are too many conflicting considerations. This research aims to solve the problem by integrating the objectives of sustainability with land use planning and innovative multi-objective land use optimization. Besides, within such kind of planning support, there are also lots of problems concerning the understanding of sustainability in land use planning and extracting the comprehensive objectives from the definition of sustainability. On the other hand, the characteristics of land use optimization such as the spatiality, large research area, multi-objectives, and requirements of efficiency and effect etc. also bring forth lots of obstacles to the development of the optimization model. Furthermore, within the planning support process, the friendly interface for the interactive operations among the planners or policy makers with the PSS and the visualization of the optimal results are valuable outcomes from the research.

The friendly interactive platform for sustainable land use planning support coupled with the objectives of sustainability on land use planning and the efficient spatial multi-objective optimization model as well as the 3D visualization module would provide meaningful support to the land use planning process. These aid taking a comprehensive look at sustainability in land use planning with diverse preferences from the planners or policy makers. Besides, this serves as a platform for the public to voice their preferences (of different objectives) and provide some kind of feedback after viewing the optimal land use planning scenarios in an intuitive 3D mode .

1.4 Research Framework

1.4.1 Questions description

Sustainable land use optimization entails arriving at a truly optimal tradeoff involving these objectives in accordance with sustainability whilst considering economic benefits, environmental conservation needs, and social equity. This serves as a quantified analysis tool to efficiently guide the planners or policy makers with the land use planning process. Combined with the comprehensive objectives pertaining to sustainability, a considerable number of compromising sustainable land use planning scenarios is obtained.

The goal of this study is to develop a kind of sustainable land use optimization prototype to enrich the field of planning support models with regard to sustainability. As for this main target of this study, there are important aspects of the problem to conquer:

The understanding of sustainability on land use which should be the objective of sustainable land use optimization. Despite considerable research in the domain of sustainability, a vast majority of this research focuses on conceptual or abstract analysis. Also, no comprehensive indicators are available for guiding the process sustainable land use optimization. Hence, it is meaningful and imminent to explore these objectives leading to sustainable land use, which could be quantified for operating the optimization.

The effective formulation of MOLU model. As a kind of multi-objective optimization problem, it is crucial to look for a suitable way to combine these objectives. Besides, this should take into account the characteristics of different multi-objective models as well as the interactive planning support process.

The suitable evaluation methods of different objectives. According to these objectives extracted from the understanding of sustainability, they cannot be used directly without the quantified modeling. The target is to look for the effective and accurate quantified model to explore the actual correlation among these variables including locations, land use types and fitness value. It is not easy to formulate such a non-linear relationship. Besides, the data is another consideration during the modeling process.

The effective and efficient multi-objectives heuristic optimization approach. Corresponding to the MOLU model, the approach to pursue the optimization of the MOLU model is another essential part to decide the effect and the overall efficiency of the entire sustainable land use optimization process. This is of particular importance when the problem is a complicated one with nonlinear nature and involves large amount of spatial variables.

The friendly interface to support the land use planning with respect to the users such as the planners, policy makers, and public. As another essential part of planning support, the interface and the visualization of these optimal scenarios are also inevitable to provide interactive capabilities and intuitive effect. Hence, the user-friendliness of the interface and rendering the results in the form of 3D visualization signify the last challenge involved in this research.

1.4.2 Research workflow

In this study, there are two main stages have been identified within the research framework. The first one is the conceptual analysis of the objectives of land use planning with respect to sustainability, the formulation of the MOLU model, and the quantified assessment of these objectives. This is to summarize the contents of sustainability on land use and develop a conceptual framework of these objectives. Furthermore, the effective and suitable evaluation methods are also developed according to these objectives and the characteristics of the case study. The latter one is to build an efficient multi-objective optimization model to integrate these considerations to generate more optimal and sustainable land use planning scenarios. Also, a friendly interface is developed with 3D visualization functionality to help make the process of land use planning more intuitive and interactive.

To contextualize the models, the workflow of sustainable land use optimization is designed as shown in figure below. The procedures could be specified as follows:

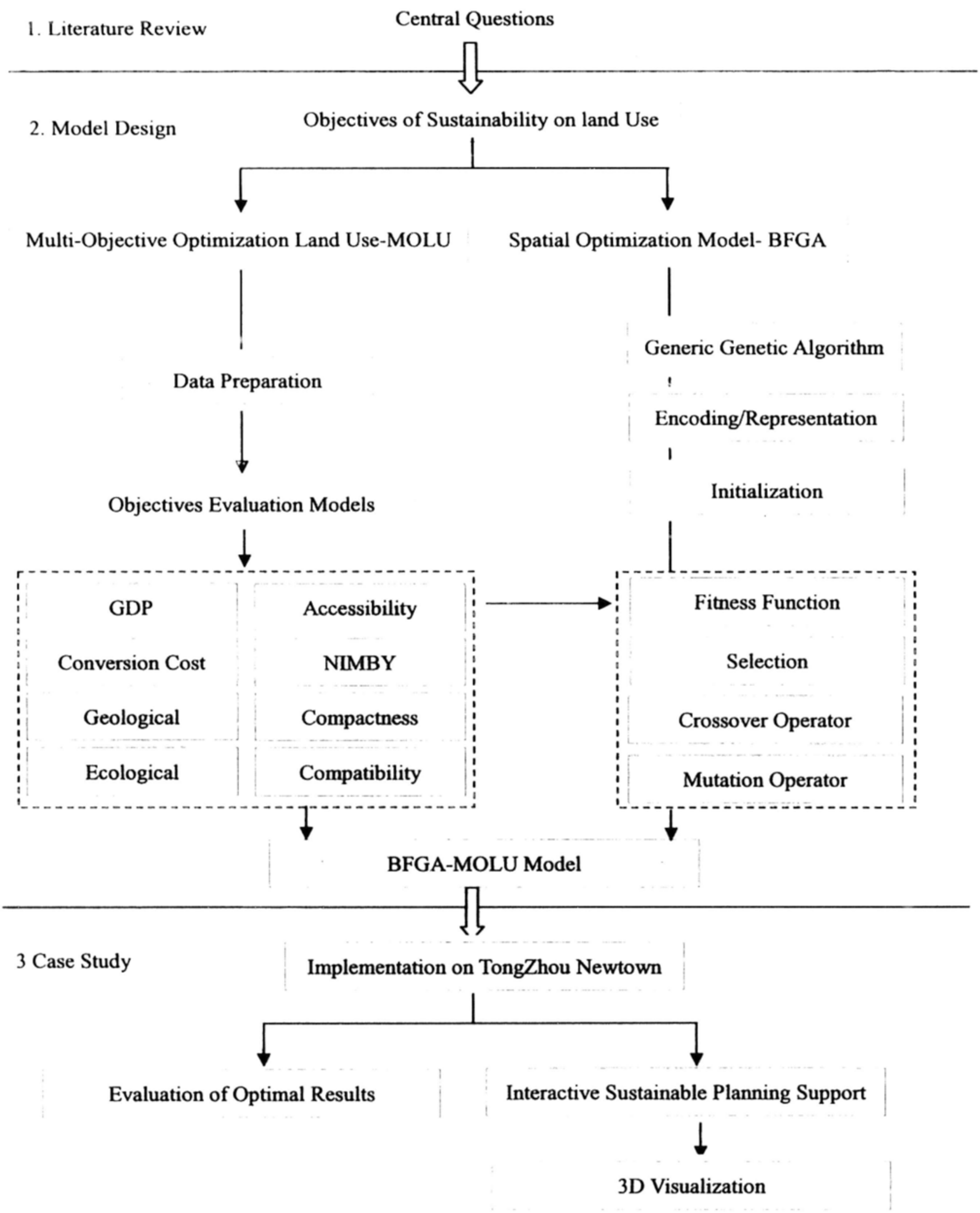

Figure 1-2 Research Workflow

Literature review and summarization of the problems related to "sustainable land use optimization". Typically, a comprehensive review of related literature is a prerequisite to gain a thorough understanding of the research domain. As has been explained above, the systematic review yielded the central question for this research: "lack of the comprehensive and operable objectives related to sustainability on land use and the need for efficient spatial multi-objective optimization models". Further, each central question also can be divided to several sub questions or sub tasks: as for the first central question, the conceptual analysis of the objectives related to land use sustainability be the first task. The formulation of the multi-objective land use problem should be the second task. The quantified evaluation methods of these objectives according to these objectives and the research area should be the third one. As for the second central question, the efficient spatial heuristic optimization model should be the first task. This should be followed by the interactive and user-friendly interface with visualization functionality to support sustainable land use planning.

Model design. The model design includes the conceptual analysis of land use sustainability, the formulation of the multi-objective model, and the design of quantified evaluation models for different objectives as well as the spatial heuristic optimization model. These steps cater to the needs and essential problems within the research domain. As for the first one, the conceptual analysis of sustainability is to extract the systematic objectives from the definition of sustainability as pertaining to land use planning, which could be used to evaluate the sustainability of the land use planning scenarios from a more comprehensive viewpoint. The formulation involves the construction of a multi-objective land use model that could organize and combine these objectives obtained from the first step. The third one, evaluation models of different objectives, results in quantified evaluation methods that could be used to compare the land use planning scenarios based on the analysis of the different objectives in the first step. The last one is to execute the multi-objective optimization using the heuristic optimization model, with due consideration of the problem characteristics. The GA with revised operators would be applied to implement the optimization computation.

Friendly interactive interface and 3D visualization. The goal of the prototype from this study is to supply the planning process with a friendly interactive platform that could reflect the essentials of land use planning. This provides the planners or policy makers with sufficient access capabilities and functionalities to sufficiently analyze and subsequently incorporate their opinion about these objectives. Furthermore, the 3D visualization is also helpful to represent the optimal result in a more intuitive and meaningful format to aid public participation.

Case study. The implementation of these models on the research area- Tongzhou Newtown, serves to test and demonstrate the sustainable land use optimization model, which is a kind of sustainable land use planning support tool. This case study proves the effect and the efficiency of the model generated in this study. Besides, the interactive sustainable land use planning support process and the 3D visualization also demonstrate the viability of this research.

1.5 Organization of the Thesis

The thesis consists of seven chapters. Following this introductory chapter, the conceptual and theoretical foundations of the thesis are reviewed in Chapter Two. Topics covered in this chapter include the concepts of sustainable development, land use planning, land use planning support to the contents related to sustainable land use optimization, the approaches for land use optimization etc.

Chapter Three focuses on the analysis of sustainability on land use planning, as well as the extraction of these objectives that could reflect this concept comprehensively. In this chapter, totally eight objectives are translated into land use dimension and formulated to the MOLU model based on revised goal programming with some constraints.

Chapter Four introduces the research area and the evaluation models of all these objectives and constraints based on either existing methods or innovative approaches. Especially for the objective of Compactness, comparing and evaluating various approaches in this field, the eight-neighbour method was found to be suitable for the optimization model.

Chapter Five explains the construction of the comprehensive BFGA-MOLU model, which includes some revised and innovative crossover and mutation operators as well as the special initialization and selection setting etc. Besides, this section also elucidates the setting of parameters and covers the robustness experiments.

Chapter Six presents the case studies, including the direct implementation of the BFGA-MOLU model on the research area as well as the evaluation of the model. This chapter covers the prototype of interactive land use PSS based on BFGA-MOLU model and the Virtual Reality (VR) based Visualization.

Chapter Seven concludes the thesis by summarizing the research and the major contributions. Subsequently, limitations of the study are discussed and recommendations are provided for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 Sustainable Development & Land Use Planning

2.1.1 Sustainable development

The conflict between the economic development and environmental protection in China became apparent starting from the late 1960s. The economic development was accompanied by uncontrolled exploitation and depletion of resources, subsequently resulting in grave environmental concerns including smoky cities, polluted rivers or lakes, pesticide residues in wildlife etc. Along with these environmental issues, it became increasingly obvious that mere progress at the local level would not suffice as the environmental degradation problems were at a much large scale. This implies that the issues of pollution transcended national borders: such as acid rain or the pollution of common waters such as the North Sea. Several issues even call for action at a global level, such as ozone layer depletion due to emissions of man-made Chloro-fluoro-carbons, and the effects of greenhouse gases, such as carbon dioxide (CO_2), methane, etc, on the global climate change.

Besides these environmental issues, there are various other global concerns such as population increase, socio-economic problems, poverty etc. All these lead researchers and analysts to doubt the long term viability and hence 'sustainability' a whole range of human activities, hence creating the need for a new 'model' of development (Munasinghe, 2009).

The terms 'sustainable' or 'sustainability' surfaced in the global lexicon in the 1980s as the electronic news media made people increasingly aware of the mounting global problems of over population, drought, famine, and environmental degradation. These were first brought forward by the 'Club of Rome', and been the subject of Limits to Growth in the early 1970s (Meadows *et al.*, 1972).

A more comprehensive definition of sustainability was developed by The World Commission on Environment and Development, chaired by the then Norwegian Prime Minister (Mrs Brundtland) came up with a more comprehensive definition of sustainability, which published the report 'Our Common Future' in 1987. This provided the most commonly used working definition of sustainable development as follows:

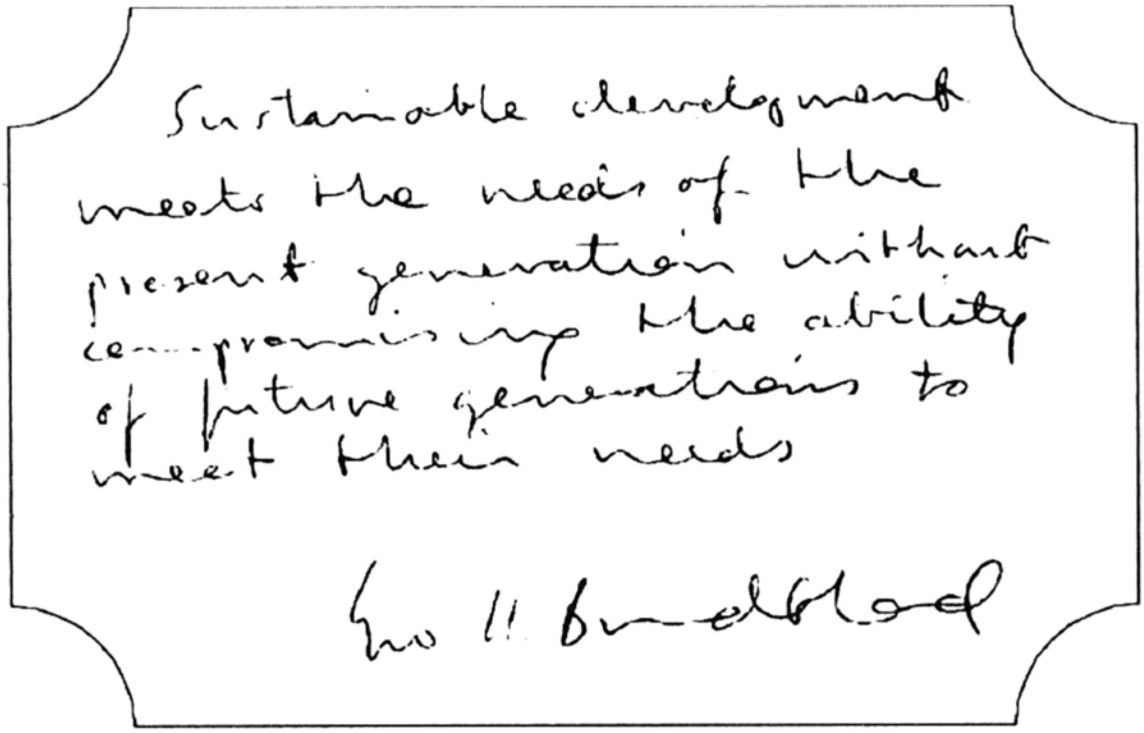

Figure 2-1 The Definition of Sustainable Development
(Autograph of Gro Harlem Brundtland)

Sustainable development (WCED, 1987) can hence be defined as:
"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs."(P.43)

Besides, there are also some other definitions, Munasinghe (1993) defined it as a process for improving the range of opportunities that will enable individual human beings and communities to achieve their aspirations and full potential over a sustained period of time, while maintaining the resilience of economic, social and environmental systems.

Since the precise definition of sustainable development is an elusive goal, a less ambitious strategy might be more pragmatic. Hence, the step-by-step approach of 'making development more sustainable' (MDMS) becomes the prime objective, while sustainable development should be defined as a process rather than an outcome

(Munasinghe, 2009).

All these definitions and concepts received substantial responses internationally, and subsequently led to the United Nations (UN) Conference on Environment and Development in 1992 (Rio Earth Summit), attended by Heads of State and Government across the globe. A number of important agreements including the Climate Change Convention, and the Biodiversity Convention emerged. One of the key outcomes of the Rio Declaration on Environment and Development was the comprehensive action plan for the pursuit of sustainable development in the next century. This was accompanied by 27 general principles supported by "Agenda 21" and 40 chapters of detailed recommendations. These were addressed to international agencies, national and local governments, and Non-Governmental Organizations (NGOs) relating to environmental, social and economic issues.

One of the chief initiatives under Agenda 21 was to establish a new Commission on Sustainable Development within the UN, and to call on governments to prepare national strategies for sustainable development. Besides, some other key recent events relating to the sustainable development include: the 1995 World Summit on Social Development in Copenhagen, the UN Millennium Summit and Millennium Development Goals (MDGs) in 2000, the 2002 World Summit on Sustainable Development (WSSD) in Johannesburg, the UN Millennium Development Project approved as a follow-up to the MDGs in 2005 and the UN decade on Education on Sustainable Development (1995-2014) etc, all of which made significant contributions to the definition of sustainable development.

By and large, there has been a general consensus on the three aspects involved in sustainable development: economy, environment, and social aspects.

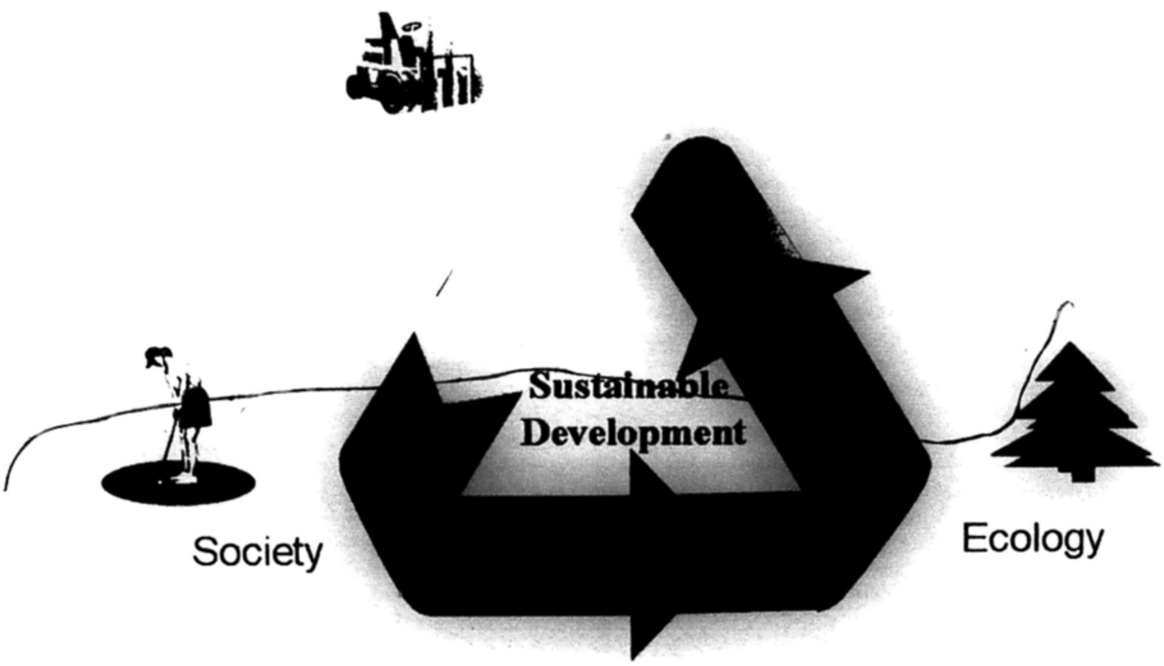

Figure 2-2 Three Aspects of Sustainability

Economic aspect: An economically sustainable system must be able to produce goods and services on a continuing basis, to build enough public facilities for the development of the society, to sustain welfare of the denizens, to manage finances properly in terms of debt and investment so as to alleviate the damages resulting from environmental deterioration. In conclusion, an economically sustainable system not only promotes social equity but also minimizes the impact of pollution on the environment.

Environmental aspect: An environmentally sustainable system must maintain a stable resource base by avoiding over-exploitation of renewable resources. Such a system conserves non-renewable resources by limited usage or depleting only to the extent proportional to the alternatives available. From a holistic perspective, this aspect should include biodiversity, other vital ecosystem functions, and the stability of energy, atmosphere, water, land resources etc.

Dasgupta and Maler (1997) point out that, until the 1990s, the mainstream development literature rarely mentioned the topic of environment (Chenery & Srinivasan, 1988 -1989; Dreze & Sen, 1990; Stern, 1989) in the context of Sustainable Development. There are also some books wrote by Faucheux, Pearce and Proops

(1996), which describe models of sustainable development. Besides, the book authored by Munasinghe, Sunkel and de Miguel (2001), focuses on the correlation between growth and environment. Furthermore, several researchers argue that environmental and geographic factors have been key drivers of past growth and development (Diamond, 1997).

Social aspect: A socially sustainable system, refers to a framework that consciously take into account the well-being of the people and the communities in which they operate. Such a system must achieve distributional equity, provide adequate social services including living, health, education, gender equity, and political participation etc. The social domain focuses on the enrichment of human relationships and the achievement of individual and collective aspirations.

Noticeably, these three elements of sustainability introduce many potential complications to the original simple definition discussed earlier. The implied objectives are multidimensional, raising various issues including the judgments of sustainable practices and the extent required to achieve balance among these related factors or objectives.

2.1.2 Indicators of sustainable development

The earlier sections provided a detailed explanation of sustainable development, especially as applicable to this study. Sustainable development has been explained from the perspectives of definition and contents. With the intention of balancing different aspects of sustainability and determining what development can be deemed sustainable, this section discusses the role of indictors in comprehensive and quantitative analysis.

Indicators provide the inevitable guidance required in the process of decision-making in ways more than one. They can translate knowledge into manageable units of information that can be applied to the decision-making process. This aids the assessment of the goals pertaining to sustainable development from different perspectives, besides offering an early warning to prevent economic, social and environmental damage.

The Earth Summit held in 1992 recognized the importance of indicators in decision-making concerning sustainable development. This has been clearly communicated in Chapter 40 of Agenda 21 mentioned earlier and developed indicators of sustainable development.

The Organization for Economic Cooperation and Development (OECD) established an analytical framework that can be used at national, regional and international levels. The first version of this framework was called the Pressure-State-Response (PSR) framework. The subsequent variation replaced the pressure indicator category with a category of driving force indicators (creating a DSR framework).Besides, there were also other variations applied to other frameworks - Pressure-State-Impact-Response (PSIR) framework. Finally, the last version encompassed all five indicator categories creating a DPSIR framework. The reasons for these developments are presented in the discussions below (Segnestam, 2002).

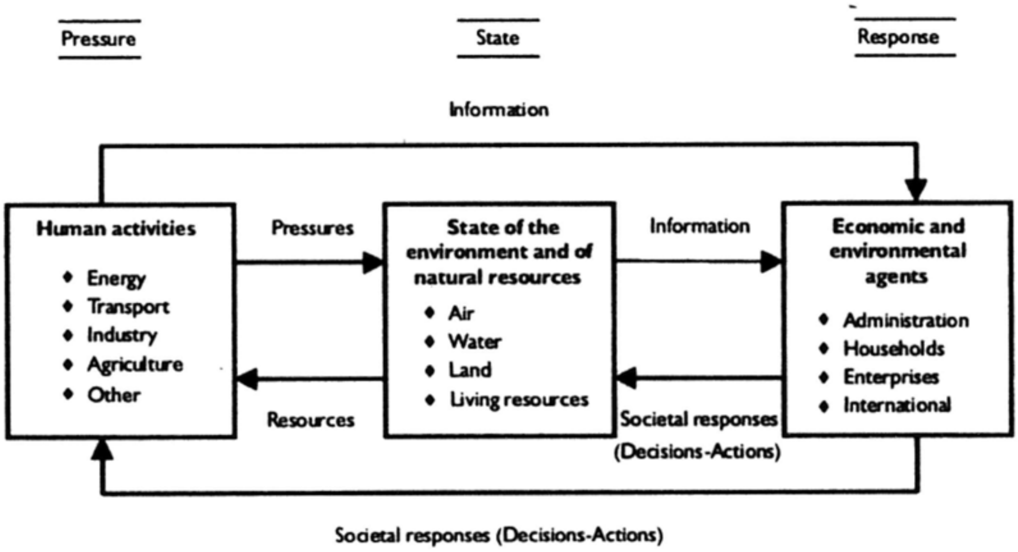

Figure 2-3 The PSR Framework (OECD, 1994)

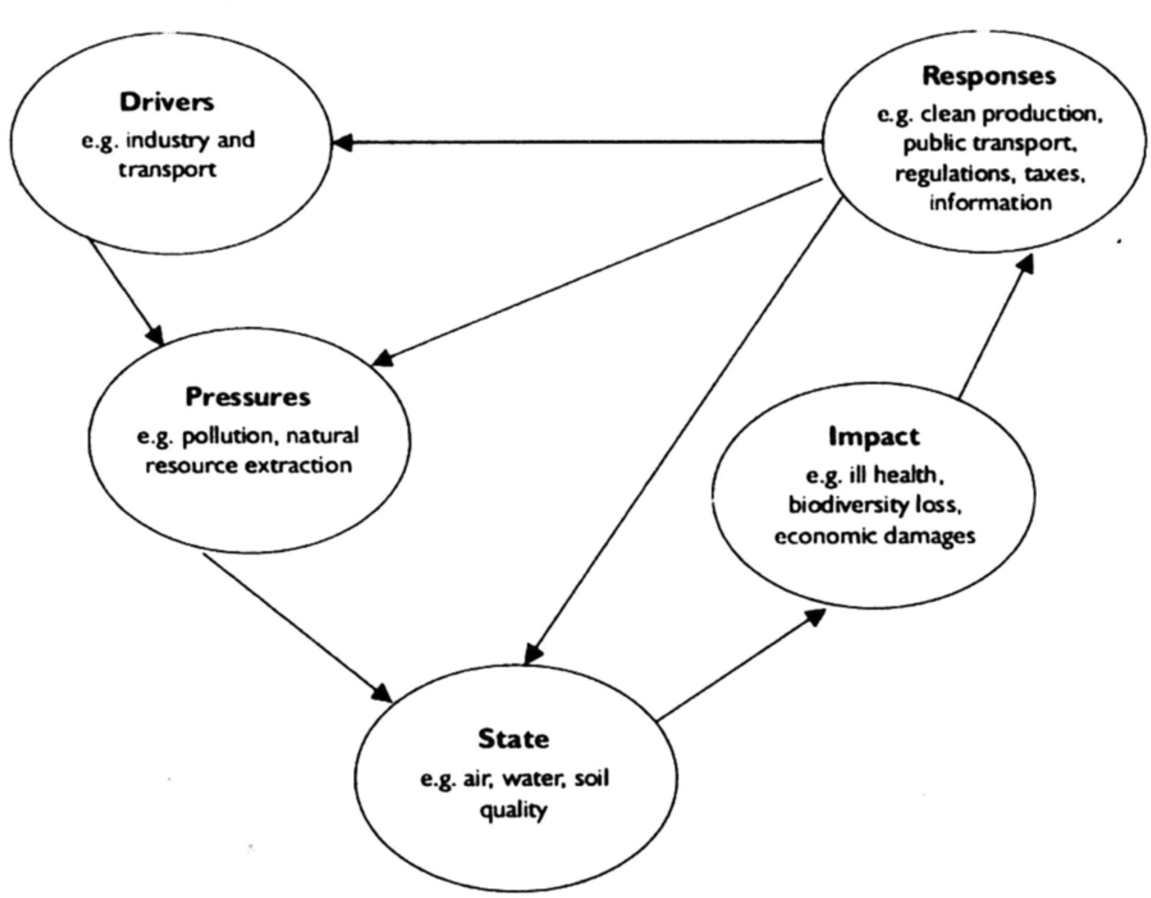

Figure 2-4 The DPSIR Framework

The PSR framework initiated by United Nations Commission for Sustainable Development (UNCSD) was seldom utilized by testing countries and was hence eventually discarded. Subsequently, the indicators selected were organized according to Major Areas, Themes and Sub-themes.

As for the production of UNCSD, the indicators are from the four primary dimensions of sustainable development namely social, economic, environmental, and institutional. Using this framework, 134 indicators were developed by UN led agencies and several other organizations. With reference to the DSR, the driving force indicators refer to the impact of human activities, processes, and patterns on sustainable development, the state indicators indicate the condition of sustainable development, and the response indicators represent societal actions towards sustainable development. This organizational framework marked a significant milestone in the efforts to identify and select indicators.

The detailed themes, subthemes, and the indicators are as follows:

Table 2-1 UNCSD Theme Indicator Framework from 2001

SOCIAL		
Theme	Sub-theme	Indicator
Equity	Poverty	Percent of Population Living below Poverty Line
		Gini Index of Income Inequality
		Unemployment Rate
	Gender Equality	Ratio of Average Female Wage to Male Wage
Health	Nutritional Status	Nutritional Status of Children
	Mortality	Mortality Rate Under 5 Years Old
		Life Expectancy at Birth
	Sanitation	Percent of Population with Adequate Sewage Disposal Facilities
	Drinking Water	Population with Access to Safe Drinking Water
	Healthcare Delivery	Percent of Population with Access to Primary Health Care Facilities
		Immunization Against Infectious Childhood Diseases
		Contraceptive Prevalence Rate
Education	Education Level	Children Reaching Grade 5 of Primary Education
		Adult Secondary Education Achievement Level
	Literacy	Adult Literacy Rate
Housing	Living Conditions	Floor Area per Person
Security	Crime	Number of Recorded Crimes per 100,000 Population
Population	Population Change	Population Growth Rate
		Population of Urban Formal and Informal Settlements

ENVIRONMENTAL		
Theme	Sub-theme	Indicator
Atmosphere	Climate Change	Emissions of Greenhouse Gases
	Ozone Layer Depletion	Consumption of Ozone Depleting Substances
	Air Quality	Ambient Concentration of Air Pollutants in Urban Areas
Land	Agriculture	Arable and Permanent Crop Land Area
		Use of Fertilizers
		Use of Agricultural Pesticides
	Forests	Forest Area as a Percent of Land Area
		Wood Harvesting Intensity
	Desertification	Land Affected by Desertification
	Urbanization	Area of Urban Formal and Informal Settlements
Oceans, Seas and Coasts	Coastal Zone	Algae Concentration in Coastal Waters
		Percent of Total Population Living in Coastal Areas
	Fisheries	Annual Catch by Major Species
Fresh Water	Water Quantity	Annual Withdrawal of Ground and Surface Water as a Percent of Total Available Water
	Water Quality	BOD in Water Bodies
		Concentration of Faecal Coliform in Freshwater
Biodiversity	Ecosystem	Area of Selected Key Ecosystems
		Protected Area as a % of Total Area
	Species	Abundance of Selected Key Species

ECONOMIC		
Theme	Sub-theme	Indicator
Economic Structure	Economic Performance	GDP per Capita
		Investment Share in GDP
	Trade	Balance of Trade in Goods and Services

	Financial Status	Debt to GNP Ratio
		Total ODA Given or Received as a Percent of GNP
Consumption and Production Patterns	Material Consumption	Intensity of Material Use
	Energy Use	Annual Energy Consumption per Capita
		Share of Consumption of Renewable Energy Resources
		Intensity of Energy Use
	Waste Generation and Management	Generation of Industrial and Municipal Solid Waste
		Generation of Hazardous Waste
		Management of Radioactive Waste
		Waste Recycling and Reuse
	Transportation	Distance Traveled per Capita by Mode of Transport
INSTITUTIONAL		
Theme	Sub-theme	Indicator
Institutional Framework	Strategic Implementation	National Sustainable Development Strategy
	International Cooperation	Implementation of Ratified Global Agreements
Institutional Capacity	Information Access	Number of Internet Subscribers per 1000 Inhabitants
	Communication Infrastructure	Main Telephone Lines per 1000 Inhabitants
	Science and Technology	Expenditure on Research and Development as a Percent of GDP
	Disaster Preparedness and Response	Economic and Human Loss Due to Natural Disasters

Besides, other successful indicator systems are available, for instance, the online directory of "sustainable development indicators initiatives". This online directory is maintained by the International Institute for Sustainable Development (IISD) and the directory included about 600 initiatives at the national and international levels by governmental and NGOs as well as by individuals.

The aforementioned indicator systems were based on the comprehensive aspects of sustainable development. Nevertheless, there also exist some other studies of indicators system for specific areas. The European Environment Agency (EEA) published the "environmental issues" and "environmental headline" indicators in the context of sustainability within Europe. Hellstrom *et al.* (2000) also built a framework for system analysis of sustainable urban water resource management. With respect to the indicators of land use sustainability, there have also been some related studies: The indicators of sustainable land use by Haberl and Schandl (1998) were based on the analysis of society-nature interrelations and their implications for sustainable development. Siko (2007) developed the indicators system for sustainable urban planning in his thesis research.

The aforementioned indicators aid understanding and extracting the objectives pertaining to land use planning in the context of sustainable development. However, the establishment of the systematic objectives entails meticulous analysis based on not only the specific domain but the study area as well.

2.1.3 Sustainable land use planning

The earlier sections have dwelled in-depth over the definition and the contents of sustainability and the general indicators. Thus, comprehending the sustainability on land use planning, which is a kind of multi-objective spatial problem, should not be very hard.

The term sustainable land use planning denotes two major areas: land use planning and sustainable development. Land use planning deals with the active planning of future land use by people to support their needs. The land use types to be allotted can be diverse, such as industrial production sites, residential zones, scenic landscapes and green spaces, ecosystems for natural flora and fauna, etc.

Of late, sustainability and sustainable development have been hot research topics. The well-known Brundtland Commission (WCED, 1987) defined it as a "development that meets the need of the present without compromising the ability of future generations to meet their own needs" (P.43). In more detail, sustainable development is understood as a process of change in which the exploitation of resources, the direction of investment, the orientation of technological development and institutional change all are in harmony by Brundtland Commission. It is obviously the direction of development.

Sustainable development, thus defined, is an important goal for land use planning, which yields the term "sustainable land use planning". The term Sustainable land use planning has to be based on the meaning and descriptions of present practices in land use planning as well as on the notion of sustainable development.

Sustainable land use planning embraces several aspects as given in following figure:

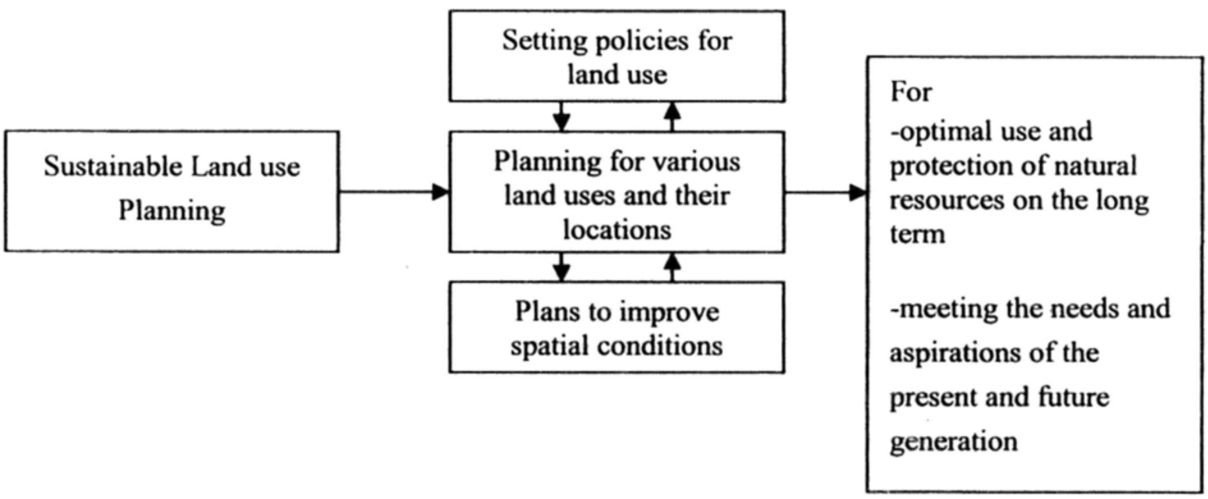

Figure 2-5 Contents of Sustainable Land Use Planning (vanLier, 1994)

In this context, sustainable land use planning can be defined as instruments to set land use policies, to implement these policies for the right location of the various land uses and for the improvement of the spatial and physical conditions for an optimal use and protection of the natural resources on the long term while meeting the needs and aspirations of the present generations (vanLier, 1994).

Briefly stated, the essential notion behind sustainable land use planning is the decision making pertaining to the location (where) and proportion (how much) of allocation of specific land use activities. Importantly, this has to be in a judicious tradeoff rooted in the three focal elements of sustainable development: economy, society, and environment.

Besides these three general goals of sustainable development on land use planning, some detailed and practical aspects should also be worked out during the sustainable land use planning process. Evidently, such an overall goal can be understood from several perspectives. A vast majority of the literature on sustainable urban development and spatial planning in wealthy and industrial countries (OECD, 1994; UN, 1998) emphasize the following elements:

(1) Minimizing energy use and emissions per capita in the area (city, municipality, or region) down to a level compatible with the ecological and distributional criteria for sustainable development at a global level.

(2) Minimizing the conversion of and encroachments on natural areas, ecosystems and soil resources for food production.

(3) Minimizing the utilization of environmentally harmful construction materials.

(4) Replacing open-ended flows, where natural resources are transformed into waste, with closed loops relying to a higher extent on local resources.

(5) Building a sound environment for the city's inhabitants, without pollution and noise, which negatively impact people's health, and with sufficient green areas to give opportunities for the population to experience nature (Næss, 2001).

2.2 Land Use Planning Support

As mentioned earlier, land use planning is a form of spatial decision making that entails the detailed analysis of a complex set of geographical information. Within the domain of land use planning support, land use optimization, which could be divided into structural optimization and spatial optimization, could reflect the process of planning support.

The regulatory land use PSSs play a critical role in the aforementioned steps. Given the nature and characteristics of land use planning, GIS, PSS, Multi-Attribute

Decision Analysis (MADA) and Multi-Objective Decision Analysis (MODA) inside Multi-Criteria Decision Analysis (MCDA) could be involved into this process.

2.2.1 PSS

PSS is a subset of computer-based geo-information systems, each of which incorporates a unique suite of components that planners can utilize to explore and manage specific activities. PSS assists the planning process not only by communicating information but also by generating solutions. These systems include instruments relating to geo-information technology that have been primarily developed to support different aspects of the planning process, including problem diagnosis, data collection, mining and extraction, spatial and temporal analysis, data modeling, visualization and display, scenario-building and projection, plan formulation and evaluation, report preparation, enhanced participation and collaborative decision-making (Geertman & Stillwell, 2004).

PSSs are very diversified, ranging from electronic conference board rooms (group DSS) (Laurini, 1998) to Web-based mediation systems for cooperative spatial planning (Gordon *et al.*, 1997; Shiffer, 1992) and support tools for different planning tasks (Geertman, 2002; Hopkins, 1998, 1999; Kammeier, 1999; Klosterman, 1999; Singh, 1999).

More precisely, a single PSS includes three sets of components as follows: the specification of the planning tasks and problems at hand, such as data assembly; the system models and methods that inform the planning process through analysis, prediction, and prescription; and the transformation of basic data into information which in turn provides the impetus for modeling and design (cyclic) (Harris & Batty, 1993).

The following discussion briefly lists numerous successful PSS: The so-called PSSD is dedicated to support the tasks of professional planners in the Baltic Sea Region to enhance the sustainability of their policies (Hansen, 2001). The New Jersey Growth Allocation Model, known as GAME, developed by the New Jersey Office of State Planning (Reilly, 2002), is a PSS designed for interactive use that identifies the implications of certain trend-based or plan-based land development scenarios. MIGMOD is another example of a PSS that deals with strategic planning support at a national level. It is a prototype internal migration modeling system that was built for the Department of Transport, Local Government and the Regions (DTLR) in the UK by a consortium of researchers from the Universities of Newcastle and Leeds (Champion *et al.*, 2002; Minister, 2002).

In this study, the target is to develop a kind of PSS to compromise different objectives of land use planning towards sustainable development, which would supply not only optimal land use planning scenarios, but also offer friendly interactive operations.

2.2.2 GIS

In general, A GIS may be defined as a computer-based information system that captures, stores, manipulates, analyzes, and displays spatially referenced data and associated tabular attribute data for solving complex research, planning and management problems (Fisher & Nijkamp, 1992).

By and large, land use planning is a spatial data business as almost all kinds of planning data are inherently related to spatial location. GIS tools linked to an integrated database of the basic social, economic and environmental information enable the planners to conduct exploratory spatial analysis for land use development. Furthermore, GIS offers the possibility of supporting sophisticated decision-making related to land use planning.

GIS has undergone rapid development since the first true GIS, the Canada Geographical Information System (CGIS), was created in 1966. GIS has moved from being primarily concerned with the spatial data processing in 1960s to managing the geographical information in 1970s, and to the step of supporting a spatial decision making in 1980s. Since the 1990s, GIS has incorporated powerful relational database management systems and presentation algorithms. This has paved the way for numerous spatio-analytical operations such as buffering, overlaying, interpolating, zoning, network analysis as well as the friendly interface to support the spatial problem-solving (Fisher & Nijkamp, 1992). Besides, the computer hardware also has improved a lot since 1980s with major breakthroughs in cost, speed, and data storage capacity. Aided by concurrent developments in GIS software, GIS technology has become extremely accessible, user-friendly, and economical. The use of GIS for complicated spatial problem-solving, including land use planning support, has become a widespread practice.

GIS is currently being extensively utilized at the local, regional, and national levels for various administrative procedures. GIS offers numerous functionalities to integrate graphical, numerical and textual information, for performing spatial analysis and modeling. GIS aid visualizing spatial information, which is of immense value to planners and decision-makers in the field of land use planning support.

Several aspects of the land use planning process can be supported by GIS:

1) Decision support of planning

During the process of planning, the main usage of GIS is for spatial data management, and spatial analysis. In addition, the visualization functions, serve as a valuable aid in the process of planning. In order to make the planning process more logical some GIS applications integrate the professional planning module with the comprehensive analysis module. Thomson and Hardin (Thomson & Hardin, 2000) exploited GIS and remote sensing to search and find low-income residential areas based on the comprehensive analysis of the related social and economic information, land use data, public facilities, and roads etc. Various other applications are available to demonstrate the capabilities of GIS for storing and analyzing spatial data for the preparation prior to the planning process.

2) Management of planning

Typically, various administrative functions of the governmental agencies are linked to the geographical location. In USA, GIS has been used widely in governmental functions, and the proportion of cities using GIS increased from 40% in 1992 to 87% in 1997 (Esnard, 1998). Somers (1991) introduced GIS applications in Virginia, which mainly focused on planning management. Fairfax started the application of GIS from the early 1980s. At the beginning, GIS was used only for graphic-related functions. However, subsequently more comprehensive and powerful GIS was developed including 75 levels of data such as the geo coding, roads, population, planning zones, land use etc. The planners could very easily query the planning and other related information for management. In the meantime, the real-time development data could also be entered into the system to offer a quick, efficient, and effective management tool for informed decision making.

3) Public participation

It is very meaningful and important to consider the opinion from the public when undertaking any land use planning exercise. Such public participation in the planning exercise had made possible by combining GIS with World Wide Web (WWW). (Kodmany, 2006) applied this notion in Pilsen, Chicago, and took advantage of GIS and WWW technologies to survey the public opinion to support planning and decision making. The residents could observe 2D as well as 3D visualization planning scenarios through internet and submit their own opinions into the web system. Based on the opinions obtained from various aforementioned planning agents and authorities, the revised planning scenarios were published in real time in order to facilitate exchange of opinion between government officials and the public.

2.2.3 MCDA

MCDA, sometimes also named as Multi-Criteria Decision Making (MCDM), is a discipline aimed at assisting decision makers who faced with conflicting evaluations. MCDA and MCDM endeavor to highlight these conflicts and arrive at a compromise. The land use planning support could be considered as a procedure in MCDA. GIS-based MCDA (GIS-MCDA) can be very helpful in the overall land use planning support process.

These two distinctive areas of research, GIS and MCDA, can benefit from each other (Chakhar & Martel, 2003; Malczewski, 1999; Thill, 1999). Indeed, GIS is often recognized as a decision support system involving the integration of spatially referenced data in a problem solving environment (Cowen, 1988). In brief, GIS-MCDA can be thought of as a process that transforms and combines geographical data and value judgments (the decision-maker's preferences) to aid informed decision-making. Numerous well-established GIS-MCDA (Banai, 1993;

Carver, 1991; Chakhar & Martel, 2003; Church *et al.*, 1992; Diamond & Wright, 1988; Eastman *et al.*, 1995; Feick & Hall, 1999; Heywood *et al.*, 1995; Jankowski, 1995; Janssen & Rietveld, 1990; Malczewski, 1999; Thill, 1999) are available today.

The generation of planning alternatives can be accomplished by two kinds of operations: MADA and MODA, which are two categories of MCDA. According the early scholars' research (Goicoechea *et al.*, 1982; Hwang & Yoon, 1981), the multi-attribute decision problems are assumed to have a predetermined, limited number of alternatives, while the multi-objective problem is continuous. The term continuous refers to the fact that the best solution may be found anywhere within the region of feasible solutions. Consequently, multi-attribute and multi-objective problems are sometimes referred to as discrete and continuous decision problems respectively.

A review of the two MCDA categories (Malczewski, 2006) revealed that GIS-MADA constitute the major category, almost 70% (Banai, 1993; Eastman *et al.*, 1995; Feick & Hall, 1999; Jankowski, 1995; Jun, 2000; Kyem, 2004; Malczewski, 1996). More than 30% of the approaches fall into the GIS-MODA category (Aerts *et al.*, 2003b; Aerts & Heuvelink, 2002; Antoine *et al.*, 1997; Armstrong *et al.*, 2003; Gomes & Lins, 2002; Stewart *et al.*, 2004; Xiang, 1993; Xiao *et al.*, 2002).

Both the two approaches have pros and cons. During the land use planning support process, the prominent advantages of the MADA approach, a data-oriented method, are its simplicity when dealing with classification and weights setting and the efficiency of the operation. The lack of the ability to generate and compare the alternatives is a disadvantage. The MODA, considered a process of Multi-Objective Optimization, does better in compromising different objectives and in generating and comparing large number of land use planning scenarios. It is more proper to simulate the negotiation process of land use planning by looking for the tradeoffs between different conflicting objectives. However, the most essential limitation of this approach is the efficiency of the spatial optimization methods especially when the increasing of the objectives and the research area.

In this research, one kind of appropriate MODA process is integrated within the research model to guide the land use planning towards the objectives of sustainability. Of course, the definition and translation of the objectives of sustainability and the effective and efficient optimization model based on GIS, PSS, and MODA would still be the key issues.

2.2.4 VR

VR (3D) is a technology, which allows users to interact with a computer-simulated environment and this environment can be a simulation of the real world or a hypothetical representation. The characteristics of VR include Immersion, interaction, and imagination. VR applications in architecture and engineering eventually led to its application within land use planning. However, this kind of utilization used to focus on the animation made by CAD and 3DMAX, which is not real time and interactive. After that, there are also lots of successful examples utilizing virtual reality to build a 3D environment. Using such environments, planners and decision-makers can perform detailed analysis using the characteristics of interaction and immersion. Besides, most of this kind of applications for land use planning support is belong to non-immersion type owing to limitations imposed by costs and infrastructure. Besides, it is also a useful tool in facilitating public participation, as such environments are comparatively easier and intuitive than 2-D planning scenario maps. However, there has always been a conflict between the details of the 3-D model and the efficiency of rendering even when employing some good methods such as Level of Detail (LOD), pyramid etc.

Therefore, for the real time land use planning support, simplified 3D models should be used to represent the architectures and the land use types. However, it is not possible to completely assume the embodied buildings or facilities. In view of the fact that land use planning support does not need so many details for the objects, it should suffice to employ some simplified 3D models to visualize the optimal land use planning scenarios.

Several applications in the domains of urban simulation and land use planning have been successfully implemented using VRML, Vega, OpenGL, DirectX, etc. Chandramouli *et al.* (2009) have successfully applied VRML to the representation of planning scenarios on the Pareto Front in the context of a vector based optimization problem.

Summarily, 3D visualization can actively support the process of land use planning with its characteristics and is utilized in this research in the form of simplified 3D models built using efficient programming and rendering languages.

2.3 Sustainable Land Use Optimization

During the sustainable land use optimization process, multi-objective optimization should be the effective land use planning support tool to help the planning process after combining the comprehensive objectives of sustainability on land use planning and the effective and efficient optimization models.

There are two key steps in generating the optimal scenarios of sustainable land use optimization: the first one is the selection of the objectives for land use sustainability. The translation and evaluation of these objectives are also very important. The next crucial step is the construction of efficient models for spatial multi-objective optimization.

2.3.1 Selection of objectives

With regards to the multi-objective problem, land use planning for sustainable development includes the same objectives discussed earlier under sustainability: economy, society, and environment. Several related researches pertaining to the definition of the objectives have been done in the past. Leccese and Mccormick (2000), in the "Charter of the New Urbanism", described a sustainable land-use planning agenda. Their manifesto emphasized infill development, environmental protection, compactness, and local geography as the main elements of a balanced urban development. Balling (1999) thought that the primary target is the minimization of traffic congestion, followed by air pollution control, affordable housing, maximization of economic development, minimization of taxes and fees, conservation of historical and cultural sites etc. Even though this seems quite comprehensive, some of these are quite hard quantify. Wang *et al.* (2004) considered the economy, forest cover, soil loss and water quality including nitrogen loss, phosphorous loss and

Chemical Oxygen Demand (COD) discharge as the objectives in his research. Ligmann-Zielinska *et al.* (2008) focused on the utilization of urban space through infill development, compatibility of adjacent land uses, and defensible redevelopment to pursue the objective of sustainability. Even though various other scholars and researchers have considered several other factors, by and large, discussions related to objectives representing sustainability invariably seem to consider economic benefit as a foremost goal. Besides, social and environmental aspects also are considered to be very important driving forces of sustainable development. Besides, in view of the spatial nature of such problems, the compactness and compatibility have also been frequently mentioned by some scholars. In this study, all the aforementioned aspects are considered.

Overall, the objectives aimed at sustainable land use planning could be listed as follows: 1) infill development; 2) compatibility of adjacent land uses; 3) defensive development; 4) the cost distance to urbanized area; 5) Compactness (Contiguity); 6) minimize the traffic congestion; 7) maximizing economic return; 8) maximizing carbon sequestration; 9) minimizing soil erosion etc.

All the aforementioned aspects for the sustainable land use optimization provide the planners or policy makers with broad suggestions or tools to aid sustainable land use planning. Nonetheless, for each case study, the authors have their own opinions and considerations when defining the objectives, which might not be comprehensive but should be sufficient to make a progress on the road to sustainable land use optimization. In this research, more comprehensive considerations on sustainable land use, also referring to all the contributions from earlier works, are explained and used to build one comprehensive sustainable land use planning support tool.

2.3.2 Optimization models

In the past, various kinds of multi-objective problems including land use optimization were solved by LP approaches. The increasing sophistication of LP and faster computers enabled such problems to be handled in accordance with a single objective. Undeniably, even for multi-objective problems, tradeoffs can be obtained by LP approach by combining objectives in setting the suitable weights. Chuvieco, Arthur and Aerts have integrated LP with GIS to undertake spatial land use planning (Aerts *et al.*, 2003a; Arthur & Nalle, 1997; Chuvieco, 1993; Stewart, 1991, 1993; Zimmermann, 1978). However, quantifying the relative weights for each of the objectives is a challenging task for the planners.

A method named "Pareto Front Optimal", derived from Pareto's original work (first published 1896; see (Pareto & Page, 1971), can be used to avoid setting the weights for different objectives The primary characteristic of the Pareto set is its independence of the relative importance of all the objectives. It is very popular owing to its ability in solving multi-objective spatial optimization problems (Balling *et al.*, 1999; Chandramouli *et al.*, 2009; Xiao *et al.*, 2002). However, the planning process is also complicated by the presence of an exponentially large number of variables. Suppose a city has 400 units with 5 possible land use types for each unit, then the number of possible land use plan is 5^{400}. It is impossible for planners to work out and assess all the plans.

This discussion elaborates the need for more efficient methods for land use optimization. A gradual switch can be observed from strict optimization to the use of heuristics to help in the interactive design of the optimal solutions. Aerts *et al.* (2003b) employed SA for land use planning within the context of multi-objective *LP*. The density-based optimization model created by Ligmann-Zielinska to obtain the sustainable land use patterns was based on HSJ method. GA, first introduced by Holland (1975), is also an effective heuristic method. GAs has been successfully used to search complex solution spaces in a variety of application domains (Goldberg, 1989; Malczewski, 1996). Balling *et al.* (Balling *et al.*, 1999) used GA to solve vector based urban planning problems. Besides, Stewart *et al.* (2004) also have taken advantage of general GA to multi-objective land use planning field in a small research area base on grid. However, even for the heuristic methods, the efficiency tends to deteriorate with increasing objectives and area. For grid sizes more than 100 by 100, the efficiency can reach unacceptable levels in both single objective based method and Pareto front based method (Datta *et al.*, 2007; Janssen *et al.*, 2008).

This research, hence, not only considers the comprehensive objectives for sustainable land use development, but also takes into account the efficiency of the spatial optimization model.

2.4 Approaches for Land Use Optimization

For multi-objective problems, the objectives are usually conflicting, and the objectives cannot be satisfied simultaneously. The solutions are based on the construction of the evaluation function for the multi-objective problem. There are two general approaches to solve multi-objective optimization, which are based on the method of construction of the evaluation function. The first one is to combine all the objectives into a single function by some feasible methods or choose only the main objective and change other objectives to constraints. The second one involves determining and obtaining the entire Pareto front or a representative set with all the non-dominated solutions.

2.4.1 Single objective based multi-objective optimization

Single objective optimization for multiple objectives is very similar to the pure single objective optimization. Earlier research involving multi-objective optimization quite frequently used this method when dealing with multiple objectives. The use of straightforward methods and models to combine the multiple objectives together makes it easy to understand and operate.

1) Constraints method:
The principle of this method is to choose one main objective from all the objectives, and then define all the other objectives as constraints. It is comparatively easy to transform the multi-objective optimization problems to single objective optimization with constraints.

2) Stratified sequential method:
This method , which is a little complicated than the constraints method mentioned earlier, takes advantage of the subjective weights of all the objectives and then satisfy the objectives one by one based on the sequence of the weights (from larger to smaller). To some extent, this method can solve the multiple objective optimization problem. However, problems arise during the weight setting procedure. The setting of weights using subjective opinion may not reflect the real or actual weights. It is more

important to note that it is possible for the user to miss some optimum through this process.

3) Efficiency coefficient method:

The key notion behind this method is to normalize the objective functions, and take the sum of all the objective functions as the final objective. This makes it more feasible to reflect the weights the users want to set, however the normalization process and the minimization and maximization of each objective are also hard to decide without systematic analysis of the objective.

4) Ideal/Utopian point method

This principle of this method is to determine the point that is the closest one to the ideal/utopian point. Nevertheless, problems exist in the process of defining the ideal/utopian point and the choosing weights for the evaluation of the objectives.

5) Linear weighted sum method

This method involves the creation of an evaluation function by the sum of weights setting for each objective. Despite its simplicity of operation, the subjective setting of weights and the non-normalization of objective can introduce some wrong solutions to the final optimum.

6) Min-Max/Max-Min method

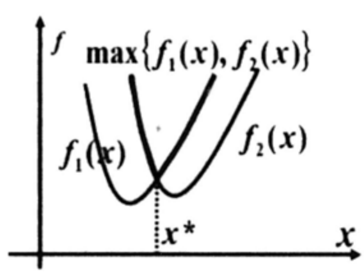

Figure 2-6 Max-Min Method for Multi-Objective Optimization

The principle of Min-Max method is to find the best strategy based on the pessimistic solutions, on the contrary, Max-Min is to find the worst strategy based on the optimistic solutions.

7) Multiply& Divide method

The target of the method is to construct an evaluation function by multiplying and dividing all the objectives, it is easy to realize but with lots of limits for using.

8) Goal programming

This is a commonly known technique to aid to solve multi-objective optimization problems, the formula is as follows (Janssen et al., 2008):

$$\sum_{q=1}^{Q}\left[\frac{f_q(x)-I_q}{\lambda_q-I_q}\right]^{\rho} \tag{2.1}$$

In this equation above, q is the index of each objective, $f_q(x)$ is the evaluation I_q is the best possible ideal value for each objective if optimized on its own, λ_q is the worst value of each objective, and ρ is a suitably large power. If the $\rho=1$, it can be considered as the sum of each normalized objective using the same weight, if the $\rho=2$, it can be understood as the related Euclidean distance's square to the ideal point, and very similar to the ideal point method without weight setting. If the $\rho=3...\infty$, it is the high dimension distance's power ρ to the ideal point. Sometimes, the high dimension can result in better results. The normalization in this method is certain to give more equal preference to each objective and yield a balanced optimal result at last. However, similar to the ideal point method, defining the reference point here is also the problem for the user. Besides, it can only yield the result with the same preference but all the optimal results.

Of course, there are also some other methods to integrate multiple objectives into one objective, such as the Compromising Programming, Weighted Sum of Squares etc. All of them are similar to each other, and actually, sufficient systematic experimentation with different weights can identify all non-dominated solutions to a convex multi-objective optimization problem (Miettinen, 1999). However, this does is not quite meaningful when in the context of non-convex multi-objective optimization problems. This kind of problems could be solved by Pareto front based multi-objective optimization methods and non-linear combination of single objective based multi-objective optimization methods.

2.4.2 Pareto front based multi-objective optimization

Hitherto, most of the multi-objective optimization methods were based on the principle of constructing a single objective from all the objectives. Besides, the second general approach involved determining an entire Pareto optimal solution set or a representative subset. A Pareto optimal set is a set of solutions that are non -dominated with respect to each other. By this method, the maximum optimal results can be obtained with different preference to all the objectives, from one solution to another solution on the Pareto front. However, this involves some tradeoff in one objective(s) to achieve certain amount of gain in some other objective(s).

2.4.2.1 Pareto Ranking

Pareto ranking, first proposed by Goldberg (Goldberg, 1989), was the essential part of the optimization method.

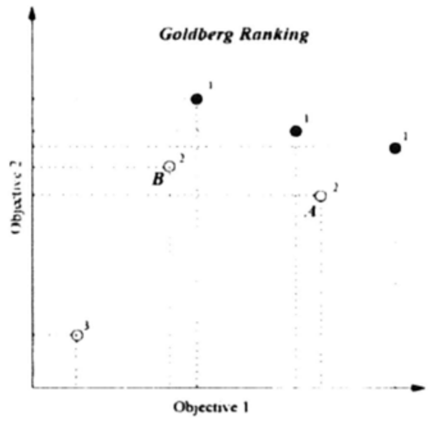

Figure 2-7 Pareto Ranking Paradigm

According to Goldberg's ranking, the non-dominated solutions are assigned the best ranking of one, following which these are removed from the consideration. The process is continued for the remaining solutions, and the new non-dominated solutions are set to rank two, and the iteration is continued until all solutions are ranked. Fonseca & Fleming's ranking (1995) is the count of the number of solutions that dominated it, and non-dominated solutions have the rank zero.

2.4.2.2 Diversity mechanism

While the use of Pareto ranking selection can guarantee the selection class of solutions by different rank number, it is not sufficient to ensure clear distribution of all solutions. Normally, the diversity mechanism can be integrated in the ranking process to distribute all the solution. Niche-based sharing approach, cell based density, and crowding distance are some approaches to accomplish this.

2.4.3 GAs for Multi-objective Optimization

The land use planning process, a kind of non-deterministic Polynomial hard (NP-hard) is characterized by spatiality, non-linearity, and existence of non-convex solutions. As a kind of NP hard problem, it is impossible to compare all the possibilities to obtain the optimum during the spatial optimization process. Heuristic approaches are effective in handling such uncertain non-convex problem involving non-linear optimization. A heuristic is defined as an iterative generation process which guides a subordinate heuristic by combining intelligently different concepts for exploring and exploiting the search space, in order to find the near-optimal solutions efficiently (Osman & Laporte, 1996).

Numerous successful examples of heuristic approaches could be found from earlier research by scholars. Such examples include Basic Local Search Approach, SA (Kirkpartrick *et al.*, 1983), Tabu Search, Variable Neighborhood Search, GA (Holland, 1975), Ant Colony Optimization (Dorigo, 1992). Every approach has its advantages and disadvantages. Considering the theme of this research, multi-objective sustainable land use optimization, GA is found to be more suitable for this kind of problem because of its mechanism and other researchers' experiences.

2.4.3.1 GA

The concept of GA was developed by Holland and his colleagues in the 1960s and 1970s (Holland, 1975). GA are rooted in the 'theory of evaluation' explaining the origin of species. During the GA process, the worst and unfit species are faced with extinction by selection. The better and stronger ones survive, and will become dominant in their population. Subsequently, these join to reproduce and yield better solutions by combining fitter elements from the earlier population.

As for GA terminology, one solution vector x is called an individual or a Chromosome, which is in turn made of discrete genes. In the early implementation of

GA by Holland, genes were assumed to be binary digits. Generally, one chromosome is related to a unique solution x in the solution space, and the relationship between the two parts is called encoding. It also can be understood as the representation of the problem in GA, which is a very important part of the overall GA procedure. A good encoding approach can yield better effect and efficiency. A typical GA process involves a collection of chromosomes, called 'Population', which is normally created randomly. Sometimes, the initial population in a GA will influence the efficiency of the algorithm. The solutions in the population get better and better iteration by iteration and the final optimal result can be found within the last population. GA also has two essential operators: Crossover operator and Mutation operator. In crossover, generally two chromosomes, named parent solutions, will be combined and random parts of every two chromosomes are exchanged with certain probability to generate the new chromosome (Offspring). Through the process of crossover, the better or fitter chromosomes will be chosen to generate a better offspring population, eventually leading the process to converge to overall good solutions. Mutation operator is also very important during the iteration process as it is used to introduce the random changes into the chromosomes. Generally, the rate of mutation is very small and depends on the length of the chromosome. The control of the mutation rate is also very essential in the iteration process. Good mutation setting can bring the iteration out of local swinging and can aid faster convergence. Reproduction also includes the selection of the population for next iteration, the fitness function definition is usually used to determine the choice of the next generation. Proportional selection, ranking, tournament selection and roulette wheel selection are the most popular selection methods. Chapter 5 provides a more detailed explanation of the GA process.

2.4.3.2 MOGA

A generic multi-objective GA can be modified to find a set of multiple non-dominated solutions in a solutions space, which maybe convex or non-convex, continuous or discontinuous. As discussed earlier, the multi-objective optimization methods could be divided into single objective based methods and Pareto front based methods. The former involves searching certain optimal solution on the Pareto front along with a certain direction, while the latter consists of searching all the optimal solutions on the Pareto front. During the optimization process, the appropriate representation method, selection, crossover, and mutation operators would greatly enhance the ability of GA to explore the complicated Pareto front.

Numerous successful examples of multi-objective optimization with GA are available. The first multi-objective GA, called vector evaluated GA (VEGA), was proposed by Schaffer (Schaffer, 1985). Subsequently, several multi-objective evolutionary approaches were generated including MOGA (Fonseca & Fleming, 1993), NPGA (Hajela & Lin, 1992; Horn *et al.*, 1994), Weighted based Genetic Algorithm (WBGA) (Hajela & Lin, 1992), RWGA (Murata & Ishibuchi, 1995), NSGA (Srinivas & Deb, 1994)(, Strengthen Pareto Evolutionary Algorithm (SPEA) (Zitzler & Thiele, 1999), Improved SPEA (SPEA2) (Zitzler *et al.*, 2001), Pareto-Archived Evolution Strategy (PAES) (Knowles & Corne, 1999), Pareto Envolope-based Selection Algorithm (PESA) (Corne *et al.*, 2000), Region-based Selection in Evolutionary Multi-objective Optimization (PESA-II) (Corne *et al.*, 2001), NSGA-II (Deb *et al.*, 2002), Multi-Objective Evolutionary Algorithm (MEA) (Sarker *et al.*, 2002), Mircro-Genetic Algorithm (Micro-GA) (Coello & Pulido, 2001), Rank-density Based Genetic Algorithm (RDGA) (Lu & Yen, 2003; Yen & Lu, 2003), Dynamic Multi-Objective Evolutionary Algorithm (DMOEA) (Yen & Lu, 2003), Multi-objective Evolutionary Algorithm Based on Decomposition (MOEA/D) (Zhang & Li, 2007)etc.

All the models listed above were tested in many applications and yielded good performance. These models have focused on different aspects of multi-objective optimization, such as the diversity, fitness function, elitism etc, which mutually influence each other, and the effect and efficiency of the optimization. Each of these problem-specific models has their own advantages and disadvantages.

Some applications of MOGA can also be cited within the realm of sustainable land use planning. Matthews (2001) used MOGA for vector-based land use planning. However, the vector representation limited the diversity of the solutions and required the vectors to be distributed. Datta *et al.* (2007; OECD, 1994; UN, 1998) used multi-objective evolutionary algorithm to solve land use management problem while considering three objectives. Janssen *et al.*(2008) took advantage of GA for land use planning support using the interactive operation on a small area (20 by 20 cells). However, when research area includes 10000 or more cells, the time consumed reached almost dozens of hours which is not acceptable. It is also the main obstacle of the development on the land use planning support of this kind of model.

While considering the specifics of multi-objective spatial optimization pertaining to a large research area, serious limitations can be observed in the existing optimization models both in terms of the effect and the efficiency. We need a more comprehensive, pragmatic, and efficient optimization model to realize an efficient PSS, which is the main research target in this thesis.

2.5 Summary

In recent years, sustainable development has been widely recognized as a critical element of land use planning. Sustainable development endeavors to strike a balance between economic development and environmental conservation whilst advocating social equity. This chapter focused on the introduction, explanation, and the review of related concepts and models including sustainable development, land use planning, land use planning support, sustainable land use optimization, approaches of optimization etc.

In the first part of this chapter, the definition of sustainable development, the indicators and the sustainable land use planning were covered in a detailed manner. Considering the three main aspects of sustainability, the planning process can be channelized by exploiting the indicators of sustainability while performing the comprehensive and quantitative analysis.

In the second part, land use planning support was introduced based on the analysis of the three related concepts: PSS, GIS and MCDA. PSS, which are used to support the planning process by communicating information as well as by generating solutions, supply the planners or policy-makers with the user-based practical support system. With powerful spatial data processing capabilities, GIS technology holds great potential to support the land use planning process. With the ability to manage a diverse set of spatial information, GIS serves as an excellent tool for the planning process. GIS tools enable planners to conduct exploratory spatial analysis for land use development. Furthermore, GIS is capable of supporting a sophisticated decision-making system to facilitate land use planning. MODA, which is one of the two approaches derived from MCDA, is closer to the scheme of the land use planning process. GIS based, PSS guided MODA will be integrated to research model in order to guide the land use planning towards the objectives of sustainability.

In the third part, sustainable land use optimization was introduced from the perspectives of selecting the objectives and the optimization models, which are the main research targets of this thesis. Most of the optimization models from LP to heuristic optimization approaches on land use planning or some other related fields were reviewed and the need for an efficient heuristic model to operate this kind of spatial optimization problem was established.

Finally, the multi-objective optimization approaches, especially for land use optimization were reviewed in detail. Many MOGA models pertaining to land use planning applications were reviewed. The limitations of the general approaches were elaborated and subsequently, the appropriateness of the heuristic approaches for this study was explained. GA was chosen eventually because of its scheme, solution searching capability, and efficiency.

CHAPTER 3: GENERAL OBJECTIVES OF SUSTAINABILITY ON LAND USE PLANNING AND MODEL FORMULATION

This chapter focuses on the general description of the objectives for sustainable land use planning as well as the MOLU model formulation. The chapter starts with the description of the general objectives of sustainable land use planning based on the three main objectives: Maximization of Economic Benefit, Maximization of Environmental and Ecological benefit, and Maximization of Social Benefit. Subsequently, this chapter explains the MOLU model formulation based on revised goal programming after explaining the analysis of the translated objectives from GDP to conversion and the constraints. At last, this chapter is provides the summary of the contents.

3.1 Description of General Objectives of Sustainable Land Use Planning

As discussed earlier, sustainability is the balance among the three main aspects namely economy, environment and society. Sustainable land use planning involves allocating suitable land use types to the various locations, not only to satisfy the needs of the present or for a planned time, but also to satisfy the needs of the future.

As a kind of multi-objective problem, sustainable land use optimization is faced with the same objectives as sustainability: economy, society and environment. However, from the specific perspective of land use optimization, there must be some translations from the three main dimensions to form the operable objectives of sustainable development for land use planning.

Different planners and policy makers have different opinions about the sustainable development of the city; however, totally, all these requirements or options can be defined in the form of objectives and constraints. All these objectives can be divided amongst: 1) Maximization of Economic benefit, 2) Maximization of Environmental and Ecological benefit, 3) Maximization of Social Benefit. From the specification of the land use optimization problem, the objectives and constraints can be divided into two kinds: general objectives, which represent the structural requirements or how much to locate the special land use types and the spatial objectives, which represent where to locate such kind of land use type.

3.1.1 Maximization of the economic benefit

Different land use types could yield different economic benefits per unit. Hence, optimizing the structure and layout of different land use is considered with a view to pursue the economic benefit maximization very effectively.

On the other hand, besides earning more, it is also important to spend less to obtain the economic benefit. Also, from multiple agents' opinion, some planners may prefer to conserve the status quo of the land use, from the cost of conversion. Thus minimizing conversion could be one of the guarantees of economic benefit based on the land use planning.

3.1.2 Maximization of the environmental and ecological benefit

Environmental sustainability is the process of ensuring that the current processes of interaction with the environment are realized with the idea of keeping the environment as pristine as possible, whilst considering the natural condition, environmental, ecological capacity and resource consumption.

Effective planning entails tending to the local environment as well as the global environment (larger scale). As Daniels (2003) mentioned, the understanding of the environment helps the planner to make informed local decisions. Therefore, the suitability of geomorphologic and geological conditions is imperative to ensure safety and to reduce consumption. Besides, the ecological value for different land use types and the spatial ecological suitability also have to and can be considered in this research to prove the environmental and ecological benefit.

In order to secure the possibilities for future generations to meet their needs, current encroachments on the natural environment and consumption of non-renewable natural resources must be limited (Haavelmo & Hansen, 1991). Besides the protection of the environment and the ecology directly, the reduction of energy and non-renewable resource consumption are also meaningful for sustainable development. As mentioned earlier, effective planning should also be responsible for the global environment. Emission of greenhouse gases is a very pertinent topic in today's context of global warming. For urban area, over 80% CO_2 emission comes from the human and automobile activities (Koerner & Klopatek, 2002). Thus in order to control and decrease the consumption of non-renewable resources, factors such as accessibility and compactness should be taken into account.

3.1.3 Maximization of social benefit

Besides the aforementioned aspects, social aspect is another essential element of sustainable development. Within the realm of land use planning, the goal should be to plan an accessible, compact, compatible, and convenient community with sufficient residential area and public facilities. Thus, accessibility of transportation, compactness of land uses, compatibilities of different patches, distance to NIMBY, and the constraints of the accommodation area should be attended to.

3.1.4 Constraints

The term "constraints" within the context of land use planning refers to the "limitations". For instance, some land parcels cannot be changed or should be reserved or there is a minimal threshold (need) for a specific type of land to satisfy the future needs. Constraints also include the limitation in the area of some special land use type, the minimal or maximal limits pertaining to some special objectives etc. Besides, each cell (of land) could only be allocated only one land use type. All these limitations or constraints might increase the complexities of the optimization problem but are inevitable.

3.1.5 Summary of objectives and constraints

The objectives are listed as follows:

Maximization of GDP

Minimization of Conversion

Maximization of Geomorphology and Geological Suitability

Maximization of Ecological Suitability

Maximization of Accessibility

Minimization of "Not In My Back Yard" (NIMBY) Influence

Maximization of Compactness

Maximization of Compatibility

Subject to

Conservation Area

Minimal Need of Accommodation Area (Residential Area)

The general objective includes Maximization of GDP, and all the other objectives and constraints are related to spatial characteristics, which make the optimization more complicated.

3.2 MOLU Model Formulation

Given that the area consists of a grid with N rows and M columns and there are K different land use types' binary variable, which equals 1 when land use k is assigned to Cell (i, j) and equals 0 otherwise, is defined. Furthermore, B_{ijk} is set as the parameter of different objective and it varies with location because it depends on specific attributes of the area according to each objective.

Accordingly, for each objective function described in last chapter, all these objective are based on the grid with N rows and M columns, therefore each objective function of them can be understood as the equations as below:

$$\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{M} B_{ijk}x_{ijk} \tag{3.1}$$

Where

$\forall k = 1,\ldots,K, i = 1,\ldots,N, j = 1,\ldots,M$

$x_{ijk} \in \{0,1\}$

$\sum_{k=1}^{K} x_{ijk} = 1$

B is the parameter based on each cell for each land use type

For each objective, the MOLU model can be formulated as follows:

Minimize:

$$-\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{M} B_{ijk} x_{ijk} \tag{3.2}$$

Where

$\forall k = 1,\ldots,K, i = 1,\ldots,N, j = 1,\ldots,M$

$x_{ijk} \in \{0,1\}$

$\sum_{k=1}^{K} x_{ijk} = 1$

B is the parameter based on each cell for each land use type

Subject to:

$$\sum_{i=1}^{N}\sum_{j=1}^{M} x_{ijk} = S_k \quad \forall \mathrm{k}=1,\ldots,\mathrm{K} \quad \mathrm{L}_k \le S_k \le \mathrm{U}_k \tag{3.3}$$

$$\sum_{k=1}^{K} S_k = N.M \tag{3.4}$$

Formula (3.1) and (3.2) specify that one and only one land use must be assigned to each cell, because decision variable x_{ijk} must be 0 or 1. Formula (3.3) and (3.4) restrict the number of cells S_k allocated to a certain land use type k between the up and low bound, depicted as L_k and U_k respectively.

For the multi-objective optimization, it is a combination of the above formulae.

For weighted sum method, this can be understood as:

Minimize

$$f_{obj} = -\sum_{o=1}^{O}\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{M} \alpha_o B_{ijk} x_{ijk} \tag{3.5}$$

Where

$\forall o = 1,\ldots,K, i = 1,\ldots,N, j = 1,\ldots,M$

$x_{ijk} \in \{0,1\}$

$$\sum_{k=1}^{K} x_{ijk} = 1 \tag{3.6}$$

B is the parameter based on each cell for each land use type

α_{o} is the wights of different objectives

Subject to (3.3), (3.4)

The formulas above show that it is clearly a multi-objective problem, which entails a tradeoff involving all the objectives. While decision makers or planners know their goals, they have difficulties in valuing or weighting the relevant attributes directly. This is particularly true when each objective value has different scale. Goal programming is a commonly used method to aid decision makers with such kind of task.

A revised goal programming approach (reference point) is being used here. For each objective, the reference point is defined. Wierzbicki (1999) used a "scalarizing" function, which measures under-achievement relative to the goals. Another generally used scalarizing function can be found in the Tschebycheff approach (Steuer 1986), wherein the goal is to minimize the sum of the deviations relative to the goals defined. Another kind of scalarizing approach is employed here, which minimizes the sum of the deviations based on corresponding weights setting by users and an ideal value. This approach can be defined as follows:

$$f_{obj} = -\sum_{o=1}^{O} \alpha_o \left[\frac{f_{objo} - I_o}{T_o - I_o} \right] \tag{3.7}$$

In this formula, I_o is the best possible (ideal) value for each objective o and T_o is the worst value for each objective. This approach facilitates avoiding the uncertainty of scale difference of each objective value. Besides, this also reflects the planners' or policy maker's preference for different objectives.

3.3 Summary

This chapter initially discusses the description of the general objectives of sustainable land use planning from the perspective of the three core objectives of sustainability, i.e. Maximizing economic, environmental, and social benefit. Based on the discussion of the three main objectives, the eight sub-objectives obtained are: 1) Maximization of GDP; 2) Minimization of Conversion; 3) Maximization of Geomorphology and Geological Suitability; 4) Maximization of Ecological Suitability; 5) Maximization of Accessibility; 6) Minimization of NIMBY Influence; 7) Maximization of Compactness; 8) Maximization of Compatibility as well as the constraints: 1) Conservation Area; 2) Minimal Need of Accommodation Area.

Subsequently, the MOLU model was formulated based on these objectives and constraints using the revised goal programming approach. This could not only avoid the uncertainty of scale difference of each objective value, but also reflect the planners or policy maker's preference for different objectives.

CHAPTER 4: STUDY AREA AND ASSOCIATED OPTIMIZATION OBJECTIVES

4.1 Study Area

Tongzhou, located in southeast Beijing, is considered as the capital's eastern gate. It is at the north end of Grand Canal and the east end of Chang'an Avenue. Tongzhou is 37 km wide (from east to west) and 48 km (from north to south), covering an area of 906.27 square kilometers. This accounts for 5.55% of Beijing's total territory and 14.3% of Beijing's plain. Tongzhou has 11 towns and 4 communities, with a population of 870,000.

Tongzhou, dating back to the Xihan Dynasty, has a long history (more than 2200 years). Relics unearthed in Tongzhou indicate that human beings had lived here as early as the Neolithic Age; In 195 BC, Liu Bang, the first Emperor of Xihan dynasty, set up the county here; In 25 AD, the first year of Donghan dynasty, the emperor Liu Xiu renamed it as Lu County; In 1151 AD, when the Jin dynasty was in power, emperor King Hai Ling set up a new feudal province and renamed County Lu as Tongzhou. In 1914, Tongzhou was renamed Tong County; In 1997, with the State Council's confirmation, it was renamed Tongzhou and became one of the districts in Beijing.

Bordered by Tianjin and Hebei province, Tongzhou is at the core of Bo Sea Economic Circle. It is new to the CBD and is 13 kms from the International Trade Center, 20 kms away from Tian'anmen Square, 16 kms from the Capital International Airport, and 110 km from the Tianjin New Harbor.

In view of the city's "Double Axis[1] -Double Baits[2] -Multiple Centers[3] layout of space in Beijing, Tongzhou lies at the east end of Chang an Avenue axis, wherein lies the sustainable development zone. It is supposed to develop into the sub-center of the capital, hence assuming an essential role.

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1 ***Double Axis***: the cross formed by Beijing traditional middle line and Chang an Avenue

2 ***Double belts***: East Development Belt is from Huairou. Miyun in the north with the focus on Tongzhou and Yizhuang; West Ecological Belt includes Yanqing. Changping etc.

3 ***Multiple centers***: the comprehensive service zones including CBD, Olympic Garden, and Zhongguancun etc.

Tongzhou, famous for its convenient transportation, has been aptly named after the character "Tong" in Chinese, which means smooth connection and free transportation, . Five main roads including the Beijing-Tongzhou Expressway and the BaTong Lightrail, connect Tongzhou with the downtown of Beijing; the Sixth Ring Road brings Tongzhou and the other suburbs of Beijing together; Seven highways from Beijing lead out almost to all parts of China, and 3 of them run through Tongzhou: Beijing-Shenyang Highway, Beijing-Harbin Highway, and Beijing-Tianjin-Tanggu Highway. Beijing-Chengde and Beijing-Qinghuangdao railways also meet in Tongzhou. Besides, the Seventh Ring Road, Subway Line Five, Beijing-Shanghai High speed Railway, and Beijing-Tianjin commuter train are also under construction (Tongzhou-Government, 2010).

Tongzhou Newtown is the concentrated urban area of Tongzhou, which, in future, will become a main downtown in the east of Beijing. Being an area undergoing rapid development, intense planning operations are in place for the proper management and sustainable development of the region. Innumerable land use planning scenarios are possible, among which the BFGA-MOLU model might be efficient as a tool of PSS for the scientific evaluation of these layouts. Considering both the characteristics and the actuality of the research area and model, the simplified land use map of the area will only include five land use types for the case study of model: a) Residential land; b) Industrial Land; c) Commercial Land; d) Green land, and e) Undeveloped land. The resolution of the grid cells are set to 100m by 100m. The case study will not only show the effect of the model on the research area for land use planning support in 2020, but also exemplify the generality of the model as a sustainable land use planning support tool.

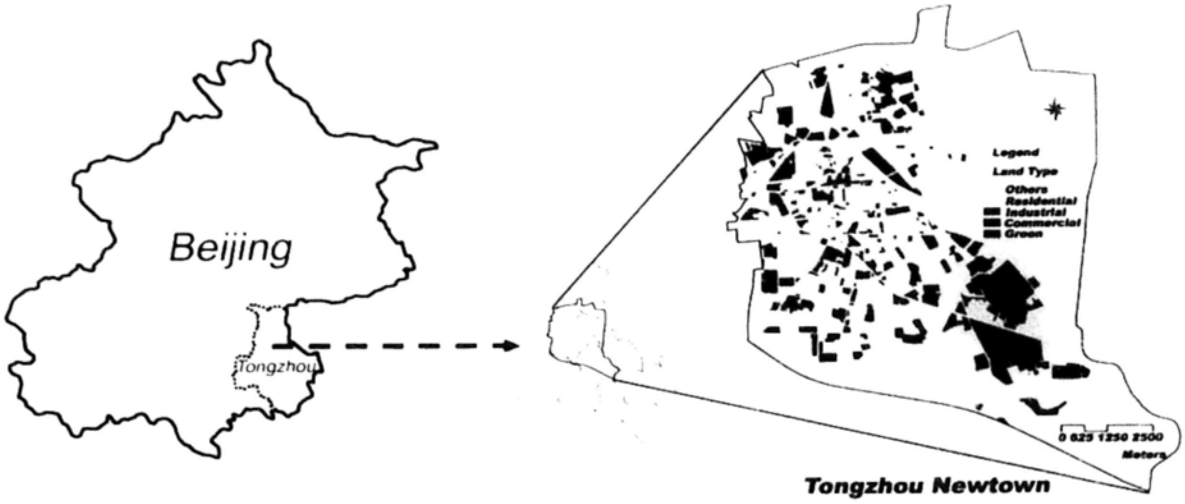


Figure 4-1 Research Area-Tongzhou Newtown

4.2 Optimization Objectives

4.2.1 GDP

The Gross Domestic Product (GDP) or Gross Domestic Income (GDI) is a basic measure of a country's overall economic output. It signifies the annual market value of all the final goods and services made within the borders of a country. In term "Gross" within "Gross Domestic Product" refers to the fact that GDP measures production regardless of the various uses to which that production can be put. "Domestic" means that GDP measures production that takes place within the country's borders. It is a common practice to correlate the GDP of a country with the standard of living, positively. GDP can be measured in three ways, all of which could yield the same result. They are the product approach, the income approach, and the expenditure approach. The product approach is the most direct one, which sums the outputs of every class of enterprise to arrive at the total. The expenditure approach follows the principle that all the products must be consumed (by somebody) and hence, the value of the people's total expenditures could reflect the economic benefit. The income approach determines GDP by finding the sum of all producers' incomes.

GDP can be contrasted with Gross National Product (GNP) or Gross National Income (GNI). The difference is that GDP defines its scope according to location, while GNP defines its scope according to ownership. GDP is product produced within a country's borders; GNP is product produced by enterprises owned by a country's citizens.

Considering the spatial characteristic of the research content, GDP is chosen as the indicator to evaluate the direct economic benefit for Tongzhou Newtown. Of course, it is not actually possible for GDP to represent the sustainable development of economy comprehensively; however, it would suffice to serve as an objective to guide the planning of the study area.

Although GDP cannot be used directly, however, different land use types yield different economic benefit(s) per unit. Of course, it is very hard to obtain the real value of each land use type (per unit) during the past years, or for the target time in 2020. However, using historical data and statistical methods, the GDP value in 2020 can be extrapolated. This should satisfy the needs of this research to a reasonable extent.

Based on the "Statistical Yearbook of Society and Economy in Tongzhou" and land use status quo, the land use and statistical data in 2002 can be used to predict the land use status quo and the GDP value for three different domains. It is assumed that only industrial and commercial land contributed to direct GDP benefit and the ratio of GDP value made by industrial and commercial land will be similar from 2002 to 2020.

Table 4-1 GDP Statistical Data for Different Land Use (SDTZ, 2002)

2002 Statistic Data	Industrial	Commercial
GDP（Ten Thousand）	45927	161254
AREA（Ha）	766.43	319.19
GDP Value	59.92	505.20

In this research, the computational data above is used to represent the economic objective as in Table 4.2:

Table 4-2 Economic Benefit

Land use types	GDP Ratio(different land use)
Residential	0
Industrial	59.92
Commercial	505.20
Green	0
Undeveloped	0

4.2.2 Conversion cost

The conversion cost could be defined as the total cost of converting the current situation into a new situation. For each pair of land use types l and k, d_{lk} represents the cost of changing land use from type l into k. Thus, for any cell (r,c) with existing land use type l, the cost of allocating a land use k to this cell could be represented as $C_{lk}d_{lk}$, where C_{lk} is the coefficient. Thus, the costs for all grids are aggregated to arrive at the total conversion cost. However, the actual cost of changing one land use type to another can not be explained in a simple and straightforward manner. This cost of conversion is influenced by various factors such as the building type, plot ration etc. In this research, also due to the data limitation, the changing coefficients will be ignored. Each kind of conversion has objectors, for different reasons, besides, each kind of conversion leads to expenditure. Thus, in order to decrease the spending and represent the profit of some groups of people, the minimization of conversion could be one reasonable objective, which could be considered as defensible development.

4.2.3 Geology

During the land use planning process, planners or decision makers require basic geographical information of the planning area such as the geology, topography, landform and zones, which are potentially unstable. These aspects are at the base of the real planning and should be the objectives of the land use optimization. They are very important in influencing the sustainability of land use.

To prepare the various derivative maps, a GIS System is used to analyze data based on four attributes. The thematic maps produced serve as a guide for the land use assessment of the proposed development project, and in land use zoning. These also serve as a valuable reference for the engineers in aspects such as preparing building plans/layouts, deciding the most appropriate earthwork plan, and the method of construction, etc. On the other hand, the geospatial maps can potentially be used as a tool for monitoring any changes in landform or natural morphology and the initial stage of geo-hazard assessment for a proposed area. Depending on these tools, these aspects could be easily integrated into the optimization model.

Under these considerations and taking into account the data iimitation, the geomorphology is one aspect that should be concentrated upon. In Tongzhou Newtown, the elevation is very low and it is also very flat in all the districts as shown in the figure below:

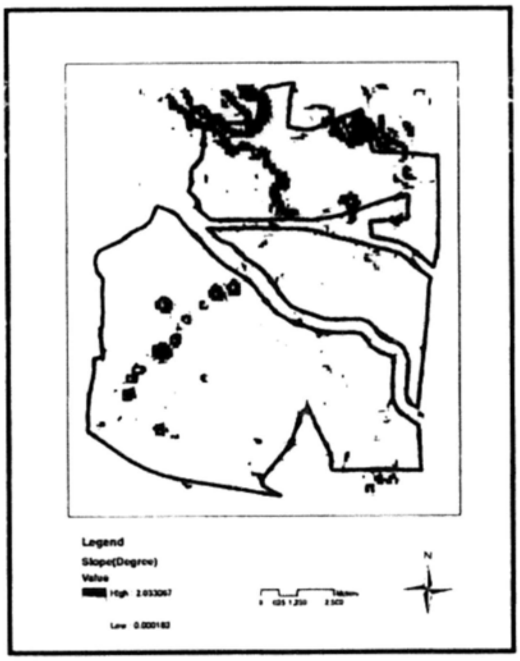
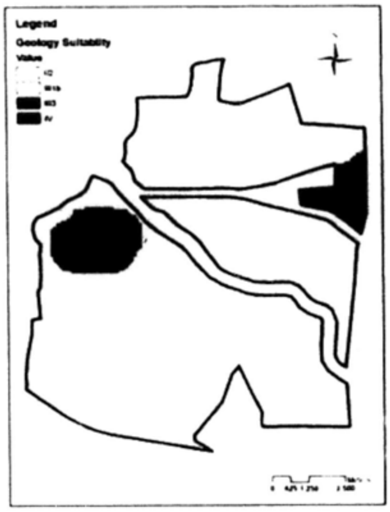


Figure 4-2 Slope of Research Area *(The black outline show the real computation area after erasing the restricted area)*

Hence, the landform condition could be ignored. Besides, the geological condition of this place is also very essential for the development of the district. The geology suitability map of Tongzhou Newtown, extracted from the geology suitability map of Beijing, is shown below:



Type	value
I	9
II1	8
II2	7
III1a	6
III1b	5
III2a	4
III2b	3
III3	2
IV	1

Figure 4-3 Geology Suitability (BJIG, 2005)

The district for geological construction from I to IV is really worse. Hence, the maximization of the summed value on all the cells of land use scenario can lead to a better solution for this aspect.

Depending on this evaluation approach, the geological condition could be considered as a quantitative objective within the optimization model. Even though the setting for the different classes is subjective, it serves to reasonably guide the planning scenarios with reference to the geological aspect.

4.2.4 Dust

In the wake of the concerns for pursuing sustainability in mainland China, the environmental and ecological benefits assume even greater significance. The environmental and ecological indicators play an important role in the process of translating the environmental and ecological benefits to the optimization model.

The terms ecological indicator and environmental indicator are often used interchangeably. However, to some extent, ecological indicators are actually a subset of environmental indicators. Generally, environmental indicators provide information on the pressures on the environment, environmental conditions, and societal responses. Nevertheless, ecological indicators refer only to ecological processes.

Most of sustainable ecological and environmental indicators from different documents focus on biodiversity, biological footprint, and some general resource quality such as water quality, air condition, soil condition, green house gas emission etc. The most famous indicator is the Environmental Sustainability Index (ESI) created by Yale University and Colombia University. This includes 21 essential indicators, with 2 to 6 variables for each indicator, totaling to 76 variables. The indicators were applied to 122 countries including China. The framework of ESI is as follows:

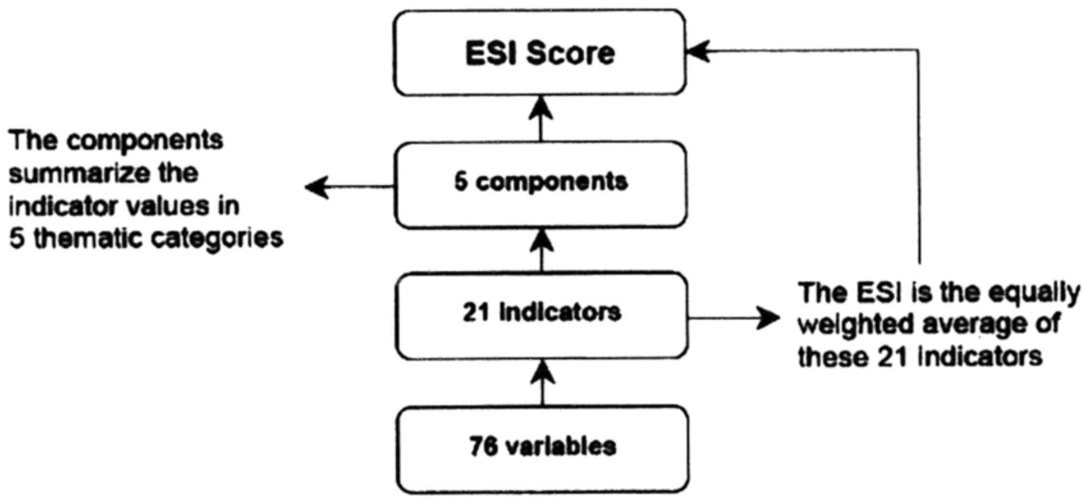


Figure 4-4 Constructing the ESI Score (Yale-University *et al.*, 2005)

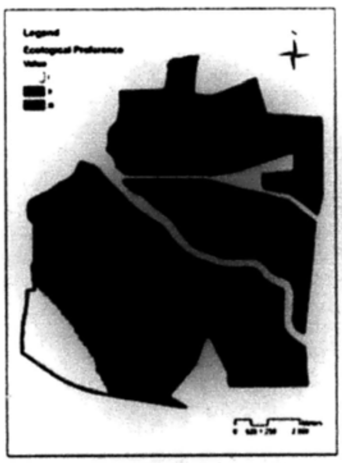
The ESI was developed to evaluate environmental sustainability. Subsequently, due to a shift in focus, the teams involved in the ESI development created, the Environmental Performance Index (EPI). The EPI based on outcome-oriented indicators, serves as a benchmark index that can be more easily used by policy makers, environmental scientists, and the general public.

However, under the consideration of land use optimization itself, most of these aspects discussed here are not suitable to evaluate the ecological and environmental contribution or their influence of different land use scenarios. In the meantime, the acquisition of the relevant data is another problem. In this research, the value of the world's ecosystem services and natural capital (Costanza *et al.*, 1997) are considered while evaluating the ecological benefit. From the table below, it can be seen that the green lands yield the most part of ecological benefit in these five land use types. On the other hand, the ecological planning of higher scale also has to be considered to yield the spatial layout of the green land.

Table 4-3 Ecological Value per Unit

Land use types	E-value
Green	2242.25
Residential	165
Industrial	165
Commercial	165
Undeveloped	0

The figure below illustrates that the districts indexed by I, II, and III, are more suitable for allocating green land. The contribution value in the table below will be counted if the district is allocated with green land. Therefore the maximization of the sum of the contribution value can be understood as the objective not only to maximize the amount of green land but also to maximize the feasibility of the green land layout.



Ecological Value	Green	Others
I	1	2
II	2	1
III	3	0

Figure 4-5 Ecological Suitability(BMEPB, 2005)

4.2.5 Accessibility

Accessibility is a general term used to describe the degree to which a product, device,

service, or environment is accessible by a larger number of people. Accessibility clearly reflects the transportation efficiency of a place.
Besides being a major goal of sustainability, accessibility is also an inevitable aspect for the efficient functioning of a city. From an industrial perspective, transportation is an inevitable factor contributing to industrial development. Accessibility is vital for efficiently transporting of goods and other finished products, which supply the day-to-day needs of the city's inhabitants. Besides, it can also help the development of tourist industry and facilitate communication in various domains such as technology, culture, politics, etc. In a word, the accessible transportation is an inevitable component of any efficient city, which is closely interlinked to all the other aspects to some extent.

Transportation planning is imperative to attain accessibility. The integration of transport and land use planning is widely recognized as essential for accomplishing sustainable development (Bertolini *et al.*, 2005).

Accessibility can contributed in ways more than one to improve the sustainability. The term "social equity" refers to a social state of affairs in which all people within a specific society or isolated group have the same status in a certain respect. From one aspect, social equity includes equal rights under the law, such as security, voting rights, freedom of speech and assembly, and the extent of property rights etc. Besides, it also includes access to education, health care, basic amenities, and other social security etc. Accordingly, the planning scenarios with good accessibility could facilitate equal rights for everyone to access the various public facilities efficiently.

Furthermore, accessibility also comes into play when considering the relationship between the greenhouse gas emission by the various modes of transportation and the environmental health. Although the EIA mentions various gases including CO_2, methane, nitrous oxide, various hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride, CO_2 accounts for the major proportion of the greenhouse gases. Hence, controlling CO_2 emission assumes significance. Humans and automobile activity contribute to more than 80% of CO_2 into the urban environment (Koerner & Klopatek, 2002). Therefore the accessible transportation can decrease the green house gas emission very efficiently. Furthermore, as accessibility is related to the compactness of different land use types, it serves to pursue the objective of compactness mentioned earlier.

Accessibility can be evaluated from the distances to facilities, or the driving or walking time to some facilities etc. In the context of this research, including the specification of the research area, the data limitation, and the need for comprehensive analysis of the whole area, the evaluation method of accessibility would is as follows. The planned transportation lines that will be formed in 2020 are considered to be the existing transportation condition during the optimization process. In China, according to the "Regulations for gradation and classification on urban land", the roads can be divided and assembled as follows: 1) main road for living; 2) main road for transportation; 3) main road for mixed use.

Table 4-4 Influence Index for Different Roads (GAQS, 2001)

	Residential	Industrial	Commercial
Main road for living	1	0.7	0.875
Main road for transportation	0.7	1	0.7
Main road for mixed use	0.875	0.875	1

The influence index in the table is obtained by the mean of range set according to the regulation. The function value of roads are calculated by

$$f_i^R = 100 \times I_i^R \quad (4.1)$$

St: f_i^R -- Function value of i type Road

I_i^R --Influence Index of i type Road (table above)

The influence decreasing index is calculated by

For commercial: $e_{ij}^R = (f_i^R)^{1-r}$ (4.2)

For residential and industrial: $e_{ij}^R = f_i^R(1-r)$ (4.3)

St: e_{ij}^R -- Influence value of i road to j point

f_i^R -- Function value of i type Road

r -- Related distance between j point to i road

The road network of the research area is as below:

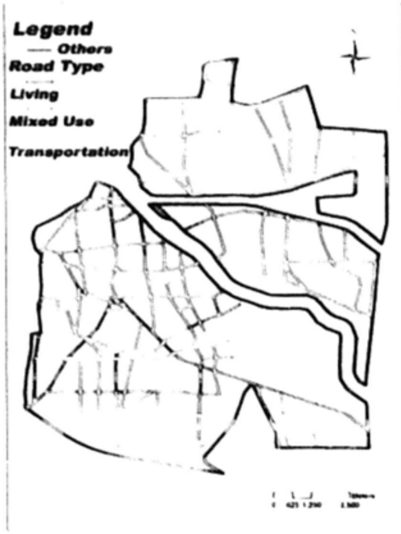


Figure 4-6 Roads Network

The road function decreasing maps of three kinds of roads are as follow:

Table 4-5 Function Decreasing Maps of Different Roads *(Decreasing from Red color to Blue color)*

Residential(Living)	Industrial(Transportation)	Commercial(Mixed Use)
		

For green land and the undeveloped land, there is no restriction of accessibility for the layout of the two kinds of land use types, however, in order to utilize accessibility sufficiently, the green land and the undeveloped land should be allocated in the place that has the worst accessibility situation (the road trees are not included owing to 100m by 100m resolution). Hence, the similar function decreasing map of green land and undeveloped land can be obtained as below (taking all the roads into account, the influence index equal 1 and influence decreasing index chooses formula (4.3)):

Figure 4-7 Function Decreasing Map for Green and Undeveloped Land *(Decreasing from Red color to Blue color)*

For each scenario, the evaluation of the accessibility is based on the function decreasing maps shown above. The maximization of the total value will lead to the optimal accessibility situation in the layout for each kind of land use.

4.2.6 NIMBY

NIMBY was coined in the 1980s by the British politician Nicholas Ridley. Residents who strenuously oppose development of land in their immediate area are often called "NIMBY," which is an important issue in land use regulation. It can impede the implementation of carefully planned scenarios, locally-desired industrial development, and the placement of aspects of urban life, such as power plants, railway and landfills (Fischel, 2000). In summary, the term is used to describe opposition by residents to a proposal for a new development close to them. For instance, people may not like a new proposal such as a new railway line, landfill field, power station etc. It is not easy to change the location of these plants or communal facilities, however, a better location for residential land, and commercial land can be chosen. In the light of the above discussion, the objective of minimize the influence of NIMBY can be integrated into the planning process.

For the optimization in 2020, lots of facilities could be reallocated to appropriate places. Owing to data limitation, only railways will be considered in this case study. This is an attempt to include NIMBY in this kind of research. The Euclidean distance based function decreasing map of railway is provided below. The description of this objective is to minimize the construction of residential and commercial land inside the high influence value of railways inside the city. The calculated method of influence value is the same as that of the accessibility of green land and undeveloped land.

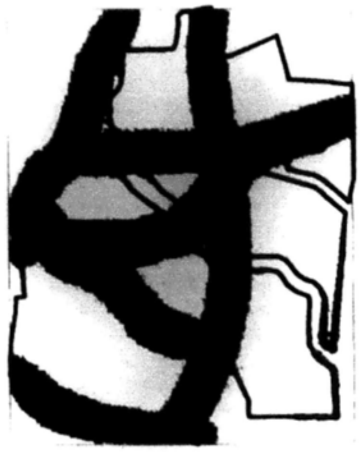


Figure 4-8 Function Decreasing Map for NIMBY

(Decreasing from Red color to Blue color)

4.2.7 Compactness

Compact land use is desired in various planning domains, such as forest management and reserve design etc. Promoting compactness/controlling fragmentation has been a common and important goal of land use planning towards sustainability, which is a hot research topic these days.

Urban sprawl is a widespread problem affecting much of the urban development that has occurred in the past fifty years. Environmentally, there are two main concerns related to urban sprawl: the extent to which it consumes the landscape, and the air pollution produced by such a high level of automobile reliance (Anderson *et al.*, 1996; Guiliano & Narayan, 2003; Williams, 1999). This also leads to the destruction of natural habitat for many species, which as a result have become endangered. Besides, the inefficient consumption of land resource greatly affects the provision of services and infrastructure by local governments. Furthermore, it also causes the need for more transportation facilities, which is accompanied by air pollution and energy consumption.

While the societal effects of urban sprawl are very difficult to measure accurately, it evidently affects sustainability by impacting social equity. Reduced social equity, negative health impact, a loss of community, segregation, polarization, and an inability to adapt to changing lifestyles and family structures are just some of the ways in which urban sprawl adversely affects social sustainability (Arbury, 2005). Furthermore, social equity is negatively impacted in many detailed ways below: limiting transport options of the poor due to the high costs of car ownership and poor public transport; increasing the likelihood of poor people living in less desirable neighborhoods; increasing fear and anxiety generated by high traffic volumes; greater exposure to air pollution and resulting poor health; and losing "a sense of community" as most people travel beyond the local neighborhood to carry on their daily activities (Hillman, 1996).

As discussed above, the negative environmental, economic, and social effects of land use sprawl are widespread, diverse, and clearly at odds with the concept of sustainability. The concept of compactness attempts to provide a more sustainable alternative style of land use sprawl. It should be one of the important objectives while planning a sustainable city.

Burton (2000) defines a compact city as a relatively high-density, mixed use city, which is based on an efficient public transport system and dimensions that encourage walking and cycling. Thomas and Cousins (1996) stated the compact city as an intense medieval city, whose limits are clearly visible, and where the hubbub of activity is confined within the city's walls. Lock (1995) perceived a compact city as one city that we make the fullest use of land etc.

Although there may be consensus that the compact land use is clearly distinct from urban sprawl, and is essential for sustainability, many questions still remain. These pertain to the evaluation of the compactness of the land use during the land use planning optimization process. This not only requires the effect of compactness but also the efficiency to evaluate land use planning scenarios as a kind of complicated spatial optimization problem.

Though the objective of encouraging land compactness is apparent, there exists no generally accepted measure of spatial compactness. For different land use types, various kinds of measures have been listed below, including similar ones on "compactness" for raster based spatial problem:

1) Non-linear integer program-neighbor method; 2) Linear integer program-neighbor method; 3) Linear integer program using buffer cells; 4) Linear integer programming (IP) using "Aggregated Blocks"/Minimization of the number of clusters per land use types; 5)Minimization of shape index (Aerts & Heuvelink, 2002; Ligmann-Zielinska *et al.*, 2008; Stewart *et al.*, 2004); 6) Spatial autocorrelation (Cliff & Ord, 1973; Kurttila *et al.*, 2002; Wardoyo & Jordan, 1996). The first one is the most direct explanation to compactness of land use, which will be explained later on. The second one is the equivalent linear reformulation of the first model, at the expense of including additional integer variables. It can be easily solved using the simple optimization method. The third one is a problem wherein one selects parcels and each reserve (one land use type) consists of core cells, and surrounding buffer zone. Compactness is indirectly obtained through minimizing the number of buffer cells around the core areas. The fourth one is based on the notion of aggregating individual cells to blocks and developing a model that minimizes the number of blocks containing only one land use type in the final allocation. In other words, the target is to reduce the number of clusters according to each land use type. The fifth one is to compute the shape index of each cluster, which sounds quite complex, but is effective in representing the compactness. The last method is from the spatial statistical perspective, by using Moran's I, Geary's C etc.

Most utilizations of compactness as the objective are direct implementations or variations of the aforementioned six models. Aerts et al.(2003a), Stewart et al.(2004), and Janssen et al.(2008) have combined the fourth and fifth models with the definition of maximization of the large cluster of each land use type to pursue the compactness of each scenario. Even though the effect is reasonably good, this applies only to a small area. Aerts and Heuvelink (Aerts *et al.*, 2003a; Aerts & Heuvelink, 2002) have compared the anterior four models in, according to the result on the testing area (8*8 grid). Obviously, the efficiency of the first measure is found to be is the best. It is also the fastest way, although it is not a linear method. These methods for obtaining the compactness for each scenario, whether linear or otherwise, the spatial statistical method can also be considered to judge if the scenario is compact or not. The spatial autocorrelation is one sample of such direction of thought. Herein, one new application of Moran's I index to evaluate the compactness of the land is tested to compare with the method-neighbor method (NM) for efficiency and the shape index method (SIM) for the explanation of compactness.

4.2.7.1 Non-linear neighbor method

The first measure can be described in terms of recording for each cell, implying the number of neighboring cells with the same land use type. In this sense, the "neighboring" cells to (i, j) are the (i-1, j), (i+1, j), (i, j-1), (i, j+1), (i-1, j-1), (i+1, j+1), (i-1, j+1), (i+1, j-1) (ignoring cells outside the region). This can be shown as follows:

Minimize:

$$-\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{M} A_{ijk} x_{ijk} \qquad (4.4)$$

Where

$$A_{ijk} = x_{i-1jk} + x_{i+1jk} + x_{ij-1k} + x_{ij+1k} + x_{i-1j-1k} + x_{i+1j+1k} + x_{i-1j+1k} + x_{i+1j-1k}$$
$$\forall k = 1,\dots,K, i = 1,\dots,N, j = 1,\dots,M$$

A neighborhood of eight cells (top, down, left, right, left-top, right-down, right-top, left-down) is defined here, but alternatively there are some other smaller or larger neighborhoods that can be defined, such as four neighbors. It can be clearly seen that minimization process can lead to compact solutions.

4.2.7.2 Shape index method

The shape index method can be calculated using the following equations:

$$Shape_{total} = \sum_{k=1}^{K}\sum_{c=1}^{C}\frac{P_{kc}}{\sqrt{R_{kc}}} \qquad (4.5)$$

Where P_{kc} stands for the perimeter of one cluster c for land use type k. R_{kc} represents the area of each cluster c for land use k. The values for the perimeters of cluster A, B, C and D are 20, 20, 18, and 14. The values for cluster A, B, C and D are 16, 13, 12, and 7, thus the value for this shape index is 21.04.

For some special situation, such as the single cell as a cluster in an optimal result, through the minimization of the shape index total, the function can show both the shape of each cluster and the number of the clusters. Of course, the complexity is also obvious.

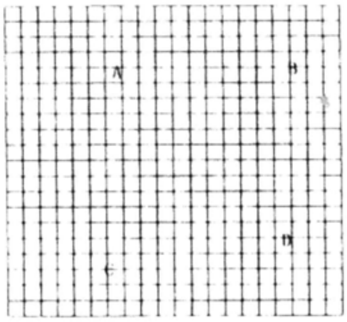


Figure 4-9 Shape Index of the Four Clusters

4.2.7.3 Moran's I method

Moran's I is a measure of spatial autocorrelation developed by Patrick A.P. Moran (1950). Like autocorrelation, spatial autocorrelation means that adjacent attribute for the same phenomenon is correlated. Spatial autocorrelation is about proximity in (two-dimensional) space. Spatial autocorrelation is more complex than autocorrelation because the correlation is two-dimensional and bi-directional.

Moran's I is defined as

$$I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} Wij} \times \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} Wij\left(x_i - \overline{x}\right)\left(x_j - \overline{x}\right)}{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2} \tag{4.6}$$

Where N is the number of spatial units indexed by i and j. X is the variable of interest; $\overline{X}$ is the mean of X ; and W_{ij} is a matrix of spatial weights.

The expected value of Moran's I is

$$\mathrm{E(I)} = \frac{-1}{\mathrm{N}-1} \tag{4.7}$$

Its variances equal

$$Var(I) = \frac{\{n[(n^2 - 3n + 3)S_1 - nS_2 + 3S_0]\} - \{k[(n^2 - n)S_1 - 2nS_2 + 6S_0{}^2]\}}{(n-1)(n-2)(n-3)S_0{}^2} - E(I)^2 \tag{4.8}$$

Where

$$S_0 = \sum_{i=1}^{n}\sum_{j}^{n} Wij \tag{4.9}$$

$$S_1 = \sum_{i=1}^{n}\sum_{j=1}^{n} (Wij + Wji)^2 \Big/ 2 \tag{4.10}$$

$$S_3 = \sum_{i=1}^{n} (Wi. + W.i)^2 \tag{4.11}$$

$$k = \frac{\left[\sum_{i=1}^{n} \left(x_i - \bar{x} \right)^4 / n \right]}{\left[\sum_{j=1}^{n} \left(x_i - \bar{x} \right)^2 / n \right]^2} \tag{4.12}$$

According to these steps, the Moran's I will be between -1 and 1, if the index is greater than 1, it means that the correlation is positive, if less than 0, it means that it is negative. The greater the value is, the larger the correlation will be, and vice versa. As Figure 4.10 illustrates, if the value is near to 0, it represents random distribution; if the value is near to 1, it represents high autocorrelation.

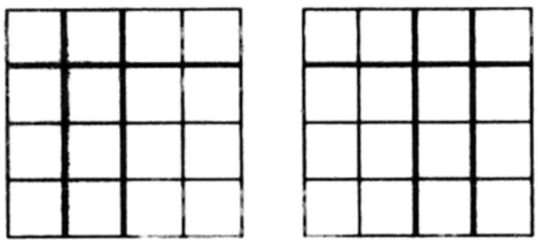


Figure 4-10 The Representations of Positive and Negative Correlation for value of 1 and -1

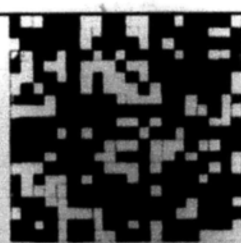
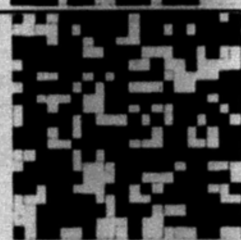
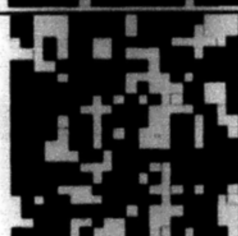
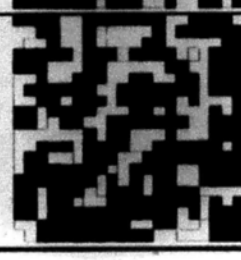
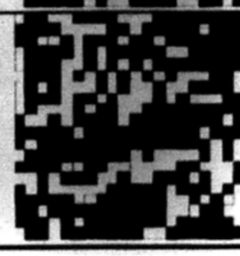
4.2.7.4 Evaluation and Comparison

In the previous section, three efficient methods encouraging compactness were presented. In this section, these models are evaluated and compared based on their effect and efficiency. The comparison will be performed on a 20 by 20 grid with 5 assumed land use types with a MacBook Pro laptop computer equipped with an Intel(R) Core(TM)2 Duo CPU P7550@2.26GHz. This will be also used for the case study, based on generic GA (See 5.1). The performance of the methods used can be evaluated using two criteria. Criterion 1 evaluates the computation time against the achieved degree of compactness. Thereafter, the characteristics of the compactness created by these methods should also be considered as the criterion 2.

Table 4-6 Comparison of the CPU Time based on Three Models *(the unit is second, and Model-1, Model-2, and Model-3 are separately related to non-linear neighbour method, shape index method and Moran's I method)*

Iteration Number	Model-1	Model-2	Model-3
100	8.39	33.34	279.17
200	10.32	45.62	387.67
500	19.46	75.64	755.04
1000	35.17	127.16	1402.36
5000	156.83	442.9	5877.64
10000	316.13	780.47	12930.07
50000	1526.12	3367.32	56595.42

Table 4-7 Comparison of the Effect based on the Three Models

Iteration Number	Model-1	Model-2	Model-3
100			
200			
500			
1000			

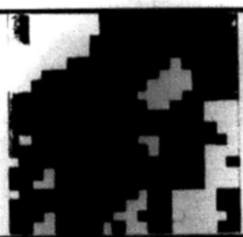
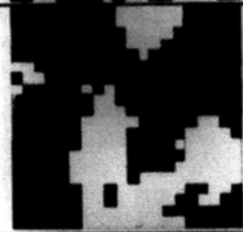
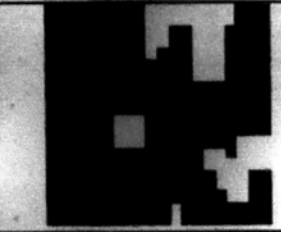
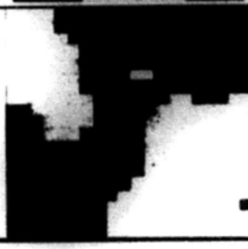
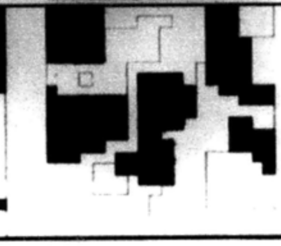
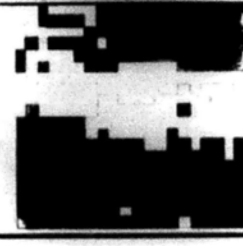
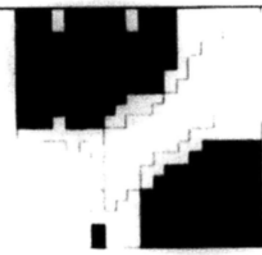
5000			
10000			
50000			

Table 4.6 above evinces that the Model-1(neighbor) is the fastest model to achieve the compactness than the other two models: shape index and Moran's I. From the CPU time perspective, Moran's I method consumes much more time than the neighbor model. From the comparison of the effect in Table 4.7, the effect of the each model is good enough to perform the optimization research. The effect of neighbor model is smoother than the other two models, which is more suitable to reflect the actual land use change. For the other two models, the effect of the other two models, shape index and Moran's I, are also good for optimization purposes, however, considering the fact that the optimization process is based on so many variables, the time spending is considerably higher.

When considering the comprehensive Moran's I, not only the compactness but also the correlation among different land use types can be reflected from the effect. The result, as seen from the Table 4.8 below, is evidently better than the Mono Moran's I using less than $1/4^{th}$ of the time. This implies that this model could be exploited to achieve two or more objectives (such as the compatibility etc) simultaneously to promote the efficiency and effect. Evidently, the weighting of the compactness and the compatibility would be the problem.

Table 4-8 Comparison of Efficiency and Effect of Mono and Comprehensive Moran's I Index *(Mono Moran's I means only considering one land use on one time; Comprehensive Moran's I means considering five land use type together)*

Types (50000 times)	Mono Moran's I	Comprehensive Moran's I
CPU Time Spending (Sec)	56595.42	10791.35
Results		

After comparison of these representative methods to evaluate the compactness, the basic Eight-neighbor method is chosen as the final evaluation method of compactness.

4.2.8 Compatibility

As the compatibility of neighbors for different land use types are different, it is very essential to guide the land use planning to allocate the compatible land use types together to establish the harmony of the complete area. Under this consideration, the compatibility of all the neighbors should be the objective for the land use planning scenarios. Some earlier research works have also considered the compatibility factor when performing land use optimization. (Ligmann-Zielinska *et al.* 2008, Chandramouli *et al.* 2009) The details can be seen in the following figure.

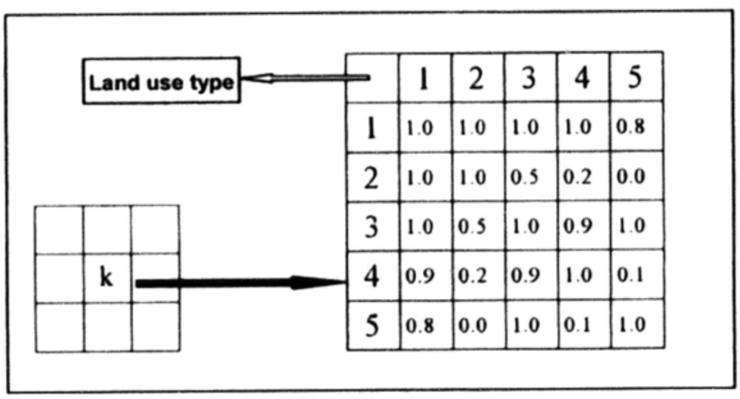


Figure 4-11 Compatibility

Each land use type has its own preference to the neighborhood with special land use types, as can be seen in Figure 4.11. For each land use type k on the left, the compatibility of the scenario can be estimated by adding all the compatibility indices showing in the right table according to the five land use types. The compatibility indices can be obtained from professionals or specialists. The more the indices are, the more compatible the scenario is.

For the compatible values setting, it is feasible to cite the indices from the opinion of experts. However, this could involve significant subjectivity as the experts might not feel the same about the compatibilities changes. Even for the same expert, it is hard to detect the relationship between every two land use types on the same level. The Pair-wise comparison could be used to solve this to some extent (David 1988, Saaty 2008). This table below refers to the opinion of the planners from Chinese Urban Planning and Design Academy. Only the pair that has the same land use will be compared.

Table 4-9 Relative Importance

	RI	RC	RG	RU	IC	IG	IU	CG	CU	GU
RI	1.000	3.000	3.000	1.500	1.500	1.000	2.000			
RC	0.333	1.000	1.000	0.500	0.500			0.667	0.500	
RG	0.333	1.000	1.000	0.500		1.000		0.500		0.667
RU	0.667	2.000	2.000	1.000			2.000		1.000	1.500
IC	0.667	2.000			1.000	2.000	2.000	1.500	0.667	
IG	1.000		1.000		0.500	1.000	0.667	0.667		0.667
IU	0.500			0.500	0.500	1.500	1.000		0.500	1.500
CG		1.500	2.000		0.667	1.500		1.000	0.667	1.000
CU		2.000		1.000	1.500		2.000	1.500	1.000	2.000
GU			1.500	0.667		1.500	0.667	1.000	0.500	1.000

After computation, the final compatibility values table can be seen:

Table 4-10 Compatibility Values

	R	I	C	G	U
R	1				
I	0.41	1			
C	0.95	0.48	1		
G	1	0.88	0.62	1	
U	0.47	0.75	0.41	0.74	1

The objective is to maximize the sum of compatibility of all the cells inside the research area.

4.3 Constraints

Within the model, there are also some constraints that need to be satisfied: the restricted area; the minimization of the accommodation area to serve future population; maximum one land use type for each cell.

The following constraints are used for the case study: Restricted area in the Tongzhou Newtown includes the Grand Canal, and the reserved green land in the northwest and southeast of Tongzhou Newtown (Pre-defined cells with special land use types as Figure 4.12)

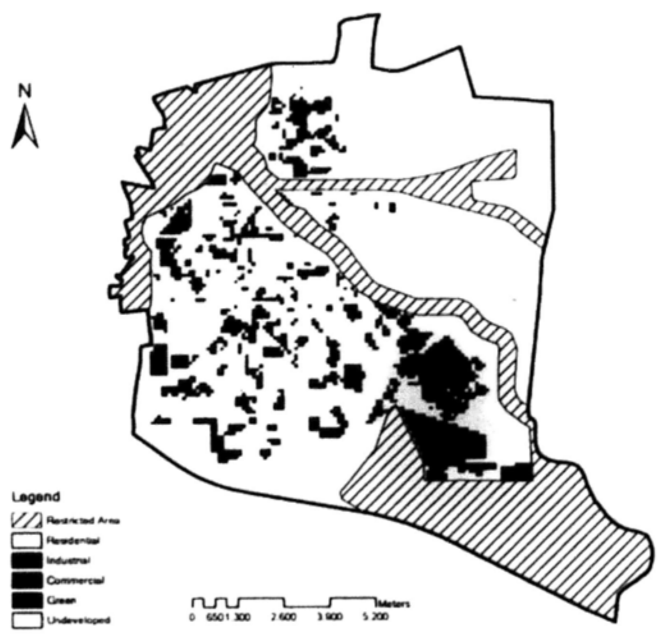


Figure 4-12 Restricted Land

Based on the prediction of the population in Tongzhou Newtown in 2020, the low bound of the plus of residential and commercial cells for accommodation is estimated to be at least 3150 cells.

4.4 Summary

In this chapter, the research area-Tong Zhou Newtown was introduced in a detailed manner covering aspects such as history, location, transportation etc. This established the background of the case study and the representativeness of Tongzhou Newtown as an area in mainland China undergoing rapid urbanization.

Besides, the objectives and the constraints were comprehensively covered from the three main aspects of sustainability: economic, environmental and social benefits. The objectives of GDP, conversion cost, geological condition, dust preference, accessibility, NIMBY, compactness and compatibility were analyzed separately. Furthermore, the evaluation of each objective has also been introduced using reasonable methods. Therein, the evaluation methods of compactness for raster based spatial problem have been reviewed along with the comparison of the effect and efficiency. At last, the eight-neighbor method was found to demonstrate the best result on the hypothesis data. The comparison still led to the usage possibility of the comprehensive Moran's I method because of its characteristic. As for the constraints, the restricted area, the minimization of the accommodation area to serve the future population, and the limit of one land use type for each cell were taken into account.

CHAPTER 5: CONSTRUCTION OF BFGA-MOLU MODEL

5.1 Introduction to Generic GA

GA originated from the research on the computer simulation of bio-system. Professor Holland from Michigan University and his students were inspired by the biological simulation technique. They created GA, which is based on biological heredity and evolution, and is suitable for adaptive probability optimization. In 1967, Bagley, Holland's student, proposed the word "Genetic Algorithm" in 1967 and also developed Replication, Crossover, Mutation, Dominance, Inversion operators. He also developed the amphiploid representation method (Holland 1975, Bagley 1967).

Professor Holland proposed the GA Schema Theorem, and published the first book about the GA and artificial adaptive system: "Adaptation in Natural and Artificial Systems". In 1960s, Professor Holland realized the first machine learning system based on GA, and introduced the innovative concept of GA machine learning. In 1975, De Jong performed numerous experiments in his doctoral dissertation about the numerical optimization using the notion of GAs. During this process, not only was the framework of GA generated, but some very meaningful conclusions were obtained (Jong, 1975). In 1989, Goldberg published "Genetic Algorithm in Search, Optimization and Machine Learning". It Systematically introduced the principal achievement of GA, and discussed the principle and the application of GA very comprehensively (Goldberg, 1989). In 1991, Davis published "Handbook of Genetic Algorithms", which eventually led to many applications of GA on scientific computation, engineering technology and social economy (Davis, 1991). In 1992, Koza proposed the concept of "Genetic Programming", which was efficient as demonstrated by lots of examples. From the perspective of the development of the GA (Koza, 1992), the 1970s was the starting point, while the 1980s witnessed the actual developments. As a kind of practical, efficient and robust optimization technology, GA has been widely integrated into numerous specialized fields to improve the effect and efficiency of the optimization including engineering, management, planning etc.

5.1.1 The concept and characteristics of GA

GA is one kind of global searching and optimization method, which simulates the natural evolution mechanism, which in turn draws from the Darwinian evolution mechanism. GAs are a particular class of evolutionary algorithms (EA) that use techniques such as inheritance, mutation, selection, and crossover. The essence of GA is its efficient and parallel optimization and searching capabilities. GAs can acquire knowledge about the search space during the searching process, whilst simultaneously and adaptively controlling the search process in pursuit of the optimum.

GA is a Random Searching Algorithms using natural selection and natural genetics. It is different from the typical optimization algorithms as most of the classical optimization methods are based on grads or higher-order statistics of single evaluation function so as to yield certain solutions. However, for some NP hard problems, this does not seem to work. GA does not depend on the grads information, but it works by simulating the natural evolution to search the optimal solution.

- The advantages of GA can be summarized as follows:

1) The universality of representation of the solutions

The representation is the essential part during the computation process in any optimization procedure. This is used to efficiently describe and hence formulate the optimization problem and this representation enables GA to be used in lots of fields.

2) Colony searching

Some typical optimization methods are based on single point searching. However, this kind of searching method might often fall into the local optimum according to the multiple peaks optimization problems. On the contrary, GA evaluates the crowd distributed among the whole search space. This characteristic gives the GA the better global optimum searching ability and parallelism.

3) No need of auxiliary information

GA only uses the fitness function to evaluate the gene. The fitness function can be defined among any definition domain and it is also not influenced by continuous differentiability. The only requirement for the fitness function is that the coding corresponds to the feasible solution space. This characteristic could extend the application field of GA.

4) Heuristic searching

GA does not use the certain rules, but the changing rules of probability to guide the searching direction. Besides, it is also one good global searching algorithm with Parallelism and parallel computation mechanism. It could also be integrated with some other algorithm(s).

- Just as a coin has two sides, GAs are not devoid of drawbacks. The disadvantages of GA include

1) Inaccuracy of Coding/ representation problem

2) For some cases, the efficiency of GA might be lower than other optimization methods

3) Premature convergence might occur in GA

4) There is a lack of efficient quantitative analysis methods for the accuracy of GA and reliability.

5.1.2 The process of GA

GA simulates the natural selection and the replication, crossover and mutation in genetics. The GA process starts with population initialization, selection, crossover and mutation operations, ends by generating new population with better fitness. The population evolves during this process and gets get better and better iteration by iteration. Finally, the desired solution is attained after the step-by-step evolution.

The whole process of GA is depicted in the figure below.

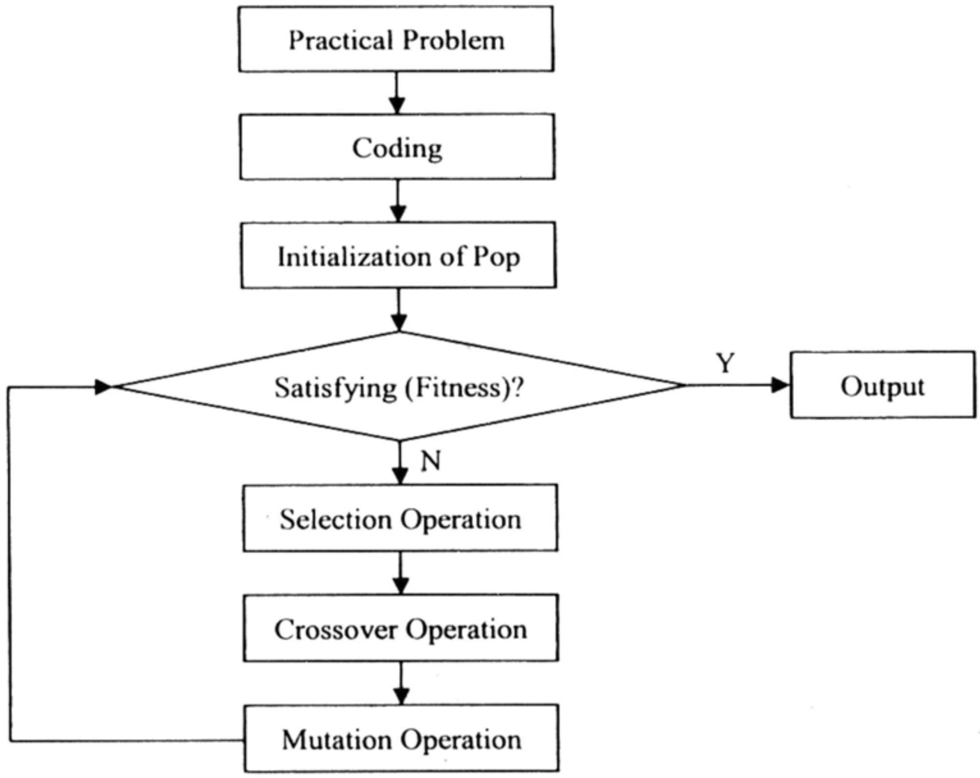


Figure 5-1 The Whole Process of GA

The GA framework includes seven steps as follows: Coding; Initialization; Setting of Fitness Function and Evaluation; Selection; Crossover; Mutation; Termination. The pseudocode of the generic GA can be explained as follows:

```
Procedure of GA
Begin
    t=0;
    initialize P(t);
    evaluate P(t);
    while not finished do
    begin
        t=t+1;
        select P(t) from P(t-1);
        reproduce pairs in P(t);
        evaluate P(t);
    end
end
```

5.1.3 Explanation of essential steps of GA

5.1.3.1. Encoding

Encoding is one of the essential steps of GA, which is also the first challenge any GA faces. During the computation process of GA, the coding of different problems will influence the computation of selection, crossover, and mutation.

Encoding can be understood as the process of transferring the feasible solutions of one problem into a search space wherein the GA can operate. On the other hand, decoding is the process of transferring from the search space. The coding of GA is the representation of the solution in the 'genetics way'. The general coding is based on the binary coding which uses 1 or 0 to form the fixed string. However, the drawback of binary coding is the Hamming Cliff, which means there is too much distance between the neighboring integer and this influences the mutation between the neighboring integers. Gray Code is one kind of method which can overcome this shortcoming of the binary coding.

Till now, there have been many different encoding methods, which can be divided to three types: binary encoding, symbolic coding, and float coding.

1) Binary Encoding

Binary encoding is the most common coding method, which is the first encoding method used in GAs' application. In binary encoding every chromosome is a string of bits, 0 or 1.

Table 5-1 Example of Chromosomes with Binary Encoding

Chromosome 1	1010001010001
Chromosome 2	1001010010111

Sometimes, this encoding is not natural for many problems and corrections need to be made after crossover and/or mutation.

2) Permutation Encoding

Permutation encoding can be used in ordering problems, such as travelling salesman problem or task ordering problem. In permutation encoding, every chromosome is a string of numbers, which represents number in a sequence.

Table 5-2 Example of Chromosomes with Permutation Encoding

Chromosome1	1 5 3 2 6 4 7 9 8
Chromosome2	8 5 6 7 2 3 1 4 9

It is only useful for ordering problems. Sometimes crossover and mutation corrections must be made to leave the chromosome consistent. The most famous example is Travelling Salesman Problem.

3) Value Encoding

Direct value encoding can be used in problems, where some complicated value, such as real numbers, which are very difficult for binary coding representation. In value encoding, every chromosome is a string of some values. Values can be anything connected to problem, form numbers, real numbers or chars to some complicated objects.

Table 5-3 Example of Chromosomes with Value Encoding

Chromosome1	1.001 2.315 5.6243 2.4556 0.3393
Chromosome2	AECDSEFGSKDHLEKDH
Chromosome3	(Back)(Back)(Right)(Forward)(Left)

Value encoding is very good for some special problems. On the other hand, it is necessary to develop some new crossover and mutation operators specific for the problem, which might increase the complexity of the algorithm.

4) Tree Encoding

Tree encoding offers a unique form of coding in order to decrease the length of the chromosome. However, understandably, the complexity could increase in the meantime. In tree encoding, every chromosome is a tree of some objects, such as functions or commands in a programming language.

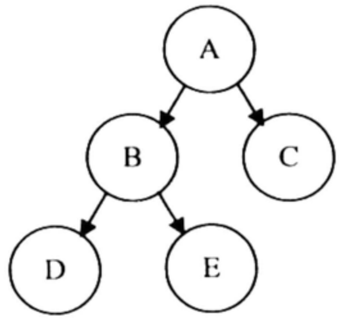


Figure 5-2 Tree Encoding

This is the example of Binomial, there are also some other applications using Quadtree, Octrees etc.

5) Gray Encoding

Binary coding is not good at reflecting the structural characteristic of the problem some times. Also, as for some continuing function of optimization, the searching ability is not very good because of the random trait. In order to improve the trait, the Gray code was proposed to code the individuals. It is just a transformation of binary encoding, the characteristic of Gray Code differentiate the two neighboring integers by only one number, not the other numbers.

Table 5-4 The Corresponding Table of Binary and Gray Coding

Decimal	Binary	Gray Coding
0	0000	0000
1	0001	0001
2	0010	0011
3	0011	0010
4	0100	0110
5	0101	0111
6	0110	0101
7	0111	0100
8	1000	1100
9	1001	1101
10	1010	1111
11	1011	1110

12	1100	1010
13	1101	1011
14	1110	1001
15	1111	1000

Generally, each kind of coding method has its own pros and cons. Hence, the choice can only be made on a case-by-case basis.

5.1.3.2. Selection

Selection, also named reproduction, is the process of selecting the better individuals according to the fitness function. The reproduction operator is used to decide the survival of the fittest individuals: the fitness is the criterion; the individual with high fitness will have more probability to survive to the next generation. On the contrary, the low one will have low probability to survive. This notion is to enhance the overall fitness of the population. The objective of selection is to avoid missing any useful genetic information and increase the global convergence and efficiency. The characteristic of the operator will decide the final result of the optimization process.

The selection operation is used to ensure the choice of fit individuals from the parent population and it also decides "how much" to choose. It is not related to the coding procedure.

The popular selection operators are as follows:

1) Roulette Wheel Selection

Roulette Wheel Selection is a kind of classical stochastic sampling method (or Proportional Selection). The probability of each individual to be chosen to the next generation depends on the fitness value divided by the sum of all the individuals' fitness value. The higher the fitness is, the more probable the individual could be chosen. Each individual is like the sector part of the roulette wheel, the degree of the sector is positively related to the individual's fitness value. The individual will be chosen when the wheel rotates randomly. The chart below illustrates this.

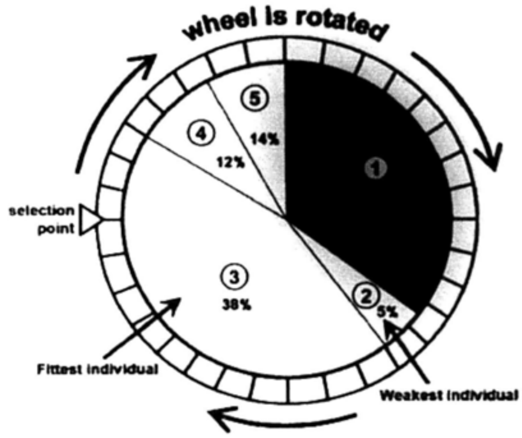


Figure 5-3 Roulette Wheel Approach: based on Fitness

2) Stochastic Tournament

Stochastic Tournament is similar to the roulette wheel method. During the selection process, two individuals are chosen for on every occasion and the better one of the pair is chosen ultimately.

3) Expected Value Selection

This selection method is based on the expected value of each individual in the next generation. The procedure is explained as follows:

The expected value surviving number should be computed first. If one individual is chosen to join the crossover operation, the expected value should be subtracted by 0.5; if one individual is not chosen to join the crossover operation, the expected values should be subtracted by 1. Secondly, the selection will depend on the expected value for each individual. Along with the selection, if the expected value of one individual is less than 0, it will not be chosen anymore.

This selection could decrease the error, but it is not a convenient method.

4) Uniform Ranking

The ranking selection does not require the fitness to be a positive or negative value. It only focuses on the correlation of each individual's fitness value. The primary notion of the ranking selection is to sort all the individuals according to their fitness, and distribute the probability by the ranking.

5) Best Conserving

In the GA process, new individuals are generated by crossover and mutation operations. Although better individuals keep coming as the population continues to evolve, the best individuals could also be destroyed. In fact, this might influence the convergence, effect, and efficiency of GA. Therefore, for better results, the individuals with the highest fitness value should be conserved to the next generation. Accordingly, this is what the best conserving method could do. The best individuals will not join the crossover and mutation operation and they should replace the worst individuals in the next generation.

The advantage is that this process can lead to the final result containing the best individual existing in all the generations. Besides, there are also some other selection operators. Every operator performs the selection operation in a different manner. It is not quite easy to decide the best one, However, as mentioned earlier, the most suitable one can be selected according to the nature of the problem being addressed.

5.1.3.3. Crossover

Nature produces the next generation using a mating process. This is accomplished by two parents creating offspring(s), with the offspring containing genetic material from both the parents. There are three options pertaining to the fitness of the offspring. The offsprings can be weaker, have the same fitness, or can even be better than their parents in terms of their fitness. If they are weaker they will die out, if they are stronger, their chances of survival get better. Typically, fit parents tend to produce fit offsprings.

Crossover (also named recombination), is to choose two individuals with a certain probability and exchange one part or some parts of the individuals. The offspring generated by this process, retains the basic characteristics of the parent individuals. The key issues in this process are to decide the point of crossover and perform the swapping between the parent individuals. It is the essential characteristic of GA, different from other forms of evolutionary computation.

Matching is the inevitable prerequisite to the crossover process. The popular matching method is by random. The real crossover process involves swapping the matching pairs.

The principles of the crossover operators are as follows:

1) One-point Crossover

One-point Crossover is also named simple crossover, it means that during the crossover operation, there is only one crossover point chosen by random for performing the exchange on the chromosome-pair.

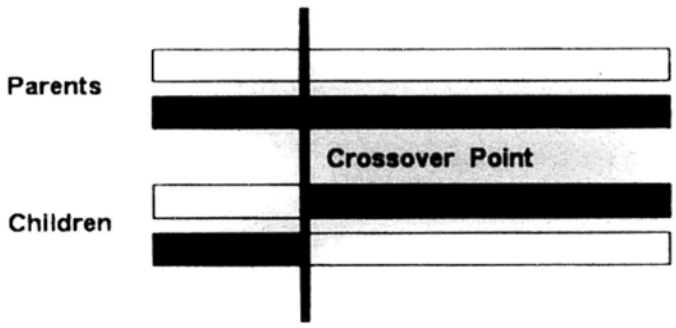


Figure 5-4 Single-point Crossover

Two-point Crossover is to set two crossover points, and do the exchange operation as follows:

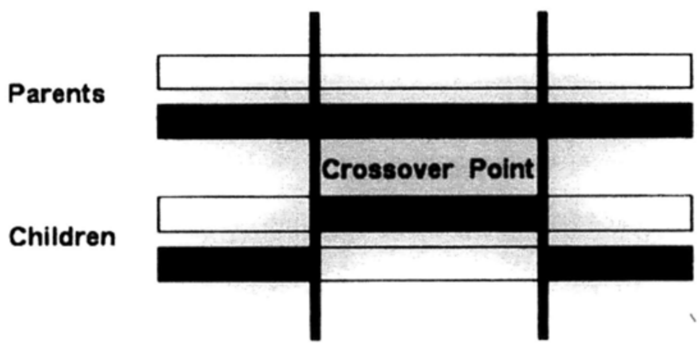


Figure 5-5 Two-points Crossover

The multi-point crossover focuses on the swapping of genes by the multi-point setting. However, this method is not quite popular as it could destroy the structure of good individuals and affect the performance of the GA.

3) Uniform Crossover

In uniform crossover, individual genes in the string are compared between two parents.

The genes are swapped with a fixed probability. In the half uniform crossover scheme, half of the non-matching genes are swapped by the computation of Hamming Distance (Hamming, 1950).

4) Arithmetic Crossover

Arithmetic Crossover refers to the process wherein the new individuals are generated by the linear combination of the pairs. Generally, the floating coding is the first step.

The convergence of GA depends on the convergence of the crossover operators to some extent. From the capability of the crossover operators, it can be safely concluded that along with the evolution, the genes inside the chromosome will be independent. The best combination must be found as long as all the genes are present. It can reflect the characteristic and capability of crossover operator to broaden the population distribution.

There are also some other crossover operators such as matching crossover, ordered crossover, loop Crossover, heuristic crossover etc. It is also hard to say which one is better without due consideration of the practical problem.

5.1.3.4. Mutation

Mutation in GA, similar to biological mutation, is an operation used to maintain genetic diversity from one generation of a population to the next. Mutation uses a small probability value to mutate some part or parts of the individuals, such as the swap of 1 and 0 in a binary coded chromosome. Mutation itself is a kind of probable algorithm; however, when integrated with selection and crossover operation, the missing of useful information can be avoided.

The main objectives of mutation in GA is to

1) *Improve the local searching ability of GA*. Crossover operators have already found some individuals with good coding structure, they are near to the optimum. However, it is not enough to find all the detailed optimum for the local scale. The mutation operator could be used to pursue the optimum by adjusting some genes from the local search perspective.

2) *Maintain the diversity of the individuals and avoid the pre mature convergence.* The new gene can change the structure of the whole individual by a certain probability. This gives the population the ability to maintain the diversity, which is very essential to the performance of the optimization.

There are some general mutation operators:

1) *Simple mutation*: A mutation operator that simply inverts the value of the chosen gene based on certain mutation probability.

2) *Uniform mutation*: A mutation operator that replaces the value of the chosen gene with a uniform random value selected between the user-specified upper and lower bounds for that gene.

3) *Non-Uniform mutation*: A mutation operator that increases the probability that the amount of the mutation will be close to 0 as the generation number increases. It can keep the population from stagnating during the early stages of the evolution.

4) *Gaussian mutation*: A mutation operator that adds a unit Gaussian distributed random value to the chosen gene.

5.1.3.5. Fitness Function

Fitness is used to evaluate the degree of excellence of the population. The individuals with higher fitness values will be more probable to survive to the next generation. The function that is used to evaluate the individuals is named "fitness function". Fitness function is different from the objective function. Typically, fitness function is all positive but objective function might be negative or positive implying that sometimes the objective looks for minimization and sometimes it looks for maximization. Therefore, the transformation between objective function and fitness function is necessary and essential. As for the transform methods, any form of fitness is ok based on these requirements below:

The requirements of fitness function include: unique value, continuing, positivity, the more the better, reasonability, coherence, which are not very hard to achieve. Besides, the fitness function should be designed to minimize the computational complexity.

This is important as the computational complexity is an essential factor influencing the efficiency for the whole optimization process. From another perspective, the specificity of the problem is the base of the fitness function.

Sometimes, it is necessary to transform the fitness function at a different stage of the optimization procedure. The transformation of the fitness scale could be helpful in solving this problem to some extent. The frequently-used transform methods are linear transform, power transform, and exponent transform.

5.1.3.6. Constraints Setting

There is no general method to handle the constraints during the process of optimization. According to the specific problems, these methods to handle the constraints method can be divided to three types:

1) Searching space restriction

The principle of searching space restriction is to restrict the searching space for the optimization according to the specific problem. According to some simple constraints, the matching of the right searching space is a very effective way to improve the efficiency of the optimization process. Nevertheless, it is not easy for user to seek the appropriate searching space.

2) Transformation of feasible solutions

The principle of transformation method focuses on the swapping process. The transformation step coupled into the process shows the individuals belonging to the constraints.

3) Penalty function method

The principle of the penalty function method is to add penalty function value to the individuals without the related feasible solution. The decreased fitness value will reduce the probability of survival in the next generation. The disadvantage of this method is that it is very hard to define the suitable penalty function and the method's poor efficiency.

5.2 BFGA-MOLU

Based on the aforementioned discussion, the essential part of the GA is to focus on the specific problem. Different problems need different kinds of encoding, and different ways to perform the selection, crossover, and mutation operations. Therefore, the special characteristics to consider in the land use optimization for sustainable land use planning support are as follows: 1) Spatial optimization; 2) NP hard problem, 3) Objectives; 4) Variables; 5) Requirement of time spending etc. The design of all the operators or the process of GA used should meet these specifications. The analysis and the design of BFGA-MOLU are as follows:

5.2.1 Encoding/Representation of land use optimization problem

GA for land use optimization requires a chromosome to encode the land uses. A simple and direct chromosome representation is a list of grid of genes, where position of each gene (cell) represents a unit, and the land-use of the unit is determined by the value. It has been used in spatial analysis by many scholars (Butcher *et al.*, 1996; Ligmann-Zielinska *et al.*, 2008; Seixas *et al.*, 2005; Stewart *et al.*, 2004). Besides, Matthews *et al.* (1999) proposed two kinds of chromosome representations based on vectors. One is fixed-length representation which directly arranged the land uses to genes, which is sensitive to the number of land blocks. The other is the variable-length representation focusing on the Percentage and Priority of the allocation of a land use. It is sensitive to the number of land use types. Considering the computational aspects including the complexity of the algorithm, in this study, the feasible method will be chosen to encode the chromosome.

5.2.2 Fitness function

As discussed in the Model Formulation, a revised goal programming approach (reference point) is utilized in this study and the objective function is as follows:

$$f_{obj} = -\sum_{o=1}^{O} \alpha_o \left[\frac{f_{objo} - I_o}{T_o - I_o} \right] \qquad (5.1)$$

Thus, function $-f_{obj}$ could be the fitness function directly.

5.2.3 Initialization of parent solutions

Initialization of parent solutions is the first and foremost step in the GA iteration process. The initialization is also very important for the efficiency of the convergence process. Good initialization of the population can yield better "near-optimal" result if the expectation is correct. However, if the preference of the initialization is wrong, it might make the iteration fall into a local optimum or negatively impact the efficiency. Hence, in this research, a typical random initialization of the population is employed with 100 as the population number, which is not only sufficient for the iteration but also ensures the computational efficiency (see 5.3).

5.2.4 Selection

The fitness function here will be evaluated by $-f_{obj}$. The proximity to the reference point is directly proportional to the superiority of the solution. The process is to evaluate all the solutions created by last operation, either random generation of parent solutions or the solutions after crossover and mutation. The solutions are sorted in accordance with the fitness function, and the solutions with high fitness values have a greater possibility of being chosen to the next iteration.

5.2.5 Crossover

The crossover step involves creating the new gene combination by swapping the genes from different chromosomes in accordance with certain or adaptive probability. GAs tend to perform a general crossover by taking one half of the solution from one "parent" and the remaining half from the other parent. This implies that if each cell is independently allocated to one of the parent by random selection, the resulting child map will tend to be highly fragmented. The major problem related to the crossover process in land use optimization problem is with respect to the compactness of the final result and the swapping of the genes. Herein, owing to the characteristic nature of this problem, the crossover process is performed according to the method shown in Figure 5.6 below. The crossover gene chosen also depends on the neighbors of the first parent. If the randomly created cell in two parents are different and the neighbors of the chosen cell in the first parent have the same gene as the chosen cell in the second parent, then the offspring-1 will succeed all the cells except the chosen cell from the parent-1 and the chosen cell from parent-2. This iteration continues until all the solutions of the generation have undergone the crossover process. Such kind of crossover model named Boundary based Crossover Operator (CBO) can protect the spatial compactness to some extent.

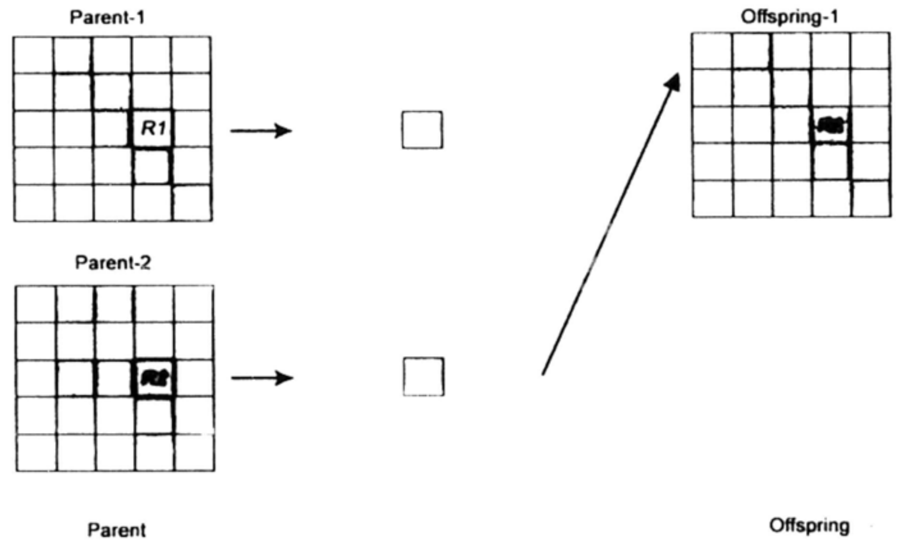


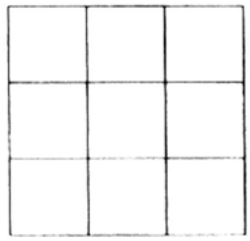
Figure 5-6 Procedure of CBO

R1 and R2 are the randomly chosen from the parents. If the two cells are different and the neighbors of R1 have the same cell as R2, the new offspring will be yielded, or another location of crossover cell will be created again till the operation is finished.

5.2.6 Mutation

Mutation is another significant operation to ensure the creation of good offsprings. Too much or too few mutation will negatively influence convergence and hence, adversely affect the optimal results. Hence, appropriately designing the mutation operation is very significant for the whole GA process. There are three mutation operators that suit the algorithm for the land use optimization problem. The first one is Patch based Mutation Operator (MPO) for maintaining diversity among the solution of a population. The second one is the Boundary based Mutation Operator (MBO). The third one is the Constraints Mutation Operator (MCO) for erasing the infeasible solutions from the population to satisfy the constraints.

1) MPO and MBO



Yellow one is the random created from the nine cells

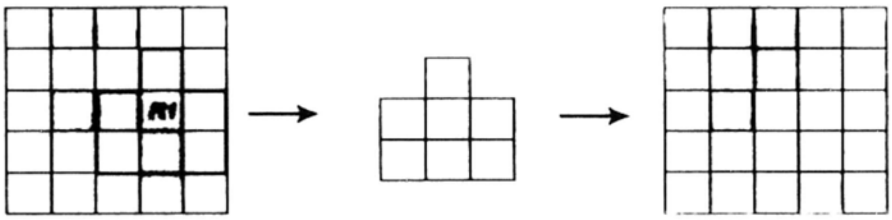


Figure 5-7 Procedure of MPO and MBO

The first step is to randomly choose the location of the mutation window and the shape of the patch with some probability. Next, the randomly chosen one land use type will be the mutation direction; finally, the original solution will be replaced by the mutation patch. The difference between MPO and MBO is that the MBO can judge if the neighbors of mutation windows have the same land use as the mutation window. If true, then the mutation will be carried out, if not, the process will repeat till all the conditions are satisfied.

2) MCO

For the constraints considered in such problem, apart from the conservation of special use of land patch, the MCO could be used to establish the structure and spatial location of specific land use. The difference between the MCO and MPO is in the second step. MCO evaluates whether the solution is satisfied with the constraints, if the area of one specific land use is more or less than the requirements. The mutation will choose the random location and the required land use type to steer the solution towards becoming more feasible.

5.2.7 Generation Gap (GG)

One of the characteristic of GA is the diversity of the generation for ability of global optimum searching. In this research, the weights of different objectives that reflect the opinions of the planners or policy makers are chosen prior to the operation. Hence, the GG will positively improve the efficiency of optimization process. In this case, the GG is set as 0.9 and the least population is set as 5 (see 5.3).

5.3 Parameters Setting and Robustness Experiments

One of the major issues in using an optimization tool is the establishment of the control parameters (Keane 1995). Preferably, few controls should be required for an optimization model to produce robust and reliable results. When an optimizer has many interrelated parameters, choice and fine-tuning of a set of control parameters that can give good results in the minimum time for a particular problem becomes a very complicated and challenging task.

The balancing rates of each operator can directly affect the GA's capacity to ascertain the optimal solution. In addition, there is no consensus in the GA literature with respect to the rate values for the crossover and mutation operators (Nunez, 2007). Some authors such as Goldberg (1989) employed a crossover rate of about 60 per cent with a very low mutation rate (of between zero to five per cent). However, there is a wide range of values for crossover and mutation for which "trial and error" tests can be used to fine-tune the rates. In fact, there exist no globally-accepted or unanimous rates of crossover and mutation operators. As mentioned already, the setting of the parameters in a GA are model or problem based. Although methods for determining useful values of genetic parameters have been reported in previous researches, the determination of these parameters still continues to be a challenging task. Thus experiments and analysis have to be specifically carried out to determine the appropriate parameter values for a particular problem, to achieve optimal performance. According to Aytug and Saydam (2002), the several key issues in designing a GA algorithm are as follows, which would be analyzed in detail:

- Different objectives considered
- Different size of research area
- Population initialization and GG
- Crossover operator

. Mutation operator

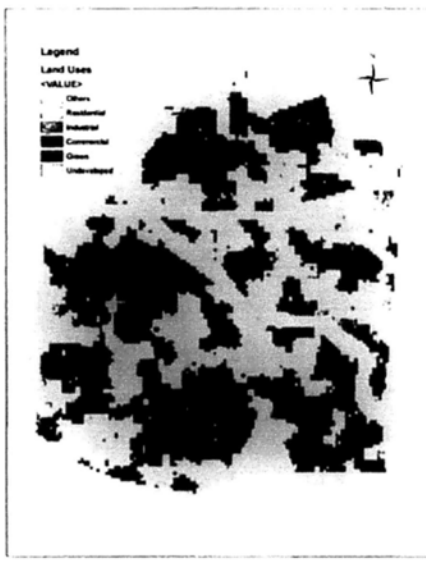
5.3.1 Different objectives considered

The model is tested by two objectives, compactness and compatibility, separately. The two objectives are operated under the environment of BFGA-MOLU with the following parameters:

Table 5-5 The Parameters Used for Single Objective of Compactness and Compatibility

Size	Iteration	Population	Crossover	Mutation	GG
141*119	5000	100	100/16779	(14,16)/16779	0.9

The optimal results are as follows:



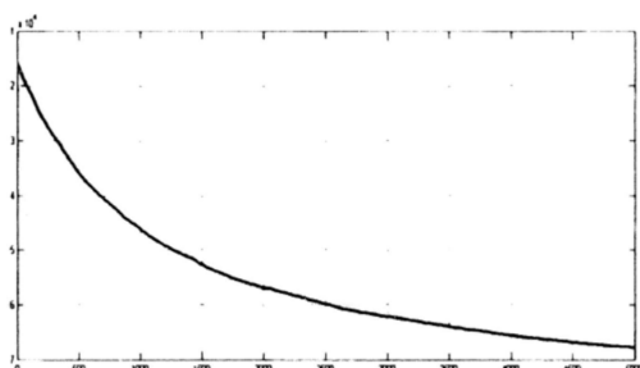


Figure 5-8 Optimal Result and Convergence Curve for the Objective of Compactness

The objective value of compactness changed from -17856 to -68628.

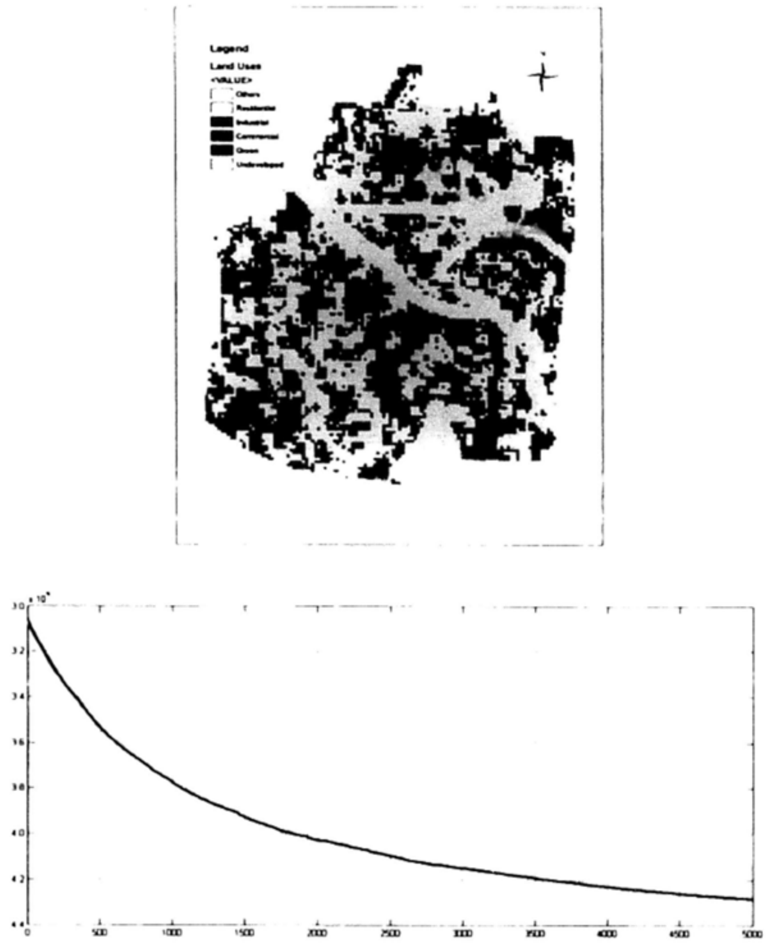


Figure 5-9 Optimal Result and Convergence Curve for the Objective of Compatibility

The objective value of compatibility changed from -32179 to -42858.

The ability of the model to generate compact solutions is evident from the figures above. A look at the convergent curve shows that the curve decreases very sharply at the beginning and subsequently, continues to become flatter, which leads to the conclusion that the model for this objective is convergent.

Also, the iteration curve reflects the convergence ability of the model for the objective of compatibility.

The other objectives are also tested on their own for thousands of iteration, the effect and the convergence of the model are all good enough. This clearly evinces that the model is stable with respect to these objectives with fixed evaluation functions.

5.3.2 Different size of research area

The size of the research area or the resolution is one of the essential parameters influencing the effect and the efficiency of the model. One of the objectives in this research is to improve the effect and efficiency for regions larger than 20 by 20 grid (141 by 119 grid in this research), which has been studied by some other scholars (Janssen *et al.*, 2008) and dozens of hours were needed for a grid larger than 100 by 100.

The model is tested using different size of research area on only one objective of GDP, which is more convenient to show the effect and the efficiency of the model. The test is conducted operated on 10 by 10 grid, 20 by 20 grid, 50 by 50 grid, and 100 by 100 grid area separately.

With all the other parameters setting as follows:

Table 5-6 Parameters Used for Single Objective of GDP for Different Size of Research Area

Population	Crossover	Mutation	GG
100	100/16779	(14,16)/16779	0.9

For 10 by 10 grid, the efficiency is very good, under the environment of (9, 7) mutation and 100 iterations. The time spending is only 3.01s for a convergent optimization.

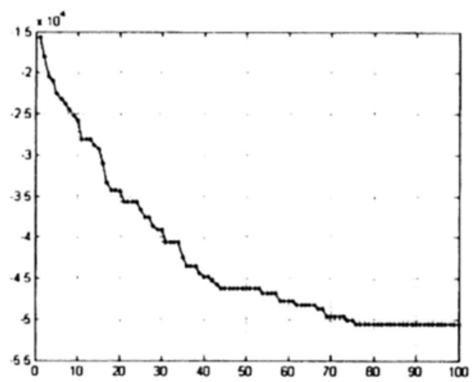


Figure 5-10 Convergent Curve of 10 by 10 Grid Area under the Environment of (9, 7) Mutation and 100 Iterations

Under the environment of (4, 3) mutation and 200 iterations, the time spent is only 3.36s for a convergent optimization.

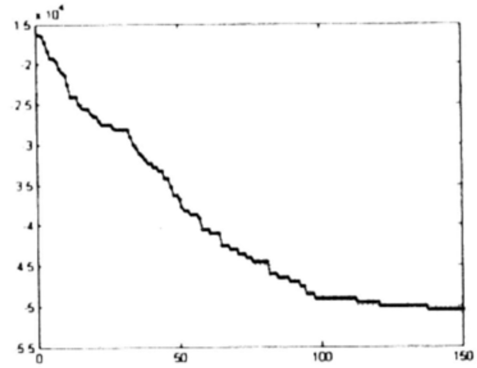


Figure 5-11 Convergent Curve of 10 by 10 Grid Area under the Environment of (4, 3) Mutation and 200 Iterations

With the similar initialization solutions and the optimal solution:

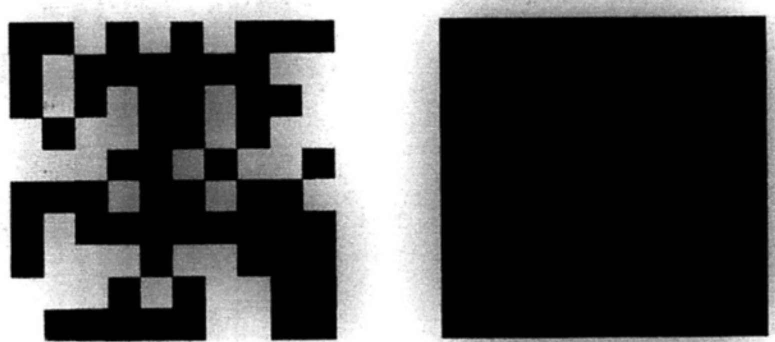


Figure 5-12 Initialization Solution (left) and Optimal Solution (right) of 10 by 10 Grid Area

For 20 by 20 grid, the efficiency is very good, under the environment of (16, 14) mutation and 250 iterations. The time spent is only 6.327s for a convergent optimization

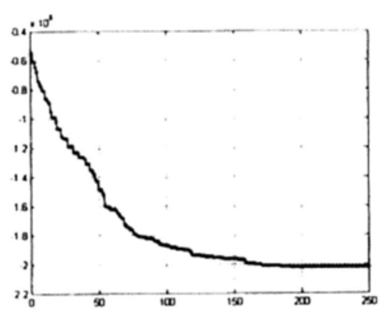


Figure 5-13 Convergent Curve of 20 by 20 Grid Area under the Environment of (16, 14) Mutation and 250 Iterations

Under the environment of (9, 7) mutation and 300 iterations, the time spent is 8.254s for a convergent optimization

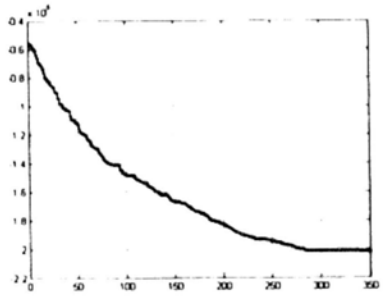


Figure 5-14 Convergent Curve of 20 by 20 Grid Area under the Environment of (9, 7) Mutation and 300 Iterations

With the similar initialization solutions and the optimal solution:

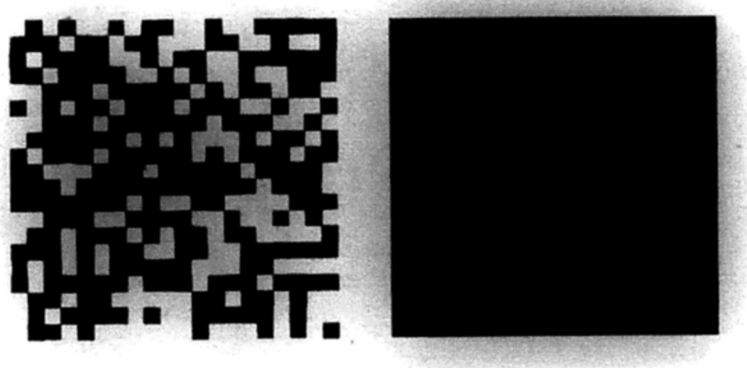


Figure 5-15 Initialization Solution (left) and Optimal Solution (right) of 20 by 20 Grid Area

For 50 by 50 grid, the efficiency is also very good, under the environment of (25, 23) mutation and 1000 iterations. The time spent is 141.603s for a complete convergent optimization

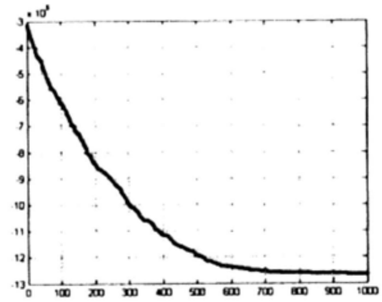


Figure 5-16 Convergent Curve of 50 by 50 Grid Area under the Environment of (25, 23) Mutation and 1000 Iterations

Under the environment of (16, 14) mutation and 1500 iterations, the time spent is

213.438s for a convergent optimization

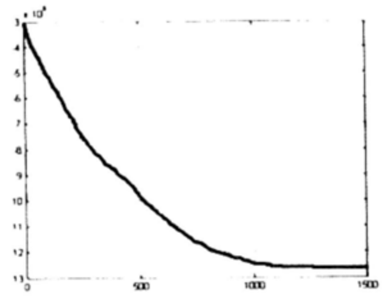


Figure 5-17 Convergent Curve of 50 by 50 Grid Area under the Environment of (16, 14) Mutation and 1500 Iterations

With the similar initialization solutions and the optimal solution:

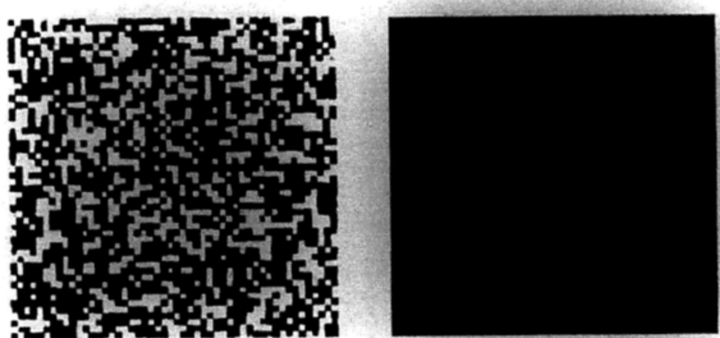


Figure 5-18 Initialization Solution (left) and Optimal Solution (right) of 50 by 50 Grid Area

For 100 by 100 grid, the efficiency is very good, under the environment of (36, 34) mutation and 1000 iterations. The time spent is 576.608s for a near-convergent optimization, which also demonstrates the convergent trend of the model.

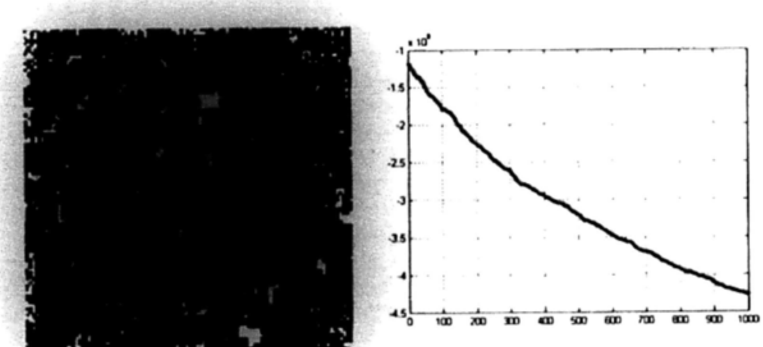


Figure 5-19 Optimal Result and Convergent Curve of 100 by 100 Grid Area under the Environment of (36, 34) Mutation and 1000 Iterations

Under the environment of (25, 23) mutation and 1000 iterations, the time spent is 565.313s for a also near-convergent optimization

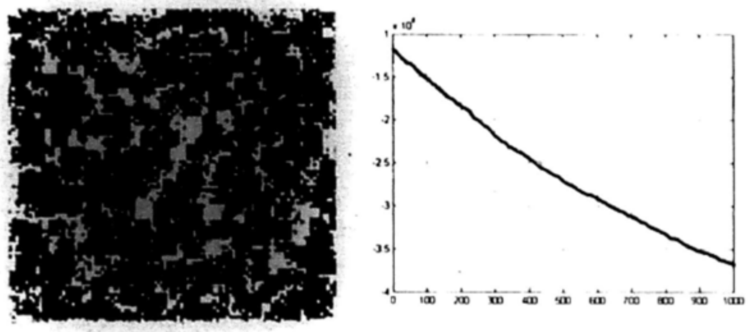


Figure 5-20 Optimal Result and Convergent Curve of 100 by 100 Grid Area under the Environment of (25, 33) Mutation and 1000 Iterations

Both the optimizations are based on the random initialization population.

The robustness and the optimization capability of the model are evident from the above tests. Especially, the efficiency on the small area and the effect on the sampling objective are shown clearly. On the other hand, the time consumption by the model increases along with the increase of the size of the research area because of the far too many variables. Besides the successful experiments on different scales of research area with different mutation setting, the test on the 100 by 100 grid also proves the efficiency of the model on this scale of research area.

5.3.3 Population initialization and GG

The population is another parameter that might also be very important in influencing the effect and the efficiency of the model. A bigger size for the initial population results in greater diversity and lower computation efficiency. There is an obvious conflict in defining the initial population to arrive at a suitable tradeoff between the diversity and the computational complexity.

On the other hand, the GG is another factor that influences the effect and the efficiency of the computation. Tests are performed considering the generation with 1, 0.9, and 0.8 with the related population consideration.

The test is performed on the research size according to the objective of GDP, which has a very simple evaluation method. Besides, as it has been confirmed that the iteration number is not sensitive to the convergent ability of the model, the tests will only work for 100 iterations to decrease the time consumed.

Table 5-7 Parameters Used for Single Objective of GDP for Different Population

Size	Iteration	Population	Crossover	Mutation	GG
141*119	100	50/100/200	100/16779	(14,16)/16779	0.9

Under the consideration of the instability of different computation, five times' tests are operated, the average of the time and values are listed in the table:

Table 5-8 Comparison of Optimal Results on Different Population Setting

Initialization population parameter							
50		100		150		200	
Time(s)	Value (10e6)	Time(s)	Value (10e6)	Time(s)	Value (10e6)	Time(s)	Value (10e6)
229.2	1.4504	242.6	1.477	257.8	1.4736	289.4	1.4974

From the table above, we can conclude that the average time spent and the objective values are almost linear correlated along with the increase of the population from 50 to 200, and there is very little influence for the population from 50 to 200. Thus, splitting the difference, we could choose 100 as the amount of initialization population, which is also the general setting by many other GA applications.

In this research, the same parameters are tested on the objective GDP with the GG 08, 0.9 and 1 separately as follows:

Table 5-9 Parameters Used for Single Objective of GDP for Different GG

Size	Iteration	Population	Crossover	Mutation	GG
141*119	100	100	100/16779	(14,16)/16779	0.8/0.9/1

Table 5-10 Comparison of Optimal Results on Different GG Setting

GG parameter					
0.8		0.9		1	
Time(s)	Value (10e6)	Time(s)	Value (10e6)	Time(s)	Value (10e6)
236	1.3255	242.6	1.477	547.27	1.57

From the table above, the solution with 0.9 as the GG seems to be much better than the solution with 0.8 as the GG (with only a little increase in time spent). However, from 0.9 to 1, both the time spending and the objective value increased a lot. As for the same situation, the model using 0.9 as the GG only needs 176 iterations and 410.3s to achieve 1.57 as the model using 1 as the GG.

Obviously, when the GG is too low, on one hand the effect will be adversely influenced because of the lack of good solutions. On the other hand, as the operators are based on the solutions themselves, the efficiency will decrease because of the lack of diversity of the solutions between generations. Thus the value of 0.9 as the GG is more suitable to be the parameter. Compared to the model using 1 as the GG, which means that there is no GG, the effect is better than the model using 0.9 as the GG. Nevertheless, the efficiency is much poorer than the latter one, thus, in this research, 0.9 is chosen as the GG.

5.3.4 Crossover operator

During the crossover operation, the crossing cells could also be set according different need, inside this model, the tests are operated on 10, 50, 100 and 150 times separately with the same other parameters as follows:

Table 5-11 Parameters Used for Single Objective of GDP for Different Crossover Setting

Size	Iteration	Population	Crossover	Mutation	GG
141*119	100	100	10,50,100,150/16779	(14,16)/16779	0.9

Considering the instability of different computations, five times' tests are operated and the average of the time and values are listed in the table:

Table 5-12 Comparison of Optimal Results on Different Crossover Setting

Crossover parameter							
10		50		100		150	
Time(s)	Value (10e6)	Time(s)	Value (10e6)	Time(s)	Value (10e6)	Time(s)	Value (10e6)
191.2	1.447	212.6	1.455	242.6	1.477	291.4	1.492

From the table above, 100 could be chosen to be the parameter in this research with its little advantage.

5.3.5 Mutation operator

For the mutation operation, the mutation window could also be set with different preference. Tests are performed on (3, 4), (7, 9), (14, 16) and (23, 25) separately with the same values for the other parameters.

Table 5-13 Parameters Used for Single Objective of GDP

for Different Mutation Setting

Size	Iteration	Population	Crossover	Mutation	GG
141*119	100	100	100/16779	(3,4)(7,9) (14,16)(23,25) /16779	0.9

Consideration the instability of different computations, five times' tests are operated, the average of the time and values are list in the table:

Table 5-14 Comparison of Optimal Results on Different Mutation Setting

Mutation parameter							
(3,4)		(7,9)		(14,16)		(23,25)	
Time(s)	Value (10e6)	Time(s)	Value (10e6)	Time(s)	Value (10e6)	Time(s)	Value (10e6)
253.2	1.438	241.7	1.461	242.6	1.477	269.3	1.489

From the table above, the time spent for each parameter almost seems to be the same. However, the objective value is increasing linearly along with the size of the mutation window. The window size should be related to the size of the research area, in order to avoid the over mutating, besides, under the consideration of the mutation window's shape, (14, 16) is chosen as the final mutation parameter.

5.4 Summary

To summarize, this chapter discusses the principles of generic GA and the design of BFGA-MOLU model based on the characteristics of the land use optimization problem.

The basic framework of GA includes steps namely Encoding, Initialization, Selection, Crossover, Mutation etc. The parameters for all of these aspects will influence the effect and the efficiency of the specific problem. In the second part, according to the characteristics of the land use optimization process, a model named "BFGA-MOLU" is built to operate the spatial optimization task compromising different objectives aimed at attaining sustainability. The model is explained in detail from the encoding step to the introduction of special parameter-GG. Herein, the revised goal programming (reference point) method is integrated into the model, which is not only demonstrates the effect of multi-objective optimization, but also the interactive operation potential as a valuable planning support tool. Besides, the crossover and mutation operators are both spatial optimization problem based. These could improve the convergent ability of the optimization process so as to improve the efficiency as well as the effect. The parameters in the construction of the "BFGA-MOLU" model significantly influence the optimization process. The robustness or the stability of the model is another essential part need to bet tested before the real application. In the third part, the experiments are performed according to different objectives, different sizes of research area, different settings of initialization population, and GG. Besides establishing the robustness of the model, suitable parameters could also be obtained. This chapter serves to demonstrate the effect and overall efficiency of the model considered in this study.

CHAPTER 6: APPLICATION AND EVALUATION OF BFGA-MOLU MODEL

6.1 Implementation and Evaluation

The BFGA-MOLU model is executed for 5000 iterations considering eight objectives: Maximization of GDP (Obj-1); Minimization of Conversion (Obj-2); Maximization of Geomorphology and Geological Suitability (Obj-3); Maximization of Ecological Suitability (Obj-4); Maximization of Accessibility (Obj-5); Minimization of NIMBY Influence (Obj-6); Maximization of Compactness (Obj-7); Maximization of Compatibility (Obj-8), and the constraints with restricted green space and the area of residential and commercial. Before the final optimization operation, each single objective above has been optimized on its own. Subsequent to these operations and after applying common sense considerations, the maximization and minimization values of the objectives are obtained to normalize the objectives to obtain the final fitness function.

The model execution on an area of 141 by 119 cells with CBO MPO, MBO and MCO mutation operators required about 5.5 hours for the 5000 generations of 100 population. A MacBook Pro laptop computer with an Intel(R) Core(TM)2 Duo CPU P7550@2.26GHz and 2 GB RAM was utilized for this execution.

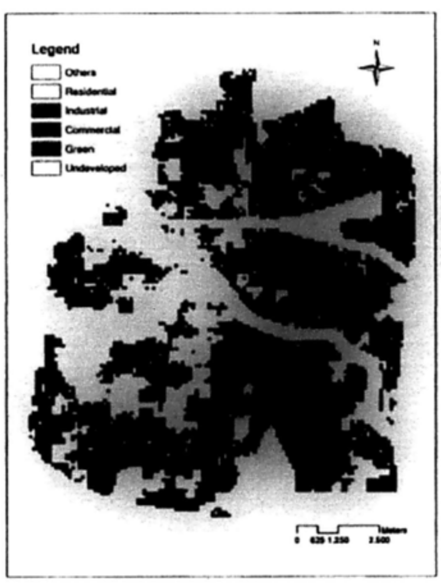


Figure 6-1 The Optimal Result based on BFGA-MOLU Model

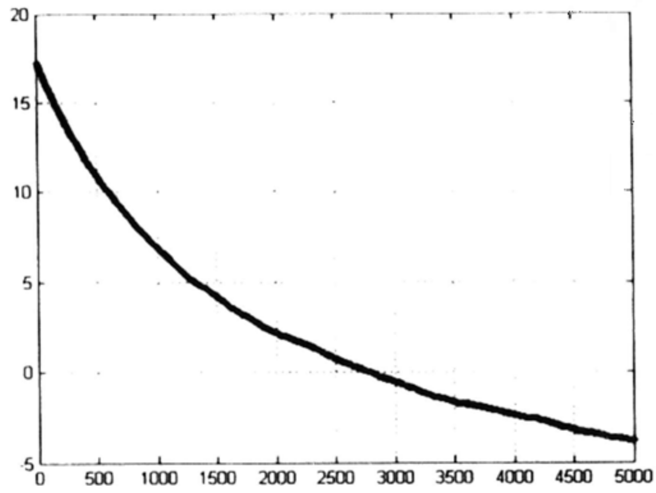


Figure 6-2 Convergence Curve of the Optimization Process

The equal weight optimal result is shown in the figure above. Based on the optimal result, the main commercial area in the future will focus on the north part, which is near the old city center. Another focus of the commercial area is towards the eastern city center, which is another dispersed new center of Tongzhou Newtown. It is beneficial for the multi-center development which effectively decreases urban energy consumption and eases the transportation pressure caused by instant urbanization. Besides, from the old commercial center to the south, the commercial density will increase. In the meantime, enough residential land around these commercial centers will also be developed to accommodate the future population. On the other hand, the green land is primarily located in the northern areas of Tongzhou Newtown. These areas are unsuitable for built up area owing to both the geological condition and the high level ecological planning background. The green land provides ecological benefit not only to the Tongzhou Newtown, but the whole of Beijing. In addition, it also gives the Tongzhou Newtown a marvelous urban environment which enhances the overall characteristic of the city and promotes the health of residents. The industrial area is mainly located in the northeast and southeast of Tongzhou Newtown. Furthermore, there are some industrial areas dispersed around the old industrial area, which is more suitable for the light industry. Within the concentration of industrial area, several commercial and residential areas are also located, thereby providing the workers with sufficient living space.

Summarily, with due consideration of the eight objectives, the optimal result seems to extremely appropriate. In order to prove the rationality of the optimization, the comparison of the optimal result and the planned scenario has been displayed below (the legend is the same as Figure 6.1. Meanwhile, the undeveloped land of the planned scenario is located among other space except the four land use types)

Table 6-1 Comparison of Planned Scenario and Optimal Scenario

		Planned Scenario	Optimal Scenario	
Figures				
Objectives	Obj-1	-815497	-1963535	140.78%
	Obj-2	-1425	-2937	106.11%
	Obj-3	-47762	-59880	25.37%
	Obj-4	-7352	-13784	87.49%
	Obj-5	-509218	-738895	45.10%
	Obj-6	-563381	-479555	-14.88%
	Obj-7	-61392	-67346	9.70%
	Obj-8	-37600	-40789	8.48%

As shown in the table above, it is obvious that there are huge improvements in all the objectives except the objective-6. Compared to the planned scenario, GDP, conversion cost, ecological suitability, have increased by 140.78% 106.11% and 25.37% respectively. Besides, the geomorphology and geological suitability, accessibility, compactness, and compatibility also have increased by 87.49%, 45.10%, 9.70%, and 8.48% in the planned scenario. Only objective-6: the NIMBY influence, decreases by 14.88% which is not too much and could be ignored and understandable. According to to the figures above, it can be concluded that the optimization could yield a more comprehensive planning scenario than the ones which mostly depend on the subjective. From the optimal scenario above, it is obvious that more green land could be found in the optimal scenario with the required ecological needs, higher suitability, more compact and mixed use of the commercial, residential, and green land, and more compatibility between different land use types etc. From another perspective, there are also some similarities between the two scenarios. Both of them allocate industry mainly in the southeast and northeast of Tongzhou Newtown and they allocate the new commercial center in the east of the urban area, etc. Of course, it is just the land use planning support tool and cannot substitute the planner's decision on the planning. However, it is meaningful for the planners or policy makers to refer to when they make a plan or a decision.

There are too many differences between the optimal scenario and the planned scenario, Firstly, the considerations might be different for the planned scenario and optimal scenario, the planned scenario is based on the analysis on the land use status quo, the suitability of different factors etc and the design by the planners or policy makers, the optimal scenario is based on the compromising the eight objectives mentioned above. The factors considered might be different, which is the first reason to lead to the differences. From another perspective, the planned scenario had left much more undeveloped land with dispersed green land, that's the main reason that there is not obvious green land in the planned scenario, however, as for the optimal scenario, what we focused is the compactness, that is another reason.

For a different set of preferences, the final result will be much different. Besides the equal weight optimal result, there are also some other optimal solutions that could be achieved: Inside the four optimization operation, each objective preferred is maintained by the weight setting as 2. The results are as follows:

Table 6-2 Four Optimal Scenarios of Obj-4 Preferred, Obj-5 Preferred, Obj-7 Preferred and Obj-8 Preferred

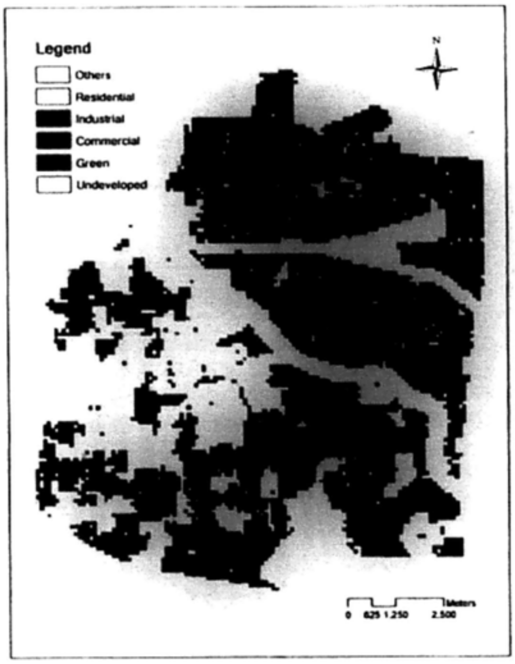
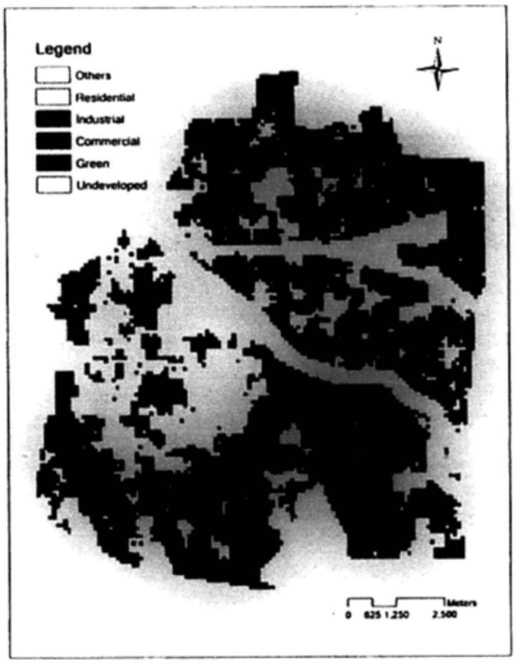
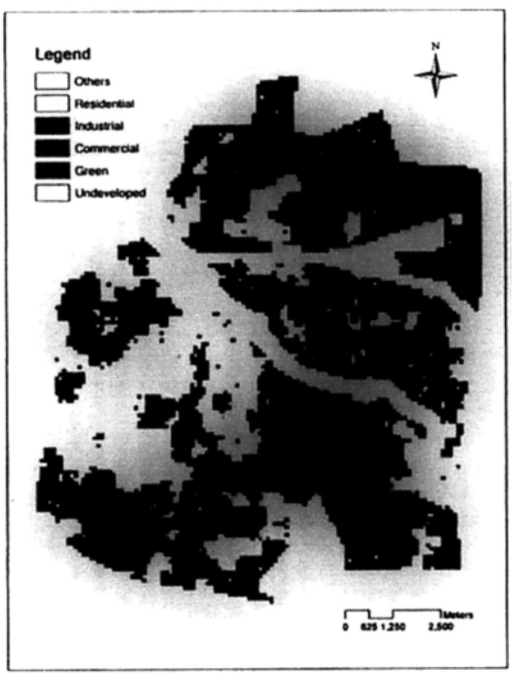
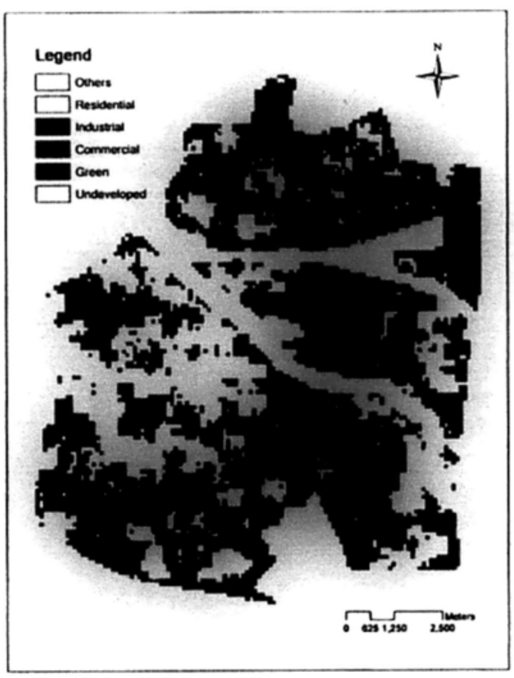
Obj-4 preferred:	Obj-5 preferred
	
Obj-7 Preferred	**Obj-8 Preferred**
	

Table 6-3 Comparison of the Objectives' values and the Structural Allocation of Obj-4 Preferred, Obj-5 Preferred, Obj-7 Preferred and Obj-8 Preferred and Equal Preferred Optimization Scenarios

	Obj-4 preferred	Obj-5 preferred	Obj-7 preferred	Obj-8 preferred	Equal preferred
Obj-1 value	-1109589	-2607065	-1678282	-2011305	-1963535
Obj-2 value	-2554	-2771	-2670	-2686	-2937
Obj-3 value	-58136	-60420	-60298	-60439	-59880
Obj-4 value	-19172	-9214	-13493	-12987	-13784
Obj-5 value	-605109	-878397	-743050	-754180	-738895
Obj-6 value	-566809	-397661	-524439	-486601	-479555
Obj-7 value	-69990	-68390	-69324	-67214	-67346
Obj-8 value	-40953	-40849	-40874	-41017	-40789
Residential	3150	3153	3161	3173	3153
Industrial	1451	2137	2285	1747	1658
Commercial	2024	4907	3051	3774	3690
Green	4235	685	2330	2168	2351
Undeveloped	32	10	65	30	40

The comparison table includes all the quantified information for each optimal solutions according to the equal preferred, obj-4 preferred, obj-5 preferred, obj-7 preferred and obj-8 preferred. Obviously, the constraint of residential area ensures satisfying the residential and consumption needs of the residents in 2020. For obj-4 preferred solution, the value of obj-4 is larger than the other solutions, for the optimal result, there are much more green land located in some place, which is more suitable to allocate green land under the consideration of the upper level ecological planning. On the other hand, the value of obj-1 is just 1109589, which is the worst among these solutions because of the limited land occupation by green land. As for the obj-5 preferred optimal solution, the value of objective-5 is much higher than the other solutions by nearly 15% to 50%, which presents the better accessibility of this solution. Along with the development of accessibility, the economic benefit (obj-1 value) is also the best among these solutions, which also shows the importance of transportation on economic development. As for the obj-7 and obje-8 preferred optimal solutions, the objective value of obj-7 and obj-8 are not much better than the other solutions, because of the characteristics of the two objectives. From the optimal results, it can be clearly found that the compactness of obj-4 preferred optimal solution is even more than the obj-7 preferred optimal solution, which is because the pursuing of obj-4 will also improve the obj-7 value. For the obj-8 preferred optimal solution, the difference or the improvement of this solution is also not very obvious. However, it is definitely the best among these solutions according to the quantified evaluation model, which demonstrates that the optimization method is very meaningful to help the planners or policy makers in finding the scenario that is better suited for the their preferences.

For the equal preferred solution, all the objectives are under the same consideration, the value of each objective is also among these values of other solutions, for the optimal result, which has been compared to the planed scenario above, is obviously balanced by each objective, which could guide the sustainable land use planning according to the equal weight preference.

During the land use planning process, the lack of quantified and comprehensive analysis of the research area is a major obstacle for suitable and sustainable planning. The model applied in the case study above demonstrates superior capability to perform quantified analysis of different objectives and the comprehensive analysis to obtain the tradeoff between these conflicting objectives. Each optimal result can cater to the planners or policy makers' opinion with due consideration of the sustainable land use planning for different area, time, and policy. According to the different requirements, or different weights, the model could help us to obtain some suggested planning scenarios, which could reflect the opinion of planners or policy makers very clearly and by the way of quantity and comprehensive analysis on each cell of the research area as well as the whole area.

With respect to the suggested planning scenarios, planners or policy makers could have a tool to support the planning. This not only refers to the main development area, but detailed compromising scenarios and areas could also be obtained. Besides, the different scenarios that result when planners or policy makers consider different objectives could be known and the users can be provided with a detailed analysis for each factor on each area.

Planning process is a process of negotiation involving experts, planners, governments, environment protectors, public etc. Through the optimization process described above, everyone's requirements or opinions could be included and by duly considering and changing the model objectives, the usage of this sustainable PSS can further be broadened.

6.2 Interactive Land Use Planning Support based on Optimal Results

The land use planning process is indeed a prolonged one for the planners or policy maker to analyze and make a sustainable, comprehensive proposal. Sometimes, the best tradeoffs from the mathematical optimization and computation will not satisfy the real need or real decision of the final planning. Even the planners or policy makers may not, at times, have the exact priority of different objectives. Hence, the interactive operation integrated into the optimization could prove to be meaningful under such circumstances. This provides the planners and policy makers more room design the plan and consummate the model applied above.

In this research, a prototype of friendly interactive interface is built around the model including the objective setting, the parameters setting, and the visualization of the optimization results. The interface is based on the feedback provided by the planners in a planning session. A typical interactive session includes several rounds. At the start of each round one optimal land use scenario is presented to the user including the planners or policy makers. The users are asked to provide feedback on this planning scenario. The model uses this feedback to generate a new version of the sustainable land use planning scenario, which will be presented to the planners at the start of the next round. The session will end when the planners or policy makers are satisfied with the optimal result.

During each round, the planners or policy makers can adjust weights of different objectives and the parameters inside the optimization. In future, even the evaluation model of each objective could be interactively defined by the planners or policy makers, which can enhance the flexibility of the model.

The interface of the interactive land use planning support prototype system based on BFGA-MOLU towards sustainable development is presented as follows:

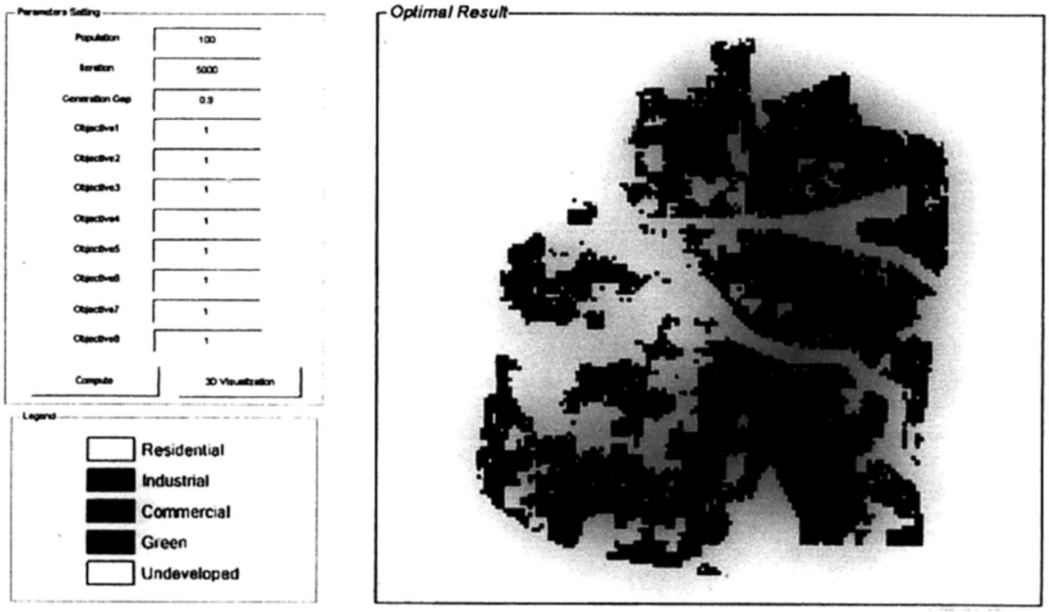


Figure 6-3 The Simplified Interface of the Interactive Land Use Planning Support Prototype System based on BFGA-MOLU towards Sustainable Development

The parameter setting area and the weighting setting area is on the left, the legend and the optimal result area is located on the bottom area and the right. Additionally, the time calculagraph is also included, which could be used to compute the time spending for each round.

Figure 6.3 above also shows the optimal result computed under the environment of equal weight and 5000 iterations with 0.9 as the GG and 100 as the population as the first round of the interactive process. The convergent curve clearly shows the near-optimal characteristic of this solution with the curve as follows:

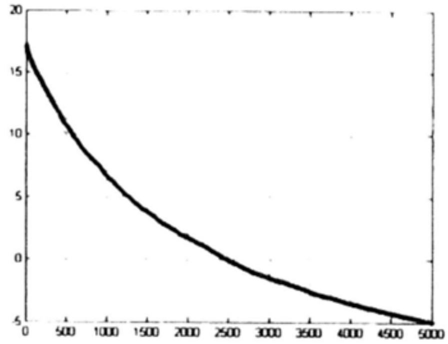


Figure 6-4 Convergent Curve of First Round

For a new round of the interactive planning process, we could take advantage of this optimal result as the initial point. If the user wants the planning scenario that can yield more economic benefit, the weight could be changed to 2 for objective-1, after 1000 iterations, which also could be defined by the users, the final result is below:

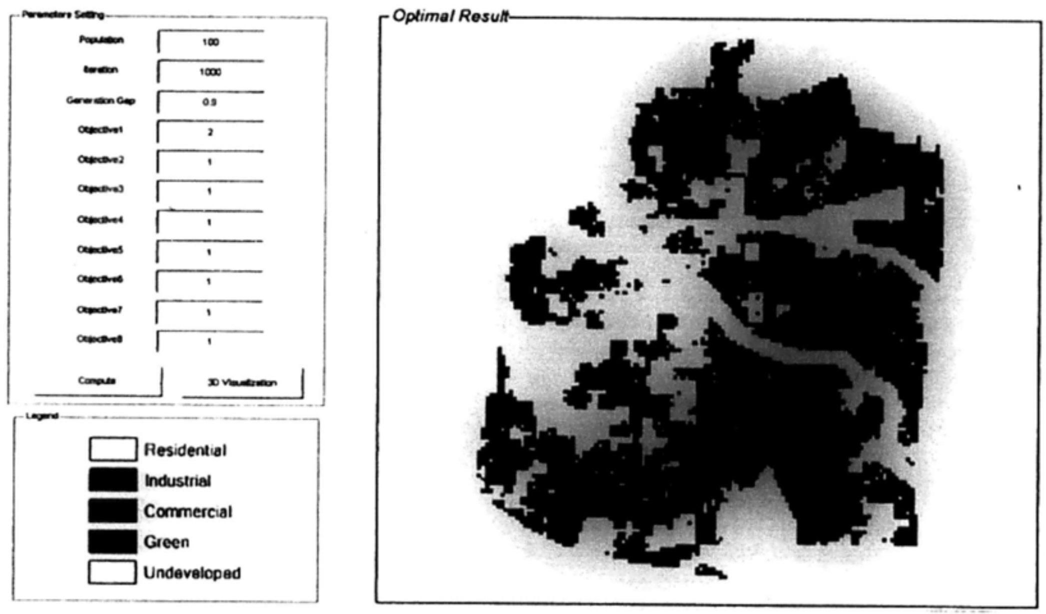


Figure 6-5 The Optimal Scenario of Second Round

For the convergent curve,

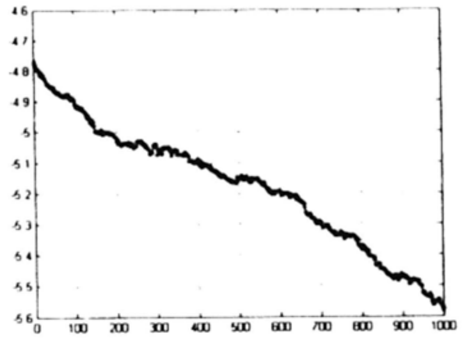


Figure 6-6 Convergent Curve of Second Round

The trend of optimization is very clear, but the convergence is not quite good. Nevertheless, the target here is to satisfy the planners' or policy makers' need or opinion. If the users think that the result is good enough, that will be the end of this round, else, more iterations are performed for this round. For the optimal result, the commercial and industrial land occupies more land than the situation in earlier scenario. Assumed that the result is good enough for the GDP objective, as the end of the second round, it is also the start of the third round.

Reflecting more on the influence of the transportation facilities on the land use planning, the next round will focus on not only the obj-6 accessibility, but also on the NIMBY which is to decrease the influence of railway on the land use planning. The two objectives will be set as 2 in the 3rd round optimization. Another 1000 iterations are performed. The result is as follows:

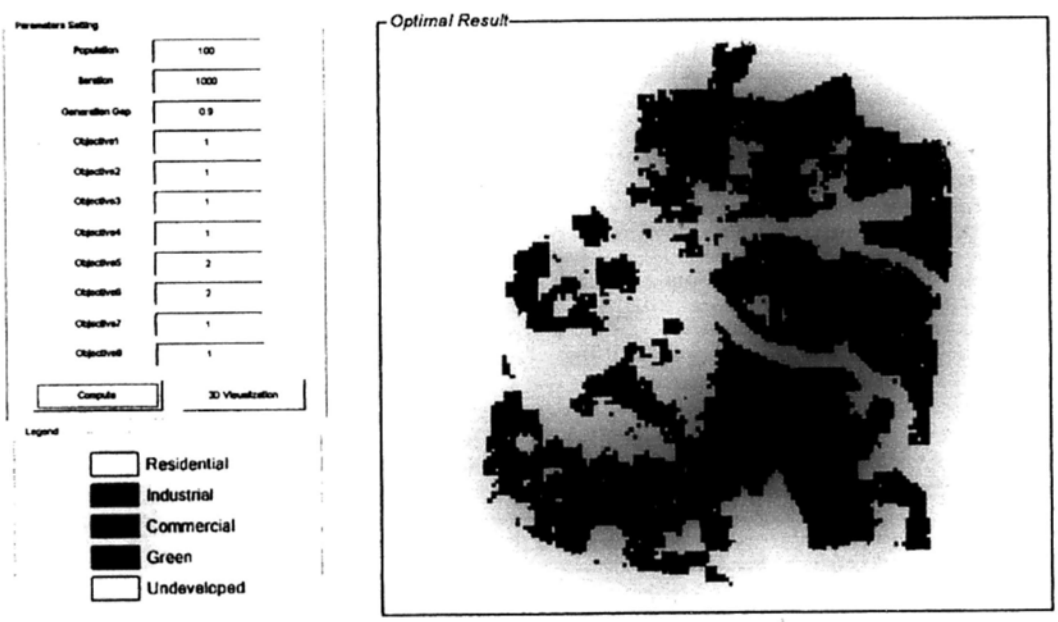


Figure 6-7 The Optimal Scenario of Third Round

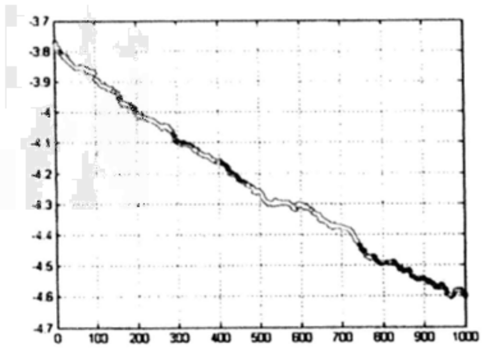


Figure 6-8 Convergent Curve of Third Round

Based on the transportation situation, the results are found to be good. If the users feels that the results are not good enough, another 1000 iterations could be performed, and this could be defined the start of the fourth round.

After another 1000 iterations, the result can be seen as follows:

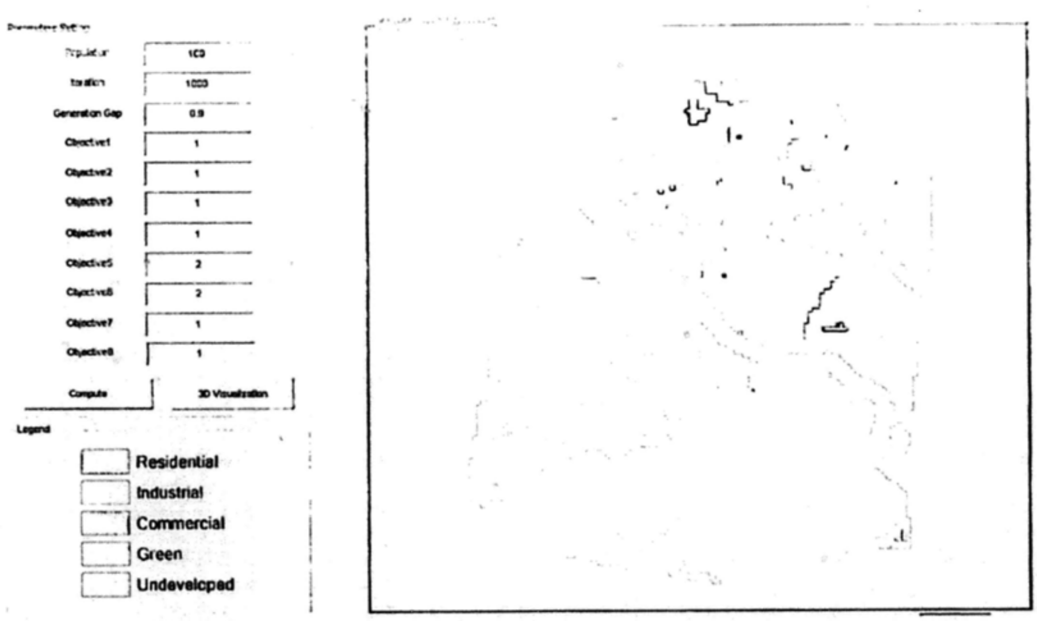


Figure 6-9 The Optimal Scenario of the Fourth Round

As well as the convergent curve:

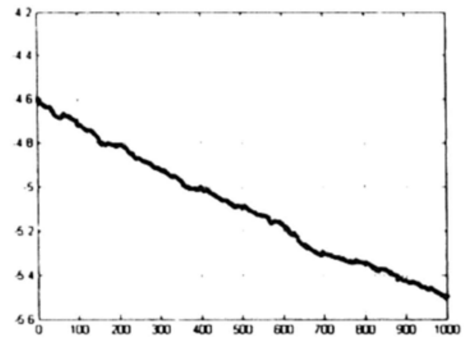


Figure 6-10 Convergent Curve of Fourth Round

If the user is satisfied with the optimal solution, the interactive land use planning support by BFGA-MOLU towards sustainable development could be terminated here. This obviously provides the planners or policy makers a reliable kind of planning support tool to make the planning process more convenient and scientific.

6.3 VR based Visualization of Optimal Result

Visualization facilitates not only presenting information, but also enables understanding hidden information among datasets. Planners who are experts in the field of land use planning can find out desirable or undesirable patterns using virtual scene renderings.

Considering the need for a simplified real time 3D visualization, as well as the characteristics of different 3D rendering tools, the OpenSceneGraph (OSG) is used here. The OSG is an open source high performance 3D graphics toolkit, used by application developers in fields such as visual simulation, games, VR, scientific visualization and modeling.

During the modeling and the rendering process of 3D visualization, an essential conflict arises between the time spending/efficiency and the extent of detailed representation for these features. Of course, owing to the advances in graphics technologies, this conflict has been alleviated to some extent. However, the more detailed the model requirement, the more complicated it becomes.

The real time 3D visualization for the PSS is only to show the virtual planned scenarios. This does not require too much 3D modeling. Hence, the simplified real time 3D visualization model is enough as part of the PSS.

The features are all presented by box, which is the most simplified representation of features, for different land use types. The color, size, and the density are different, the color is in accordance to the color of the land use type as per the 2D map; the size and the density are related to the common sense factor that the commercial features are higher than residential and industrial features.

For the 3D visualization, the features could be zoomed in and out, rotated by any angle, and the path of the cruise can be set. All these can help the users observe the sustainable land use planning scenarios in a more intuitive manner.

The overview of one scenario is as follows:

Figure 6-11 Simplified 3D Visualization of Optimal Land Use Scenario (full scene)

When zooming in:

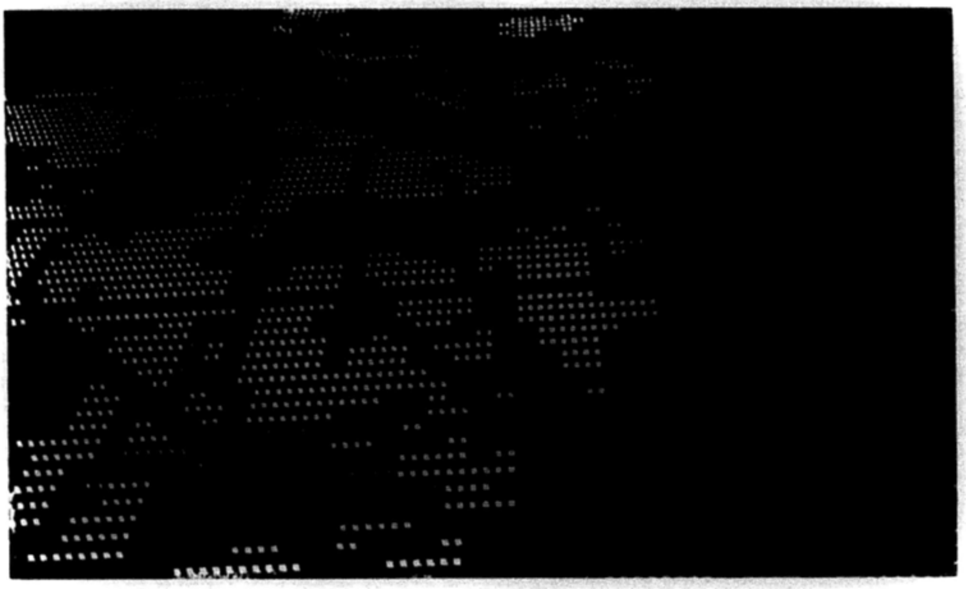


Figure 6-12 Simplified 3D Visualization of Optimal Land Use Scenario (part scene)

Unmistakably, real time presentation of the detailed features is also an important research topic. For more real representation of the features, one kind of building features database could be built including more detailed features for different land use types, which also could be presented by random or interactive choice of the planners or policy makers according to much more background information, such as the plot ratio, greening ratio of special land block.

6.4 Summary

In this chapter, the BFGA-MOLU model was applied in Tongzhou Newtown not only for the equal weight preference, but also some other options such as obj-4 preferred, obj-5 preferred, obj-7 preferred, obj-8 preferred. All of these applications showed the optimization ability of the model, besides, different preference applications could supply different suggestions during the planning support process. The equal weight optimization result was compared to the planned scenario in 2020, from the eight aspects. Most of them have improved a lot, especially for the obj-1, obj-2 and obj-4, which increased respectively by 146.68%, 92.35% and 87.58%. According to the different objective preferred, each optimal solution is better than other solutions on the related objective.

The second part discussed the prototype of interactive PSS based on BFGA-MOLU towards sustainable development with friendly interface. This was based on the optimal results, which include the choice of the objective and the weights, setting of the parameters, and the evaluation model. The case study is operated for 4 rounds, for different opinions or preferences of the users including the planners or policy makers, and the public as well. Finally, the final optimal interactive result is pursued, which could reflect the entire process of thought of the users or the negotiation.

Furthermore, a prototype of 3D visualization for the optimal land use planning scenarios is built based on OSG technology, which represents the trend of the planning support visualization. Although only the simplified 3D features are constructed to present the optimal scenarios, the effect is also enhanced by the characteristics of VR such as immersion, interaction, and imagination.

CHAPTER 7: CONCLUSION

As described in Chapter One, this research primarily aims to develop an optimization model that is capable of generate sustainable land use scenarios to support the land use planning process according to the planners' or policy makers' preference. This chapter summarizes the primary achievements and contributions of the thesis. Finally, the chapters provide the results and limitations of the study, and offer some directions for future research.

7.1 Summary of the Research

This research focuses on five important issues for sustainable land use optimization and planning support. The first one is the understanding of objectives on sustainable land use planning, which is used to translate the sustainability to land use dimension and guide the land use planning process accordingly. The second one is the effective formulation of the MOLU model to combine these objectives together. The third one is establishment of a suitable evaluation model for each objective. The fourth one is to set up an efficient heuristic optimization models to realize the tradeoffs of the multi-objective land use model. The final objective involves the design of a friendly interface and the visualization of the optimal results. This plays an important role during the sustainable land use planning support process.

Sustainability can be understood from three main perspectives: economy, environment, and society. Land use planning is a process of resource allocation, which involves allotting different activities of uses to specific units of area within a region, such as residential land, industries, recreational facility, green land etc. Comprehensive sustainability on land use planning can be defined as the attainment of the long-term balance among economic development, environmental protection, efficient resource use, and social equity.

This research comprehensively reviews and analyzes the related contents of sustainability and land use planning. This includes the indicators of sustainability, objectives used by other scholars in similar studies etc. Subsequently, eight objectives are chosen for evaluating and guiding sustainable land use planning: Maximization of

GDP; Minimization of Conversion; Maximization of Geomorphology and Geological Suitability; Maximization of Ecological Suitability; Maximization of Accessibility; Minimization of NIMBY Influence; Maximization of Compactness; Maximization of Compatibility. These objectives are subject to the data limitation pertaining to the research area- Tongzhou Newtown. Besides these objectives, the trade-off process should also consider the constraints, such as the restricted area and the maximization or minimization of special land use types etc. The revised goal programming method is used to formulate the MOLU model to smoothly integrate these objectives and constraints together.

All the aforementioned objectives except Maximization of GDP are complicated, whose evaluation entails more effective methods. The maximization of GDP is simply based on the sum of each cell with each special land use type, which might yield different amount of GDP value. The GDP values created by different land use types are computed using historic data and statistical method. The second objective, Minimization of conversion, which is generally calculated using the conversion table with different cost for different conversions from special land use types to different special land use type, is only considered as the minimization of change due to the uncertainties in the general method. The third (Maximization of Geomorphology and Geological Suitability) and the fourth (Maximization of Ecological Suitability) objectives are evaluated using handy suitability maps with different grades for different land use types. Both the fifth and the sixth objectives, Maximization of accessibility and the Minimization of NIMBY Influence, are evaluated based on the GIS analysis and the computation of decreasing function for line features. After comparison of all the possible evaluation methods of compactness, the simple eight-neighbor method is chosen for this research due to its superior effect and efficiency. As for the compatibility, which is evaluated by the sum of all the relationships between the two neighboring cells, the indices are computed using Pair-wise comparison method, which could decrease the subjectivity of the simple DelPhi method. Of course, as mentioned earlier, all these evaluation models are influenced by the data limitation. As for the constraints, the restricted area is erased directly from the computation area, and the minimization of accommodation area (residential are) is considered and set finally.

Based on the objectives, constraints, and the related models, and after considering the characteristics of different optimization models such as linear optimization model and non-linear optimization model, general optimization model, and heuristic optimization model etc, finally, the BFGA-MOLU was developed. The BFGA-MOLU is a kind of interactive multi-objective optimization model based on revised goal programming, and BFGA optimization model is characterized by grid representation, random initialization, special crossover and mutation operators including CBO MPO, MBO and MCO operators, and special parameters setting etc.

For the case study, the developed model in Tongzhou Newtown was operated on an area of 141 by 119 cells, using a MacBook Pro laptop computer with an Intel(R) Core(TM) 2 Duo CPU P7550@2.26GHz and 2 GB RAM. This process took 5.5 hours for the completion of 5000 generations with a population size of 100, and this demonstrates the effect and the improved efficiency when compared to other similar studies on compatible scales. Besides, the optimal result is compared to the planned scenario in 2020, the scenario created by this model is clearly superior than the planned one. This does not mean that it can replace the direct land use planning but can certainly serve as a meaningful tool to help the planners or policy makers to understand the planning situation in a lucid manner and arrive at a sustainable planning scenario. Considering the sustainable land use planning support process, the design of friendly interface with interactive operation by users assumes significance. In the second case study, according to the changing preference of different objectives, the computation of the model and the interactive prototype show the characteristics of interaction and robustness.

Finally, the visualization of the optimal planning scenarios is also very important because it can facilitate not only presenting information, but also enables understanding information hidden among datasets. The 3D visualization functionality employed in this research enhances the intuitiveness and interactivity of the overall framework. OSG, belonging to the open-source category of software and being independent of operation systems, supplies the visualization modeling process with efficient algorithms. In this case study, only the prototype with simplified real time 3D visualization of optimal planning scenarios is developed. While it only uses simple features to represent the buildings and land use types, it could also show the characteristics of 3D visualization during the sustainable land use planning support process.

7.2 Contributions

This research concentrates on building a comprehensive spatial multi-objective optimization model to support the sustainable land use planning process. It contributes to literature by demonstrating the evaluation of sustainability in land use planning and the integration of these objectives to form an effective and efficient spatial optimization model. The study includes significant innovative aspects that contribute to the improvement of existing approaches and serves to facilitate user participation in the planning support process. During the process, this research has made a number of methodological contributions.

1. No reliable and comprehensive considerations are available with respect to the objectives of sustainability for land use optimization problem. Most studies considered only three or less objectives simultaneously, which are only from some special aspect of sustainability. In this research, in view of the three main elements of sustainability: economy, environment, and society, total eight objectives are considered: Maximization of GDP, Minimization of Conversion, Maximization of Geomorphology and Geological Suitability, Maximization of Ecological Suitability, Maximization of Accessibility, Minimization of NIMBY Influence, Maximization of Compactness, and Maximization of Compatibility. These are extracted from the analysis and review of existing indicators for sustainability and with due consideration of the data limitation.

2. In this research, with regard to the review of other applications and the sustainable land use planning support process, MOLU model is constructed with its characteristics of goal programming, interaction, normalization etc.

3. Besides, an exhaustive evaluation of each objective and constraint for the further optimization process is also essential. In this research, all of these eight objectives are translated into quantified forms with reasonable and efficient evaluation models. Especially the objectives namely, Maximization of Accessibility,

Maximization of Compactness, and Maximization of Compatibility (with some innovations) are integrated into the optimization model effectively. For the objective of accessibility, the decreasing function with GIS analysis is brought into the evaluation model, which shows better representation of the decreasing influence by different roads. For the compactness, after comparing the existing six types of evaluation approaches, the simple eight-neighbor method was chosen because of its effect and efficiency, which is a significant problem in other similar studies. Besides, the comparison also provides a kind of new comprehensive Moran's I method, which shows better efficiency than Mono Moran's I method and the comprehensive ability to consider two or more objectives concurrently. Although it is not chosen for this research, it provides a meaningful direction for future research. With regard to the objective of compatibility, Pair-wise comparison method is employed in this research, which could decrease the subjectivity of simple DelPhi method.

4. The design of the effective and efficient optimization model is also important especially for this spatial non-linear multi-objective optimization problem. This research uses GA with revised crossover and mutation operators, including CBO MPO, MBO and MCO operators, which is named as "BFGA". The BFGA shows the improvement of both the effect and the efficiency than other existing models in similar research background and compatible research scale.

5. The central objective of this research is to support the sustainable land use planning process. Thus, in this research, a friendly interface of the sustainable land use planning support prototype system with 3D visualization is developed with the flexible parameters setting, interactive operation, and intuitive representation etc.

All of the five aforementioned aspects are the major contributions of this research to the related fields.

7.3 Future Research Directions

The preceding section outlined the contributions that this research has made in the fields of sustainable land use planning support. However, further efforts are required in a number of areas to extend this research. This research concentrates on guiding the land use planning process towards sustainability. The evaluation system has brought generality into the design of the optimization model, and the objectives and evaluations models considered in this research are related to the research area and data limitation. This might decrease portability of this model to some extent. While there has been much improvement of the effect and efficiency of the BFGA-MOLU model, it takes more than 5 hours for obtaining the solutions. All of these aspects not only show us the shortcomings of this research, but also the future directions.

1. More comprehensive objectives, constraints, and scientific evaluation models should be the first future direction of this research. In this research, as two of the main issues in this research, the objectives of sustainability on land use planning and suitable evaluation model for each objective are based on the detailed review of existing similar researches and analysis of the indicators of suitability on land use planning and the available data of research area. Although the objectives and constraints system and the evaluation models have been established by the case studies, there is also some space to improve the generality of the objectives and constraints systems as well as the evaluation models.

2. The optimization model with more powerful crossover, mutation operators, and suitable parameters setting should be an important aspect to move this research forward. The BFGA-MOLU model used here takes more than 5 hours to obtain the solutions, although the efficiency has improved significantly. Thus, in the future, more suitable or compatible operators among the entire GA process from encoding, initialization to mutation as well as the related parameters could be modified to improve the performance of comprehensive model.

3. Other kind of multi-objective optimization models with different principle of selection or ranking functions such as SPEA, NSGA etc. should exist, which could be classified as diversity preferred multi-objective optimization model. From this perspective, the BFGA-MOLU model used in this research could be classified as efficiency preferred multi-objective optimization model. The characteristic of the former optimization model shows the potential to create a

kind of real time interactive sustainable land use optimization model by large amount of computation beforehand.

4. The interactive prototype created in this research facilitates friendly operation during the land use optimization process. However, besides the weights setting, parameters setting, some more operations such as choosing objectives and defining the evaluation model etc could be made available to the users. This aspect is another future possible direction of this research, which could improve the flexibility of this model.

5. The simplified 3D visualization prototype with its characteristics of immersion, interaction, and imagination provide more intuitive observation and interactive operation. However, the simplified prototype, which is a tradeoff between the time spending and the rendering of 3D features influence the users' perception of the VR environment. This could be another future direction for this research, which can lead to enhanced rendering effect and efficiency.

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