GIS BASED AND ANALYTICAL NETWORK PROCESS BASED MULTI CRITERIA DECISION AID FOR SUSTAINABLE URBAN FORM SELECTION OF THE STOCKHOLM REGION

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DEDICATION

“Muliye, Mom, always remember you.”
Sustainable urbanization is possible only when reliable planning and decision making is performed at master plan development level. In this respect, accurate and realistic consideration of urban sustainability criteria viz. land-use and transportation system together with public participation will help planners and decision makers to understand the dynamic balance between environmental, economical, and social sustainability. However, the presence of a large amount of interrelated, interdependent, and sometimes conflicting criteria make problem formulation very complex. Geographical information system (GIS) based Multi Criteria Decision Aid (MCDA) using Analytical Hierarchy Process (AHP) is the most commonly used method for planning and decision making. However, Analytical Network Process (ANP) is a new MCDA approach that considers interdependencies and feedbacks among criteria, which are unrealistically oversimplified in the previous method. To compare the practicality of both methods, this study used planning and decision making of the Stockholm region urban form selection in a choice between a compact, a polycentric, and a diffused scenario. To attain this, a theoretical revision was made on the concepts of sustainable urbanization and decision making systems and separate methodologies were developed and the results were displayed and discussed. While processing the two methods differed in their problem formulation capabilities, decision processing, and output display. However, both methods provided reasonable results. The GIS-based MCDA method provided models in the form of maps that helped to critically evaluate the sustainability criteria both visually and computationally. However, over-simplification of criteria and unavailability of GIS data, particularly for socio-economic criteria, may mislead the planning and decision making process. On the other hand, the ANP based MCDA method provided models in simplified table formats that make decisions easier. However, it is very difficult to visualize the results in the form of spatial maps. Still, its provision of a group of expert’s judgment in the analysis makes the method more efficient, reliable, realistic, and workable for evaluating different scenarios even with scarce information. The study concluded that both methods can be used for sustainability planning and decision making processes, preferably the ANP based MCDA method depending on conditions, and that GIS is an important process aid tool. Simultaneously, compact scenario that follows the city’s fundamentally established polycentric pattern was pointed out as the best alternative urban form for a sustainable development of Greater Stockholm. Moreover, to fully consider the three dimensional problem structure of the sustainability criteria, integration of GIS and ANP based MCDA would create an environment that combine and take advantage of the synergy of both tools.
Sammanfattning

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ABSTRACT

Decision making processes of natural resources for sustainable development are very complex processes that contain large amounts of contradicting criteria and alternatives and/or objectives. Hence efficiency of planning and decision making is highly dependent on the structure of the decision problems. In this respect Multi Criteria Decision Aid (MCDA) is the most widely used method. Particularly GIS-based MCDA using the Analytical Hierarchy Process (AHP) is a well-known method in this respect. However, there are interrelationships and interdependencies among problems of the real world. As a result, many spatial problems cannot be structured hierarchically because the importance of the criteria determines the importance of the alternatives, and the importance of the alternatives also determines the importance of the criteria. Analytical Network Process (ANP) based MCDA is a new planning and decision making approach that allows the decision problem to be modeled considering feedbacks and interdependence among criteria. This study critically reviews GIS-based MCDA using the AHP method and the ANP based MCDA method and forwarded recommendations for future works. To attain this, practical decision making processes were used of urban form selection for a sustainable development of the Stockholm region. For this purpose literature was reviewed, separate methodologies were developed, criteria were formulated to be analyzed using GIS and SuperDecision software’s, and finally reasonable results were achieved and separately presented to critically evaluate both the methods and the outcome. This study showed that GIS has the potential to be an important decision aid tool, that the ANP seems to give more realistic results than the GIS-based MCDA method, and that a compact scenario that over time follows already established polycentric pattern would be the best alternative urban form for a sustainable development of Greater Stockholm.

Key words: Analytical hierarchy process; Analytical network process; Geographical information system; Multi criteria decision aid.

INTRODUCTION

It is difficult to consider a sustainable development of the current and coming generations without deep considerations of a planned and controlled growth of urban areas. The rationale for this is that cities all over the world are growing and most probably will grow at a much faster rate than their infrastructure can accommodate. According to the 2009 revision of the United Nations World Urbanization Prospect by the end of 2050 about 6.3 billion i.e. above 70 percent of the world’s human population will live in urban areas (UNDESA, 2009). This reveals that urban areas will become the main arena of human activities, the greater consumer of natural resources, and the greatest polluter of the environment. Only with responsible decision-making processes, cities hold promising opportunities for social and economic advancement and for environmental improvements at local, national, and global levels. For reaching such responsible decision-making, sustainable urbanization needs an integrated approach to planning, of e.g. land-use and transportation systems via incentive-based participatory methodologies.

A participatory approach to urban planning and decision-making can provide an integration of urban land-use and transportation system. In this respect, Geographic Information System (GIS) applications play a comprehensive role for land-use studies, urban planning, and decision-making processes. Past land-use studies will help to understand the present and to forecast for the future, which is a key in identifying problems and finding appropriate urban development areas. A reason for this is that, land-use is the main element used to guide urbanization to the right direction for infrastructures development and transportation system, both at planning and decision-making stages. In this respect, transportation systems improve public mobility to link social and economical sectors and will guide urban form.

Urban form can be seen as a spatial network involving the shape and density of the city, which channels public movement and provides public spaces. There are three main concepts of urban form: compact, polycentric, and diffuse. These concepts are used to measure efficiencies of land-use, transportation systems, and utilization of energy and resources for sustainable urbanization. The aim with such research is to guide planning and decision-making concerning urban form, which eventually will determine the growth direction of the city towards sustainability.

However, the planning and decision making process at an early stage is not an easy task, since natural resource management in urban areas is a
very complex process that contains many problems and alternatives in its very nature. In this respect, Multi-Criteria Decision Aid (MCDA) based on Geographic Information System (GIS), using the Analytic Hierarchy Process (AHP) method is the most commonly used technique. GIS is thus used to integrate MCDA and AHP, to model, to simulate, and to visualize the results. In this technique, AHP is a mathematical method used to reduce complex and multi-dimensional intangibles into one-dimensional (independent) problems to fit them in to an MCDA system of prioritization. However, in reality, urbanization problems are dependent on and influencing each other. Another method, the Analytical Network Process (ANP) method, is a newly developed MCDA technique for integration of disparate but interdependent criteria in decision-making such as concerning sustainable urbanization. It is based on a theory of relative measurements that considers dependencies and influences of elements between and within clusters of criteria to derive composite priorities.

In this research, the new ANP approach and the traditional GIS-based MCDA approach using AHP methods were critically evaluated when applying to it a decision-making process for sustainable urbanization of Stockholm. The reasons why of choosing this decision process are the complexity of its nature and the availability of practical data. To address these, the first part of the thesis is devoted to a theoretical review on the concepts of sustainable urbanization and their elements, the application of GIS for urban planning and decision-making, spatial analysis and decision support systems, GIS-based MCDA using the AHP method, the ANP method, and a comparison of AHP to ANP methods. Separate methodologies were developed, the results were displayed, and critical evaluations were performed for the two methods. For this purpose, already developed compact, polycentric and diffused scenarios of future Stockholm urban forms were compared for sustainability criteria. Finally, the two methods were compared and recommendations were forwarded for further research.

**Problem statements and aims of the study**

Sustainability decision-making is a very complex process that contains a large number of conflicting criteria. Criteria are naturally linked in a network and could thus be seen as three dimensional. GIS-based MCDA using AHP is the most widely used method for sustainability planning and decision making. However, this method functions well under independently assumed and prioritized criteria. Such unrealistic assumptions of three dimensional criteria into a one dimensional criterion may mislead decisions, since the method cannot exactly forecast future impacts. However, the ANP method provides incorporated feedbacks and interdependence between and within criteria for reliable modeling and planning and decision making. The main aims of this study are to:

1. Distinguish basic concepts behind AHP and ANP MCDA methods for sustainability planning and decision making processes.
2. Make a recommendation for decisions on Stockholm urban form, for a sustainable urbanization in the future.
3. Forward further research recommendations, both concerning methods and decision-making.

**THEORETICAL REVIEW**

The theoretical background of this study is focused on the concept of sustainable urbanization and its planning and decision making processes. The concept of sustainable urbanization is wide and contains, among others, the concept of sustainable development, sustainable urban form, land-use and transportation systems, strategic environmental assessment (SEA), participatory planning processes and application of GIS for planning and decision making at SEA level (Rabinovitch, 1996; Rabinovitch & Leitman, 1996; Spiekermann & Wegener, 2004; Kyem & Saku, 2009).

**Sustainable development**

Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). The concept stands on the notion of a dynamic interaction between environmental sustainability, economical sustainability, and social sustainability. Therefore, it is considered to maintain a strong balance between the deep need of human-kind to improve his lifestyle and well-being on one hand, and preservation of natural resources and ecosystems that the current and future generations depend on the other hand.

**Sustainable urbanization - the ongoing process**

The term sustainable urbanization also refers an urban development that meets the needs of the present without compromising the ability of future generations to meet their own needs. The current fast urbanization all over the world and
the dependence of about half of the world’s populations in them for political and socio-economic matters have made the question of urban sustainability undeniable. This shows that urbanization is an ongoing process and urban areas are moving and/or will move to the forefront of global socio-economic change and democratization (UNDESA, 2009).

Continuous economic growth, resources redistribution, participation, and human development are essential parameters of sustainable development to alleviate burden from the poor by maintaining society’s democracy, equity and environmental care (Sachs, 2000). However, our past tells us, that any human activity cannot continue to use resources at the present rate without jeopardizing opportunities of the future. For this reason, early recognition of the concept of sustainable urbanization at a master plan level is crucial since planning is a future-oriented activity that is strongly conditioned by the past and the present. However, integration of urban land-use and transportation systems via public participation needs strong commitments.

**Participatory planning of land-use and transportation for sustainable urbanization**

Incentives-based participatory urban planning and decision making to integrate land-use with transportation systems can be a lifeline for sustainable urbanization. In this respect public participation, land-use, and transportation systems can be seen as three complementary factors that can guide sustainable growth of cities.

**Public participation**

Ideally, sustainable urbanization is working with urban majorities for their benefit in participatory, democratic, and pluralistic administrations. Via experience, it has been shown that urban problems could not be solved only by financial capacities, technological advancements, and experts’ efforts, since proper planning and decision of what, why, when, how much, and where to invest always need public participation. For that reason, sustainable urbanization is an interactive give and take principle between different groups of stakeholders who hold their parts, such as authorities, experts, citizens, private sectors, and other cooperative agencies.

**Land-use**

Integrated land-use planning or designing with nature can comprehensively address urbanization problems and guide urban development towards spatially appropriate areas. In this process, past land-use studies will help to understand the present and to forecast the future. Aggregated results of these studies can be used: (1) to designate sensitive land resources and areas, (2) to protect nature and cultural reserves, (3) to guide and discourage excessive urban sprawl, and (4) to promote open spaces and urban green. In modern cities integrated urban planning is based upon research supported long-term urban land-use and land valuation systems for population distribution, new land developments, and water and energy provisions for infrastructures and transportation expansion.

**Transportation**

Transportation, which is a third complementary factor, is the movement of people and/or goods from one place to the other. Its effectiveness is measured by system parameters such as coverage, speed, safety, mode, and convenience. When transportation covers larger area with speed, safety, and convenience it creates fast mobility links between social and economical sectors that increase time value of citizens for other development works.

In this respect, the building up of fuel-efficient, space saving, and healthy lifestyles promoting a green transportation system provides positive contributions to environmental, social and economical sustainability. This is the reason why nowadays advancements in the transportation system and in their infrastructures become measuring sticks of sustainable urbanization. The urban transportation system is the main spatial imprint that determines urban form, size, and growth rate.

**Urban form and sustainability**

Urban form refers to the spatial imprint of the urban transport system and its adjacent physical infrastructures. The relationships that arise between urban form and its underlying interactions of people, freight, and information are referred to as the urban spatial structure. As a result, urban form is seriously influenced by the transportation system, street layout, population density, employment areas, and urban growth issues such as urban sprawl, growth patterns, and phasing of developments.

The past trend of concentrating industries in big cities has created serious villager migration problems. People continue to expel from the countryside in large numbers looking for better work, education, and living standard with suitable facilities, which are abundant in cities. Because of this, cities of the world are getting bigger in size, simultaneously creating new patterns of urban form. The level of their sustainability depends to
a larger extent upon the amount of attention given to guide them towards a healthy growth rate.

A healthy growth rate of urban areas demands research-based standardization of land-use, transportation system, infrastructure development, and related elements. The standardization determines urban forms based on the speed, shape, and density of growth rate. However, there is no single applicable mode of a sustainable urban scenario in all situations (Guy & Marvin, 2000). Nevertheless, fundamentally, there are three main principles of urban form: compact, polycentric, and diffused. Definitions and principles of each urban form are stated below (Elkin et al, 1991; de Roo & Miller, 2000; Balfors et al, 2005; EEA, 2006):

1. Compact urban form: This is a highly dense urban settlement that has central area revitalization, mixed-use development, and compact services and facilities. Effective spatial structure creation (by overlapping activities to reduce journeys), city densification (by concentrating several activities), social and commercial centers connection, energy reduction, waste recycling, and cultural tolerance are the main principles behind this form.

2. Polycentric urban form: This is a collaborating multi-centered urban settlement for shared labor and service markets. Educational and other social facilities including transportation are based on common economic development. Besides satellites and arraying around the main center, creation of cheap land ownership, labor markets, and small businesses are the main principles of this form.

3. Diffused (sprawl) urban form: This is a low-density urban settlement with separate developments and dispersed services and facilities. Principles behind this form are just the opposite of compact urban form.

There are some widely accepted principles of sustainable urban form that might serve as criteria for evaluating particular urban alternatives. These principles include abilities: to create high density, to preserve urban region’s and existing built form, to provide mixed land-use and open spaces, to encourage moderate parcel sizes, to limit buildings to a moderate size, and to provide a mix of building types, sizes, and ages (Brenda & David, 2002).

In this respect, compact urban form is the most inspired economic model of urban dynamics with a “Central Business District”. However, due to economic development, low land cost, flat topography, rail-based transportation, an originally radial type street and other factors the central business district is at risk of losing its primacy and gradually evolve into a polycentric form. Further increase in average speed of a polycentric transport system demands more spaces that reduce urban density, moving towards urban sprawl. These systematic urban form change patterns can be seen as verifying the need of SEA for sustainable urban planning and decision making process.

Strategic environmental assessments for sustainable urbanization

SEA is a systematic way to evaluate environmental consequences of proposed policies, plans or programs by ensuring that they are fully included and appropriately addressed on par with economic and social considerations at the earliest stage of planning and decision making processes. Application of SEA in planning and decision making processes provides threefold sustainability advantages (Balfors et al, 2005):

1. To counteract limitations of project-based Environmental Impact Assessment (EIA);
2. To promote participatory sustainable development contributions; and
3. To assess cumulative impacts.

Early integration of urban socio-economic developments with ecological aspect at SEA level will ensure sustainability of the current rapid urbanization and industrialization, which is the major challenge of this and coming generations. For safe handling of these challenges, use of GIS applications in urban planning and decision making processes will amplify advantages and integration capability of SEA.

GIS for sustainable urban planning and decision-making at SEA level

Originally, GIS is a set of computer tools to collect, store, retrieve, transform, analyze, and display spatial data. Nowadays GIS has received worldwide acknowledgement for its synergistic processing ability of temporal and multiresource geo-referenced spatial problems with standardized data processing, digital mapping, and environmental modeling. It enhances sustainable urban planning and decision making processes by integrating decision support tools and methods, since natural resource models collect information from various sources (Easa & Chan, 2000). GIS information provision at regional level and its flexibility of models with respect to variations in natural resource parameters contribute a great deal for planners and decision makers at SEA level.
Decision-making and decision systems

Decision-making is a process of defining a problem and its environment, identifying alternatives, evaluating alternatives, selecting an alternative, and implementing the decision (Małczewski, 1999). Since it is a selection from several choices of products or ideas and involves taking action, decision-making is regarded as a mental process for making up one’s mind to select an action or an opinion among several alternatives with respect to one or more criteria. Simon (1960) suggested three major phases for the construction of any of these processes: (1) intelligence, (2) design, and (3) choice, i.e. identification of: problems or opportunities, decision alternatives, and the best alternative, respectively.

In decision-making processes, criterion or criteria is a generic term that includes the concepts of both decision attribute and objective whereas alternatives are means for achieving decision objectives. As a result, the degree of decision-making complexity depends upon the amount of criteria and/or alternatives in the process (Małczewski, 2006). For instance, it is very complex in natural resource management because large amounts of conflicting and/or contradicting criteria or alternatives are involved. In this respect, appropriate analyzing tools are required to deal with these problems using qualitatively and quantitatively mixed sets of data, accommodating expert opinions, and a collaborative planning and decision making environment. Therefore, for better planning and decision making processes narrowing of information gaps via qualitative data and experimental knowledge within the participatory environment play key roles, since the process is iterative, participative, and integrative.

Decision-making process is primarily iterative because the decision maker uses a set of generated alternative solutions for evaluation and to gain insights and inputs used to define further analyses. Since decision makers play an active role in defining the problem, carrying out analyses, and evaluating the outcomes, the process could be considered to be participative. It can also be integrative in the sense that judgment values that materially affect the outcome are made by decision-makers who may have expert knowledge. This means that qualities of decisions for most decision-making situations are governed by the structure of spatial decision problems and selection of appropriate decision systems (Małczewski, 1999).

The structure of spatial decision problems ranges from completely structured to completely unstructured situations. Here the former is programmable and solved in the computer whereas the later is not. These structures are classified based on four elements of problem solving activities: data, procedures, evaluation criteria and constraints, and strategies (Sprague & Watson, 1996; Małczewski, 1999). However, in the real world, it is difficult to find neither completely structured nor completely unstructured spatial decision problems. This is the reason why the core concept of decision support systems (DSSs) is based upon the type of decision problem structures and problem solving elements (Simon, 1960; Małczewski, 1999).

Thus, there are four types of decision systems: data processing systems, expert systems, expert support systems (ESSs), and DSSs (Małczewski, 1999). Parallel extension of these concepts to spatial (geographical) problems can be distinguished as spatial data processing systems, spatial expert systems, spatial expert support systems (SESSs), and spatial decision support systems (SDSSs), respectively.

Spatial data processing systems

Spatial data processing systems are purely computer algorithms or models and used to solve decision problems. In this system, all four elements of problem solving activities are well defined hence the decisions are not flexible (Małczewski, 1999).

Spatial expert systems

A SES is a computer-based system that employs reasoning methodologies in a particular spatial problem domain in order to transfer expertise and render advices or recommendations (Małczewski, 1999). It is a spatial knowledge (or logic) based decision method that follows the way of
how the expertise solves a problem. SES provides the same result as expertise for non-expertise when they apply established procedures to similar problems in a different situation (Maleczewski, 1999; Rao & Bhaumik, 2003). This is the general assumption behind the system. SES can also be used for model data pre-computation, right model selection, modeling, model interpretation, and impact prediction. However, it solves only narrow problems with simple methods and falls short to make decision of very complex and ill-defined problems (Lein, 2003).

Spatial expert support systems

SESS is integration of SDSSs and SESSs technologies to obtain quality and efficiency of both (Zhu & Healey 1992; Spraque & Watson 1996). It combines experiences of SDSSs in data collection, implementation, and interface utilization with capabilities of SESSs in intelligent advice, explanation and expansion of computer based decision-making process (Maleczewski, 1999). In SESSs, knowledge of multiple experts can be made available to work simultaneously and continuously hence the level of expertise may exceed that of a single human expert. This makes the system capable of solving semi-structured problems; that relevant knowledge of flexible problem solving cannot be encoded (Maleczewski, 1999). Rao and Bhaumik (2003) point out the following as key characteristics of an SESS, the system: (1) capability of solving spatial problems better than human experts can do, (2) use of expert knowledge in the form of rule or decision trees, and (3) interaction with decision makers. There are a number of attractive features of this system that includes less cost, increased reliability and availability, steady and unbiased responses at all times, and fast response with a user friendly environment (Maleczewski, 1999).

Spatial decision support system

The term SDSS is used to describe a computer based system designed to help decision makers to make higher effective decisions concerning e.g. the built environment by identifying ill-structured spatial problems using data, knowledge, and communication technologies (Densham & Goodchild, 1989; Maleczewski, 1999; Baloye et al, 2010). This shows that the concept of SDSS is based on Simon (1960) seminal works on structure of decision problems and is contains all characteristics of DSS with additional capabilities and functions (Geoffrion, 1983).

Adopting Sprague’s (1980) DSS framework, Armstrong and Densham (1990) proposed five modules architecture for SDSS that include: (1) a database management system, (2) analytical modeling capabilities, (3) graphical display capabilities, (4) tabular reporting capabilities, and (5) a user interface. Dansham (1991) also suggested the following six basic characteristics of SDSSs: (1) explicit design to solve ill-structured problems, (2) powerful and easy-to-use user interface, (3) ability to combine analytical models flexibility with data, (4) ability to explore the solution space by building alternatives, (5) capability of supporting a variety of decision-making styles, and (6) allowing interactive and recursive problem solving.

In order to make effective decision-making support for complex spatial problems, SDSSs will need to (Dansham, 1991): (1) provide mechanisms for spatial data input, (2) allow representation of complex spatial relations and structures, (3) include analytical techniques that are unique to spatial and geographical analysis, and (4) provide output in the form of maps and other spatial forms.

Considering all the facts of SDSSs when dealing with highly varied, complex, and uncertain urban problems in planning and decision making process the common approach is to depend upon perceptions. These include previous knowledge, judgment, and adaptive problem solving since they cannot be solved by standard operating system. In the later case environmental impact assessment is used to define, analyze, and evaluate decision problems (Lein, 2003). In this respect, SDSSs can be helpful for sustainable urban planning and decision making processes to improve the perception of planners and decision makers on interrelationships between natural and socio-economic variables. To this end, higher effectiveness of planning and decision making processes can be achieved from a system that can supply timely and accurate information and an interactive computer based system with capabilities of analytical modeling, database management, tabular reporting, and graphical display. Nowadays, multicriteria-SDSS, which is an extension on GIS, becomes more relevant to generate an encouraging decision-making environment (Baloye et al, 2010).

Multi criteria decision aid

Multicriteria decision aid (MCDA), often referred as multicriteria evaluation (Jankowski 1995), is a set of procedure for analysis of complex decision problems involving incommensurable conflicting criteria on the basis of which alternative decisions are evaluated. Maleczewski (1999) listed six funda-
mental components that are involved in MCDA problems:
1. a goal or set of goals that the decision maker attempt to achieve,
2. the decision maker along with preferred evaluation criteria,
3. a set of evaluation criteria i.e. objectives and/or attributes,
4. the set of decision alternatives,
5. the set of uncontrollable variables i.e. decision environment, and
6. The set of outcome associated with each alternative.

There are also three distinguished dichotomies in MCDA: (1) decisions under certainty versus decision under uncertainty, (2) individual versus group decision makers, and (3) multiobjective decision analysis (MODA) versus multiattribute decision analysis (MADA) (Malczewski, 1999; Malczewski, 2010).

In general, quality and quantity of decision maker’s information or knowledge can categorize decisions into being taken under certainty or under uncertainty. When the decision maker has perfect knowledge of MCDA problems, the decision is made in a deterministic situation; otherwise, the decision is made in an uncertainty situation. In the later type of MCDA, problems can be divided further into probabilistic or stochastic decision situations, which is associated with limited knowledge, and fuzzy decision situations (associated with fuzzy or imprecise descriptions) (Malczewski, 1999; Malczewski, 2010).

Depending on the goal preference structure of the decision-makers, the MCDA approach is also categorized into two types of problems: assuming an individual decision maker or a group of decision makers. Regardless of the number of individuals actually involved, the former is referred to as a single goal preference structure but the latter is referred to as different goal preferences structure.

Since criterion is a generic term that includes both the concept of objective (set of attributes) and attribute, MCDA is an umbrella term that includes multiple objectives, MODA and multiple attribute, MADA. To be more specific, the main distinction between MODA and MADA is their objectives and attributes classification criteria, respectively. Therefore, an attribute is a measurable quantity or quality of a geographical entities or a relationship between geographical entities. Based on location of the best solution MODA and MADA problems are referred to as continuous and discrete decision problems, respectively, (Hwang & Yoon, 1981; Malczewski, 1999; Malczewski, 2010). This shows that spatial MCDA (SMCDA/SMCDA) is vastly different from conventional MCDA techniques, due to inclusion of an explicit geographic component. Therefore, GIS and MCDA are the two major elements involved in an SMCDA framework (Fig.1) (Simon, 1960; Malczewski, 1999).

SMCDA framework consists of three hierarchical phases of Simon (1960): intelligence, design, and choice to represent decision-making process and a sequence of elements, such as problem definition, evaluation criteria, alternative constraint maps, decision rules, sensitivity analysis, and recommendations. The framework mainly combines spatial (GIS) and MCDA capabilities (GIS-SCDCA) for the importance of SMCDA and each stage of the framework involves both GIS and MCDA methodologies. The GIS component of the framework plays a major role in early stages of decision-making processes. It supports the three major phases of decision-making and provides capabilities of data acquisition, storage, retrieval, manipulation, and data analysis. But the MCDA component of the framework plays a major role in the later stages of decision-making processes. It supports the three major phases of decision making, provides a methodology for guiding decision maker(s) via criteria evaluation, and defines relevant values to decision situations (Malczewski, 1999; Malczewski, 2010).

**GIS-based multicriteria decision aid using the analytical hierarchical process method**

GIS-based MCDA using the AHP method is an implementation of the AHP technique for MCDA using spatially prepared GIS data that follow a systematic evaluation to integrate GIS

![Fig.1. Framework for spatial multicriteria decision making (Malczewski, 1999)](image-url)
and MCDA. The AHP capability of integrating a large number of heterogeneous data and its simplicity in obtaining weights of large amounts of alternatives (criteria) is seen as a key factor for this popularity (Wu, 1998; Rambaldi et al, 2006; Chen et al, 2009; Malczewski, 2010). A pairwise comparison, which is developed by Saaty (1977), is the most commonly used evaluation method in this respect. Sometimes the whole process is also referred to as GIS-based AHP or Saaty’s approach (Saaty, 1977; Saaty & Vargas, 1991).

In this method, GIS is used to integrate MCDA with AHP and to develop helpful decision support tools such as analytical and/or spatiotemporal models, simulations, and visualizations. This integration power is the corner stone of the decision-making process. Thus, this MCDA method involves a set of weighted evaluation criteria of raster maps to classify each unit into a suitable level and to form a single index from spatially geo-referenced multisource data that meet a specific objective by evaluating several alternatives. The use of the AHP technique makes combination of several criteria possible which may be more or less impossible to combine otherwise. The most common way to perform this is the building of a suitability map from interactive effects of several contributing constraint and factor images.

Constraint images are raster maps that exclude certain areas (such as water bodies) from consideration using conditions of union (logical OR) or intersection (logical AND). However, factor images are raster maps that are extracted from a classified land-use. Then a single factors map is prepared by Weighted Linear Combination i.e. by linear weighting of each factor and summarizing the results (Malczewski, 1999; Chen et al, 2009; Kyem & Saku, 2009):

\[
S = \sum_{i=0}^{n} (w_ix_i)
\]

where \( S = \) suitability; \( w_i = \) weight of factor \( i \); and \( x_i = \) criterion score of factor \( i \).

To build up a suitability map, first, all criteria are reduced to logical suitability statements and then combined using logical operators (OR and AND) to form a constraints map. Then factors are weighted to a standardized common scale before combining them via means of weighted overlay to form a factors map. Here the weighted overlay used a common measurement scale and weights according to the factor’s importance, to overlay several rasters. Finally, a suitability map is developed by masking constraints to accommodate qualitative criteria for the final decision making, after a sensitivity analyses for different alternatives.

**The analytical hierarchy process procedure**

AHP is a mathematical method used to analyze complex decision problems with multiple criteria, following three principles based standard procedures: decomposition, comparative judgment, and synthesis of priorities (Saaty, 1977; Malczewski, 1999).

First, decision problems are decomposed into a hierarchy that captures essential elements of them, i.e. problems are decomposed from three-dimensional into one-dimensional elements. Then, pairwise comparisons of decomposed elements are taken place within a given level of a hierarchical structure with respect to the next higher level. Finally, a composite set of priorities for elements at the lowest level of the hierarchy is constructed from each derived ratio scale of local priorities at various levels.

A continuous 9-point fundamental scale (called Saaty’s scale, Table 1) and an eigenvector are used for comparison and prioritization, respectively. After taking the eigenvector corresponding to the largest eigenvalues of the matrix, a weight value is calculated from the AHP matrix by normalizing the sum of components to one.

Even though the AHP method is a traditional approach for most of planning and decision making processes, it adopts a linearly structured problem formulation. Since problems in the real world are multidimensional, there are interactions and interconnections among elements, which is a missing but essential components in AHP. Therefore, as the method assumes not only that the significances of alternatives are determined by the criteria, but also that the alternatives determine the significance of the criteria. This demands another planning and decision making process.

### Table 1. The fundamental 9-point continuous scale used in the Analytical Hierarchy Process method.

<table>
<thead>
<tr>
<th>Intensity of Importance</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal</td>
</tr>
<tr>
<td>2</td>
<td>Between Equal and Moderate</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
</tr>
<tr>
<td>4</td>
<td>Between Moderate and Strong</td>
</tr>
<tr>
<td>5</td>
<td>Strong</td>
</tr>
<tr>
<td>6</td>
<td>Between Strong and Very Strong</td>
</tr>
<tr>
<td>7</td>
<td>Very Strong</td>
</tr>
<tr>
<td>8</td>
<td>Between Very Strong and Extreme</td>
</tr>
<tr>
<td>9</td>
<td>Extreme</td>
</tr>
</tbody>
</table>
that can deal with feedback to choose alternatives according to their consequences (Büyükükyazıcı & Sucu, 2003; Saaty, 2005; Saaty & Özdemir, 2005).

**The analytical network process for MCDA**

ANP, which is developed by the AHP method pioneer Thomas L. Saaty, is a new approach that captures the outcome of dependence and feedback within and between clusters of elements in planning and decision making processes. Fifteen years later, after introducing the ANP approach with the 1-9 fundamental scale; Saaty developed the concept of ANP further in his book named “The Analytic Network Process” (Saaty, 1980; Gencer & Gurpinar, 2006). His development provided the use of AHP to handle the problem of independence of alternatives or criteria and to solve the problem of dependence among alternatives or criteria. Therefore, ANP is a MCDA technique that supports decision processes by making systematic transactions possible for all kinds of dependence and feedback (Navarro et al, 2008).

Basically, ANP is a general theory of relative measurements used to derive composite priority ratio scales from individual ratio scales, which represent relative measurements of elements’ influence (Saaty, 1996; Saaty, 1999; Saaty, 2005). The supermatrix, whose elements are themselves matrices of column priorities, captures the outcome of dependence and feedback within and between clusters of elements.

Problem formulation of the method is simplified by subdividing the ANP network structure into different control nodes, viz. Benefits, Opportunities, Costs, and Risks (Saaty & Vargas, 2006). Benefits, Opportunities, Costs, and Risks nodes ease decision problem modeling by making a top level network and four subnets control criteria. Keeping in mind the main fact of ANP as replacing the hierarchical structure of AHP with a network structure (Gencer & Gurpinar, 2006; Lombardi et al, 2007), fundamental concepts behind the approach are summarized as; ANP (Saaty, 2005; Saaty & Özdemir, 2005):

1. is a nonlinear structure that deals with sources, cycles, and sinks;
2. prioritize not just elements but also clusters of elements in the real world;
3. is built upon the AHP; however, it goes beyond by including interdependencies;
4. deals with dependence within a set of elements (called inner dependence) and among different sets of elements (called outer dependence);
5. utilizes the idea of control network to deal with different criteria, eventually leading to the analysis of benefits, opportunities, costs, and risks; and
6. makes possible the representation of any decision problem without concern for what comes first and what comes next by benefits, opportunities, costs, and risks, as in a hierarchy.

**The analytical network process procedure**

In general, the ANP approach requires four steps (Saaty, 1996; Lombardi et al, 2007; Saaty, 2008):

**Step 1:** Decision model structural development: Identification of decision goals and all the relationships between clusters, elements, criteria, and alternatives of the network.

**Step 2:** Pairwise comparison and relative weight estimation: Element and cluster level comparisons that lead to relative weighting using an eigenvalue method.

**Step 3:** Supermatrix: Supermatrices for weighting interrelationships of elements and clusters that lead to a weighted supermatrix of values.

**Step 4:** Global priority vectors and weights calculation: Achieving of final priority vectors from the weighted supermatrix.

**Analytic hierarchy process over analytical network process**

Originally, AHP is a theory of relative measurement of expert judgments for both tangible and intangible criteria using fundamental scales. To fit them into a system of priorities, this theory reduced three-dimensional intangibles into one-dimensional (independent) problems (Saaty, 1996; Saaty, 1999). However, ANP provides a framework to deal with decisions without making assumptions about the independence of higher

**Table 2. Summarized comparisons between the Analytical Hierarchy Process (AHP) and the Analytical Network Process (ANP).**

<table>
<thead>
<tr>
<th>AHP</th>
<th>ANP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Used for MCDA</td>
<td>Used for MCDA</td>
</tr>
<tr>
<td>Decision problems are structured into a hierarchy i.e. from top to bottom.</td>
<td>Decision problems are structured as a network i.e. not from top to bottom.</td>
</tr>
<tr>
<td>Every element is considered as independent. Therefore every decision criteria is considered as independent.</td>
<td>Every element is considered as dependent, therefore every decision criteria is considered as dependent of one to another.</td>
</tr>
<tr>
<td>Alternatives are considered as independent from the decision criteria and each other.</td>
<td>Alternatives are considered as dependent of the decision criteria and each other.</td>
</tr>
</tbody>
</table>
level elements from lower level elements and the elements within a level (Saaty & Vargas, 2006). Therefore, to derive composite priorities, ANP is a theory of relative measurements that consider dependences and influences of elements between clusters and within cluster (Saaty & Özdemir, 2005).

However, both AHP and ANP are MCDA methods that use pairwise comparisons to weight components of the structure and to rank alternatives in decision-making processes. The difference between the two methods lies in problems modeling and ratio scales computed for final alternatives prioritization. In this respect, ANP use a network without the need to specify levels as in a hierarchy (Saaty, 2005). As a result, the problem structure of AHP is simple and hierarchical whereas that of ANP is an interdependently connected network that shows interaction among elements (Fig. 2) (Gencer & Gurpinar, 2006). Nodes of the network refer to components of the system whereas arcs represent interactions between them. Considering AHP as a special case of ANP, fundamental differences between the two MCDAs can be summarized (Table 2) (Saaty, 1996; Saaty, 2005).

**STUDY AREA**

Stockholm is the capital of Sweden, which today has about 1.76 million inhabitants with 25 municipalities linked in a mutual dependence for work, housing, recreation, and transportation (Fig.3). This interdependency is the heart of comprehensive regional level planning of greater Stockholm which is performed by the county council, however not legally binding in Sweden. Generally in Sweden, planning is largely done by involvements of local governments, the municipality, and the state. Democratic and decentralized decision making, a balance between competing interests, and ecological and social needs and values are main ingredients of Sweden's planning system. The Swedish environmental code also promotes sustainable development planning by protecting human health, biodiversity, and natural and cultural environments, by providing good managements of land, water, and nature, and by promoting reuse and recycling, both in urban and rural areas.

An autonomous municipal system with taxation power has a fundamental economic and social background with a long historical tradition in Sweden (Romanos & Auffrey, 2002). This tradition provides a general public participation on municipalities main decisions. Sweden is one of the few countries in the world having a most experienced and successful cadastral system. Computerized land-use and land valuation systems are already implemented both in urban and rural areas of the country, in which Stockholm is the center of all.

In Stockholm, the property formation act will demand sustainability and suitability of the new land use before making any land use change. For this purpose in 1930s, the city harmonized cadastral and transportation systems for planning of radial development pattern with green 'wedges' in between.

The transportation system of Stockholm is relatively effectively organized compared to cities of the world. The city has a network of subway, commuter trains, buses, trams and ferries. The underground network of the city is one of world most safe, punctual, and extensive network with more than 110 kilometers of track and 100 stations. Stockholm also owns a well-organized and experienced ethanol bus system, one of the largest in the world. Moreover, the Stockholm County Council has set a target that at least 50 percent of all passenger transport in its territory should use renewable fuels by 2012.

**METHODOLOGIES**

This study utilized literature and GIS data for planning and decision making model development using GIS-based and ANP based MCDAs. The two methods were systematically evaluated using decision-making processes of urban form selection for sustainable development of the Stockholm region.

**Materials**

Data required for the accomplishment of this study were acquired from the National Land survey of Sweden (2008), the Swedish Geological
survey (1996), the Swedish County Council’s webpage (2010), and the Office of Regional Planning and Urban Transportation (2004, and unpubl.). Table 3 shows the descriptions of the spatial data used. ArcGIS V.9.3.1 (ESRI 2008) and SuperDecision V.2.0.8.0 (Creative Decisions Foundation 2009) softwares were used for the execution of GIS-based AHP and ANP decision models, respectively.

**Methodologies**

This study reviewed significances of dependences and feedbacks between decision elements i.e. influences of decision elements between clusters and within cluster of the same groups. To meet these two alternative sets of MCDA models were developed one for GIS-based MCDA using the AHP method, and another for the ANP based MCDA method. Both methods were critically evaluated using a fictive planning and decision making process for sustainable development of the Stockholm region. In the process, three alternative growth scenarios: a compact scenario, a polycentric scenario and a diffused scenario were compared from environmental, economical, and social sustainability points of view (Fig. 4). Finally, the results were evaluated and recommendations were summarized for future studies.

**Table 3 Data used for this study and their description.**

<table>
<thead>
<tr>
<th>Data type and source</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation, DEM (National Land Survey of Sweden, 2008)</td>
<td>Elevation at each 50 m pixel in the study area</td>
</tr>
<tr>
<td>Geology/soil (Swedish Geological Survey, 1996)</td>
<td>Classes of soils and bedrock</td>
</tr>
<tr>
<td>Land use (National Land Survey of Sweden, 2008)</td>
<td>Categories of land-use</td>
</tr>
<tr>
<td>Roads (National Land Survey of Sweden, 2008)</td>
<td>Main and intermediate roads</td>
</tr>
<tr>
<td>Railway (National Land Survey of Sweden, 2008)</td>
<td>Main railways</td>
</tr>
<tr>
<td>Biodiversity (Swedish County Administrative Board, SCAB, 2010)</td>
<td>Distribution of natural grasslands, forests, and wetlands</td>
</tr>
<tr>
<td>Nature reserves (SCAB, 2010)</td>
<td>Legally protected nature area</td>
</tr>
<tr>
<td>Natura2000 (SCAB, 2010)</td>
<td>Areas protected as Natura2000</td>
</tr>
<tr>
<td>Water protection (SCAB, 2010)</td>
<td>Legally protected water areas</td>
</tr>
<tr>
<td>National urban park (National Land Survey of Sweden, 2008)</td>
<td>Legally protected national urban park</td>
</tr>
<tr>
<td>National park (SCAB, 2010)</td>
<td>Legally protected national park</td>
</tr>
<tr>
<td>Experience/recreation values (Office of Regional Planning and Urban Transportation, 2004)</td>
<td>Classes of recreation</td>
</tr>
<tr>
<td>Scenarios for future urban growth of the Stockholm County (Office of Regional Planning and Urban Transportation, unpubl.)</td>
<td>Spatial extent and density of the Dense, Polycentric and Diffuse scenarios, raster with 100 m pixel size</td>
</tr>
</tbody>
</table>
Methodology for GIS-based MCDA using the analytical hierarchy process method

For the implementation of GIS-based MCDA using the AHP method, standard GIS steps were followed to combine information from several criteria and to form a single evaluation index. These steps were: database development, data processing, integrated analysis, display, and reporting.

Database development

Since GIS plays an integration role between MCDA and the AHP technique, it is used for collecting, storing, transforming, analyzing, and displaying of spatial data. When developing the database for this purpose available spatial data of Stockholm region were acquired from sources mentioned earlier. Data were converted into compatible ArcGIS V.9.3.1 format before they were projected and re-sampled into the same coordinate system, and fitted into coverage area to make them ready for processing.

Data processing

GIS processing began by establishing evaluation criteria based on their relevancies and data availability. Criteria were established for slope, geology, land-use, roads, railways, biodiversity, nature reserves, protected water areas, Natura2000, urban and national parks, culture reserves, and recreational values. Criteria data were reclassified into a common scale after transforming vectors into raster formats. To identify the criteria of interest, distance operations were performed on roads, rails, and protected areas. However, evaluation criteria were not established for some important sustainability elements such as economic and employment factors because of lack of data. Lastly, the derived criteria maps of the study area were adjusted for achieving a better visualization for MCDA.

Multicriteria decision-making and display

This is the main part of GIS-based MCDA modeling, which was used to create a suitability map from summarized effects of several contributing constraint and factor images. A constraints model and a factors model were developed for this purpose (Appendix I). For the constraints model (Appendix I.a), Boolean maps were developed for each constraint to exclude them from the suitability map. There were eight different constraint maps: high slopes, water bodies, protected water areas, nature reserves, culture reserves, urban park, national park, and nature of national interest. An Euclidean distance of 100 m from water was assigned as a constraint considering the shore protection law, however, wetlands were not considered as constraints because of their potential use for e.g. wetland water treatment. Finally, all maps were combined using Boolean overlay to prepare a final constraints map. Using factors models (Appendix I.b); factor maps were prepared by extracting relevant criteria from the land-use map and other data sources. In this process, a continuous 9-point inverse fundamental scale was used for rating purposes, which indicated 1 for the least suitable and 9 for the most suitable scale factor. Each factor was ranked based on its significance to make preferences from them. This ranking provided a standardized common scale for each factor. In this fashion, factor maps were prepared for slope, geology, land-use, intermediate roads, combined rails and main roads, dispersion of grasslands, wetlands, and coniferous and deciduous forests, nature reserves, protected water, Natura2000, national park, urban park, nature of national interest, culture reserves, and recreation values such as sightseeing, variation, and services (like toilets and grilling places). Finally, all factor maps were weighted by means of weighted average to combine them.

After weighting each factor and applying a pairwise comparison, which is the AHP method in the context of decision-making, a single factors map was prepared. This map was the result of map overlaying using linear combination of all factor maps i.e. after multiplying each standardized factor map by its factor weight and then summing the results. Comparison matrices were used for informing the weighted overlay applied in the model. A suitability (composite) map was derived by masking the constraints from the factors map to accommodate qualitative criteria for the final planning and decision making process. Then a sensitivity analysis was also conducted on this map to examine how sensitive the choices were, using attribute values and overlaying weights. Two sensitivity maps were developed by changing the factor weights of the suitability map, one on the plus side and another on the minus side.

After thus checking the robustness of the analysis, a final suitability map was overlaid with different scenarios to visualize their extent and to evaluate the patterns of future Stockholm region expansion. The scenarios were three; the Dense, Polycentric and Diffuse scenarios, created in the process of the Regional Development Plan for the Stockholm region (Office of Regional Planning and Urban Transportation, 2010). While
Fig. 4. Maps that show initial scenarios; (i) Compact, (ii) Polycentric, and (iii) Diffused scenarios.
evaluating, each scenario was compared with respect: (1) to total study area, (2) to their net area coverage, (3) to their coincidence with very suitable urbanization areas, and (4) to their overlapping to other scenarios. Pixel counts were multiplied by pixel size to obtain effectiveness of area variations among the scenarios. Visual evaluation was also conducted between the scenarios, particularly on the Färingsö Island. Finally, a prioritization was performed among alternative scenarios, a final decision was suggested for a suitable urban form of Stockholm, and recommendations were forwarded for future studies both on MCDA modeling and for the decision.

**Methodology for the analytical network process**

For ANP based MCDA process criteria were systematically categorized into benefits, opportunities, costs, and risks clusters. Under each cluster network, environmental, economic, and social sustainability criteria and their sub-criteria were developed. Then the whole network was connected and associated through rating spreadsheet, which was used to evaluate the importance of the criteria for the decision. Lastly, a decision network was created for each control criteria with the appearance of alternative scenarios within them. After determining the clusters and their elements pairwise comparisons were performed on elements within clusters and between clusters to prioritize alternative scenarios. A sensitivity analysis was finally performed to check the robustness of the decision process before the prioritization analysis was made between the scenarios. The whole process could easily be presented in the three levels of the ANP networks: the top level, the control criteria, and the decision networks (Fig. 5).

**Top level network**

In this network, priorities of the benefits, opportunities, costs, and risks merits were determined for environmental sustainability, economic sustainability and social sustainability evaluation criteria. Biodiversity, the physical environment, and the greening of Stockholm were considered as the three sub-criteria that measured the environmental sustainability of the city. The biodiversity criteria were used to evaluate threats of urbanization on terrestrial and water ecosystems whereas the physical environment criteria were used to evaluate concerns on waste generation and environmental pollution. However, the greening of Stockholm was used to measure future benefits of urbanization from plantation, artificial ponds, and public transportation boosting.

Economical criteria were used to measure land value, infrastructure investments, and ecosystem restorations. Here land value and infrastructure investments were observed jointly whereas ecosystem restoration cost was used to measure the city’s environment friendly economic growth pattern. However, for this particular study these values were estimated by “expert’s estimations based on best judgments”.

The top level network of the social sustainability cluster was composed of elements related with social services, employment, transportation, social mobility, and other social values. Here social services referred to health, fire, education, and other services whereas social mobility referred to distance to the city center, to education centers, to work, and to market places. However, transportation criteria covered mode, safety, comfort, speed, and volume of transportation. All resources that were related with job opportunities were compiled in the employment criteria. Social values such as friendliness, housing, cultural activities, religious activities, parking, way of life, and others were also included in the social values cluster. For this particular study these values were also estimated by “expert’s estimations based on best judgments”, considering the nature of scenarios.

**Decision network**

The decision network was the bottom level but the most important network that contained alternative scenarios for each control criteria. Two researchers P. Brokking (KTH, Department of Urban Planning and Environment department) and U. Mörtberg (KTH, Department of Land and Water Resources) participated in this fictive decision-making process. From their research, professional experiences and personal exposures to realities they continued to the weighting scheme. For instance, risks under the sub-criteria “pressure on the ecosystem” were weighted between environmentally sensitive areas, biodiversity, and the physical environment.

From the synthesis analysis in the decision network, priority vectors for alternatives at decision network level were achieved. In the same way, priority vectors for alternatives in the control networks were obtained from the overall decision networks. Finally, a priority vector for the ANP model, which represented the most suitable scenario, was obtained from the weighted supermatrix of control networks.
GIS based and analytical network process based multi criteria decision aid for sustainable urban form selection of the Stockholm region

Fig. 5. The Benefits, Opportunities, Costs, and Risks (BOCR) model
Synthesized priorities of the supermatrix for the pairwise comparison of all networks were displayed in columns in raw, normal, and ideal values format. The raw numbers were obtained from synthesized commands of the supermatrix or by combining ideal values of subnets depending on the network. Then, a normal form was obtained by summing raw values of alternatives and dividing them to the sum whereas the ideal form was obtained by dividing raw values of each alternative to the largest raw value. However, the usual way of reporting priority results is the normal column priority presentation.

**Sensitivity analysis**

Sensitivity analyses were conducted for control criteria to measure robustness of the models. These analyses were performed after developing limited matrices and synthesized limiting priorities considering benefits, opportunities, costs and risks. Different values were used until comprehensive synthesized priorities were obtained.

**RESULTS**

The developed methodologies of this study produced reasonable results that can be useful for decision-making of Stockholm’s future urban form. Even though both methods were MCDA methods, they displayed the results differently. The results of the GIS-based decision-making using the AHP method were displayed in the form of maps whereas the results of the ANP-based MCDA method were displayed in the form of tables. For clear distinctions of the two methods, the study results are presented separately: first for the former method and then for the later method.

**Results of the analytical hierarchy method**

Via GIS-based MCDA using the AHP method, continuous factor and constraint criteria maps were prepared to select and evaluate suitable urban growth scenarios. While developing factors maps, factors were standardized to a common scale and then combined by weighted linear combination to obtain a single map. However, the constraints map was developed using a Boolean overlay. Then a suitability map was developed and a sensitivity analysis was conducted. Finally, each scenario was overlaid on the suitability map to evaluate the patterns of future Stockholm expansion by taking suitability conditions into account.

After standardization of the spatial data, individual constraint maps were prepared for high slopes, water bodies, protected water, nature reserves, culture reserves, urban park, national park, and nature of national interest (Appendix II). The darker color denotes the constraints to be excluded. Then all constraints were combined to develop a final constraints map (Fig. 6). Constraints were distributed over the whole study area and water constraints covered the largest areas of these constraints.

In contrast, factors were denoted by extracting them from the land-use map and other spatial data as environmental, economic, and social factors. In this way, environmental factor maps were prepared for biodiversity elements (namely for deciduous forests, coniferous forests, natural grasslands, and wetlands) and protected water bodies whereas economical factor maps were prepared for land-use, main roads, intermediate roads, rails, and slopes. However, social factor maps mainly included recreational values such as sightseeing, variation, services (such as toilets, parking lots, and grilling places), culture reserves, cultural places, nature reserves, urban park, national park, Natura2000, and nature of national interest. Then all factor maps were weighted into a common scale (Appendix III). Darker colors denote the most suitable areas whereas lighter colors denote the least suitable areas.

After weighting factors according to their suitability, a factors map (Fig. 7) was prepared by overlaying them using linear combination. This map indicates suitability of the study area, considering there are no constraints. Darker and lighter portions of a map represent, respectively, the most suitable and the least suitable areas for urbanization of the Stockholm region. After developing the final suitability map from the constraints and factors maps (Fig. 8), a sensitivity analysis was performed to check the model robustness.

There were only little variations between the suitability and the sensitivity maps. The majority of suitable urbanization places (represented by darker portion) are located along the main transportation routes and their neighborhoods, whereas the suitability for urbanization was reduced further away from them (Fig. 9). Maps of alternative scenarios were overlaid on the suitability map to evaluate the patterns of the future Stockholm expansion (Fig. 9). A visual inspection revealed that the compact scenario covered a small portion of the study area, whereas the diffuse scenario covered a much larger portion. For instance, Färingsö Island which is
Fig. 6. Constraints map.

Fig. 7. Factors map.
located west of Stockholm (Fig. 9 (i) letter “a”) looks free from urbanization in the compact scenario whereas completely urbanized in the diffused scenario.

Overlaid maps were also used for computation of a critical evaluation among scenarios with respect: to total study area, to net areas of each scenario, and to their coincidence (Table 4). Moreover, comprehensive results were obtained for coincidences of each scenario: (1) with very suitable urbanization portion, (2) main urban portions that lay on very suitable areas, and (3) with another scenario (Table 5). Compactness coefficients were computed with respect to the compact scenario using net scenario areas (Table 4). Coefficient values show that the compact scenario is about two times denser than the polycentric scenario and four times denser than the diffused scenario. This also agreed with net coverage area comparisons with the non constrained study area (204720ha), which are 9.6, 18.8, and 37.4 percent respectively for the compact, polycentric, and diffused scenarios. There were also 76.1, 60.5, and 38.0 percent coincidence between very suitable urbanization areas (78569ha) and the compact, polycentric, and diffused scenarios, respectively. Moreover, main urbanization areas and very suitable urbanization areas coincided by 64.0, 46.3, and 29.7 percent respectively in the compact, polycentric and diffused scenarios.

About 86 percent of the compact and polycentric scenarios, about 44 percent of the compact and diffused scenarios, and about 52 percent of the polycentric and diffused scenarios were overlapping each other (Table 5). These results were obtained by dividing the respective overlapping areas to the net areas of the compact, compact, and polycentric scenarios, respectively.

**Table 4 Coincided area analyses of scenarios.**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Net covered area (ha)</th>
<th>Compactness coefficient</th>
<th>Coverage w.r.t. study areas (%)</th>
<th>Coincided with very suitable areas</th>
<th>Coincided area with very suitable areas (%)</th>
<th>Coincided main urban with very suitable areas (ha)</th>
<th>Coincided main urban with very suitable areas (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compact</td>
<td>19629.0</td>
<td>1.00</td>
<td>9.6</td>
<td>14942.8</td>
<td>76.1</td>
<td>9566.5</td>
<td>64.0</td>
</tr>
<tr>
<td>Polycentric</td>
<td>38496.8</td>
<td>0.51</td>
<td>18.8</td>
<td>23308.0</td>
<td>60.5</td>
<td>10801.9</td>
<td>46.3</td>
</tr>
<tr>
<td>Diffused</td>
<td>76584.3</td>
<td>0.26</td>
<td>37.4</td>
<td>29131.3</td>
<td>38.0</td>
<td>8649.4</td>
<td>29.7</td>
</tr>
</tbody>
</table>
Fig. 9. (i) Compact, (ii) Polycentric, and (iii) Diffused scenarios overlaid on suitability map.
For instance, the compact and polycentric scenario overlapping was calculated by dividing net overlapping of the two scenarios (16856ha) to the net compact area (19629ha).

**Results of the analytical network process method**

In the ANP based MCDA method, sustainability criteria and sub-criteria were stylishly categorized to form benefits, opportunities, costs, and risks clusters into top level, control criteria, and decision networks. Then the consulted “experts” were providing their opinions on elements within clusters and between clusters considering the goal of the decision-making process.

From pairwise comparisons at all networks, synthesized prioritization among scenarios was achieved and sensitivity analysis was conducted. Synthesized priorities of the alternatives were obtained at network subnets for benefits, opportunities, costs, and risks (Table 6). The resulting priorities for the alternative scenario under the benefit subnet were compact (0.60), polycentric (0.21), and diffuse (0.19).

However, priorities for the alternatives under the opportunities subnet were compact (0.57), diffuse (0.22), and polycentric (0.21) scenario. In the same way, priorities for the alternative scenarios under the costs and risks subnets were respectively diffuse (0.46 and 0.43), compact (0.30 and 0.30), and polycentric (0.24 and 0.27).

The sensitivity analysis for the control criteria that was performed to check the strength of the decision process showed that there was no change in the overall ranks. The results of the final synthesis were obtained from an analysis of the priority vectors in the control network (Table 7). The overall results of the priorities for the analyses of the alternative scenarios were compact (1.0), polycentric (0.69), and diffuse (0.48) scenarios.

**Table 5. Overlapping area analysis of scenarios.**

<table>
<thead>
<tr>
<th>Overlapping Scenarios</th>
<th>Overlapping area (ha)</th>
<th>Scenario area (ha)</th>
<th>Overlapping (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compact and Polycentric</td>
<td>16856.0</td>
<td>19629.0</td>
<td>85.9</td>
</tr>
<tr>
<td>Compact and Diffused</td>
<td>8686.0</td>
<td>19629.0</td>
<td>44.3</td>
</tr>
<tr>
<td>Polycentric and Diffused</td>
<td>19949.8</td>
<td>38496.8</td>
<td>51.8</td>
</tr>
</tbody>
</table>

**Table 6. Synthesized priorities for the alternatives from the networks subnet under benefits, opportunities, costs, and risks.**

<table>
<thead>
<tr>
<th>Network subnets</th>
<th>Scenarios</th>
<th>Ideals</th>
<th>Normal</th>
<th>Raw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefits</td>
<td>Compact</td>
<td>1.000</td>
<td>0.602</td>
<td>1.000</td>
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<tr>
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<td>0.187</td>
<td>0.312</td>
</tr>
<tr>
<td></td>
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<td>0.350</td>
<td>0.211</td>
<td>0.350</td>
</tr>
<tr>
<td></td>
<td>Compact</td>
<td>1.000</td>
<td>0.568</td>
<td>1.000</td>
</tr>
<tr>
<td>Opportunities</td>
<td>Diffused</td>
<td>0.389</td>
<td>0.221</td>
<td>0.389</td>
</tr>
<tr>
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<td>0.372</td>
<td>0.211</td>
<td>0.372</td>
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<tr>
<td></td>
<td>Compact</td>
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<td>0.300</td>
<td>0.505</td>
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<tr>
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<td>0.406</td>
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<td>0.297</td>
<td>0.559</td>
</tr>
<tr>
<td>Risks</td>
<td>Diffuse</td>
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<td>0.434</td>
<td>0.817</td>
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<tr>
<td></td>
<td>Polycentric</td>
<td>0.619</td>
<td>0.269</td>
<td>0.506</td>
</tr>
</tbody>
</table>

**Table 7. Overall result of final synthesis of the alternatives.**

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Ideal</th>
<th>Normal</th>
<th>Raw</th>
<th>Priorities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compact Scenario</td>
<td>1.000</td>
<td>0.461</td>
<td>0.840</td>
<td>1st</td>
</tr>
<tr>
<td>Polycentric</td>
<td>0.687</td>
<td>0.317</td>
<td>0.577</td>
<td>2nd</td>
</tr>
<tr>
<td>Diffuse</td>
<td>0.480</td>
<td>0.222</td>
<td>0.403</td>
<td>3rd</td>
</tr>
</tbody>
</table>

**Discussion**

The planning and decision making process of sustainable urbanization is a very complex phenomenon that mainly depends on existing conditions, quality and quantity of decisive data, and selection of the right planning and decision making processes with commitments to implement them. With respect to the three key existing sustainable urbanization parameters viz. public participation, land-use, and transportation, Stockholm has been considered to be well experienced. A long historic tradition of autonomous municipal system with taxation power (in Sweden) has been seen as providing participative, democratic, and decentralized planning and decision making opportunities for the city (Romanos & Auffrey, 2002). Stockholm is also center of an experienced and computerized land-use and land valuation system with a sustainability demanding property formation policy (SER, 2007). The 1930s radial master plan for Stockholm harmonized the cadastral and transportation systems of the city. The underground tunnels saved much land that contributed to the effectiveness in the city land-use. Therefore, it is logical to consider existing conditions of the city for any type planning and
decision making processes related with sustainable future urban form.
In any sustainable urbanization planning and decision making process, a combination of conflicting and contradicting decision elements and their significance make the process complicated. Consequently, suitability of a decision method can be measured by its managing efficiency of the problem elements, both in number and in kind. In this study, despite the facts of their differences in problem formulation, analysis, and way of output display, both MCDA methods provided helpful results. For ease of critical evaluation in light of sustainable urbanization criteria that include integrated land-use, transportation system, and infrastructure planning (for expansion and/or reuse), the results of each decision method are discussed separately.

**Discussion on the analytical hierarchy method**

In GIS-based MCDA using the AHP method, determination of criteria (factors and constraints) played a key role for the rest of the decision-making process. Their identification, relation and interdependence evaluations, and prioritization provided clear guidance for factors standardization scores and weights.

While weighting, greater values were given for land-use and transportation systems because of their major influences in determining urban form, growth rate, and sustainability. This is the reason why most of the suitable urbanization areas were located along the main transportation corridors (Fig. 7). This coincides with fundamental principle of the 1930s planning of Stockholm for a radial development pattern, which resulted in the so-called with green wedges being left in between. It laid a strong notion to consider this pattern for any sustainable planning and decision making of the city (Office of Regional Planning and Urban Transportation 1991).

Due to data errors and uncertainties, small variations were allowed between suitability and sensitivity maps. These variations were shown by the change of areas from one scale to another, for example, from very suitable to between very suitable and suitable or from suitable to between suitable and moderately suitable areas. In this respect, only small changes were observed between the two maps. This reflects that the study analysis can be considered to be robust, the factors weighting should be acceptable, and that the suitability map can be used for further evaluation of the scenarios.

The overlying of the maps reflects a common notion that all three scenarios were mainly following the areas that were outlined as suitable for urbanization (Fig. 9). This can be seen as an indication of the existence of a strong harmonization between land-use and the transportation system and of the significance of this harmonization in determining the sustainability and urban form of the future Stockholm region. This also can be seen as an indication of the existence of logical coincidences between the emphasis given for land-use and the transportation system of this study and the basic assumptions of the scenario developments. However, the visual and comprehensive results (Table 4 and 5) show that the compact scenario covered the smallest area and lay in the most suitable urbanization portion of the area, whereas the diffused scenario was just the opposite. However, the polycentric scenario was between them.

Specifically the compact scenario was developed in the already existing urban areas, in very small and suitable urbanization portions of the Stockholm County. This spatial effectiveness will make the city dense, with mixed services, and short travelling times with preservation of the green belt. As a result, there are encouragements in small expansion and/or reuses of the existing transportation infrastructure, for development of an efficient public transportation system, and land reduction i.e. reuse of land. This has the potential to provide higher land value, population density (floor-to-space ratio), social movement with cultural integration, and public and non-motorized transportation in one hand, and a lower energy and resource consumption and pollution for this scenario. The coincidence of about 60 percent of the main city and the highly suitable urbanization portion in conjunction with the already existing extensive subway system of Stockholm thereby provide the potential to preserve greater rates of land, economy, and environment.

The polycentric scenario was moderately developed in already existing routes and suitable urbanization portion of the city. However, its compactness coefficient was small and had only a smaller amount of coincidence between the main city and the highly suitable urbanization portion. Hence, the scenario required more expansion of the transportation system with adjacent infrastructure. As a result there was less preservation of land, economy, and environment than the compact scenario. However, its radial expansion along the main transportation systems reflected a notion that in the fullness of time due to natural
constraints and population increase the city will become dominantly polycentric.
In the case of the diffused scenario, the compactness coefficient (i.e. 0.26) and coincidence with suitable urbanization portion, and floor to space ratio were low. This can be assumed to require a greater ecological footprint. In other words, it has a much lower rate of land preservation and needs a very high infrastructure expansion or construction than other scenarios. As a result, the scenario encourages lower land value, population density, and social movement, and higher private transportation, pollution, and energy and resources consumption.
Since the concept of sustainability is relative and fundamentally there is no single sustainable urban form (Guy & Marvin, 2000), the study of scenarios overlapping will help to estimate which scenario comes next. In this respect, more than three fourth of the compact scenario was overlapped with the polycentric scenario and about only 40 percent was overlapped with diffused scenario. This shows that if the compact scenario was going to be adapted as the greater Stockholm's urban form, by the time it is fully developed and with natural constraints, the form transition would go from compact to polycentric. This can also be perceived from sequential observation of overlaid scenarios (Fig. 9).
Finally, when visually examining the Färingsö Island it will be completely free from urbanization in the compact scenario whereas small coastal areas are proposed to be developed in polycentric scenario, but it will be completely urbanized in the diffused scenario. Considering the same facts when perceiving implementation of each scenario in the light of land-use, transportation system, and infrastructure developments, the compact scenario seemed to be the most sustainable, the diffused scenario seemed to be least sustainable, and the polycentric scenario would be in between.

Discussion on the analytical network process method
In the ANP based MCDA method development of the benefits, opportunities, costs, and risks model, pairwise comparison, relative weighting, and priority analysis were the main procedures. Development of the network model for environmental, economical, and social criteria and sub-criteria were core steps of the method, since the determination of suitable sustainability criteria, categorization of them into clusters, and identification of network of interrelationships between the clusters, elements, criteria, and alternatives were included in this step. The pairwise comparison using the supermatrix based on the expert decisions on elements within clusters and between clusters of all networks was performed by the software. The analysis of the supermatrix for pairwise comparisons was performed using the SuperDecision software and the display of the synthesized results was as simplified prioritization in columns with the raw values as benefits, opportunities, costs and risks for each scenario. The normal synthesized priorities of the benefit subnet showed that the compact scenario was more beneficial for this decision process (Table 6). In this reporting, the best choice had a priority of 1.0 concerning ideal values. However, the other scenarios were expressed in terms of first priority, in this case the compact scenario. Therefore, the polycentric and diffused scenarios were about 35 percent and 31 percent as beneficial as the compact scenario, respectively. The compact scenario also had more sustainability opportunities, but the polycentric and diffused scenarios were only about 37 percent and 38 percent as opportunistic as the compact scenario, respectively. In the same way, the diffused scenario was more costly and risky than the compact and polycentric scenarios, respectively.
In this method, an additive formula was used for the final synthesis. Thus, alternative values coming up from the subnets of benefits and opportunities were un-inverted values whereas those values coming from costs and risks subnets were inverted values. Therefore, the overall priority of the benefits, opportunities, costs, and risks model depends on the values of un-inverted and inverted products. For this study, the compact scenario had a greater un-inverted and smaller inverted product whereas the diffused scenario had the reverse. This is the reason behind the overall priority of the ANP model that showed the compact scenario as the most suitable urban form for a sustainable development of the Stockholm region. Whereas the polycentric scenario was 69 percent as suitable urban form as the compact scenario and the diffused scenario was 48 percent as suitable as the compact scenario (Table 7). This shows that the compact scenario was ranked first and the polycentric and diffuse scenarios were second and third.
This may agree with the concept of sustainable urbanization when it is examined from the balancing point of needs of humankind to improve his lifestyle and well-being on one side and preservation of natural resources and ecosystems for the present and coming generations on the
other side. The reason is that when living, working, shopping, and recreating places are within short travel distances this will save resources, energy, time, and ecology. Under such conditions, mixed buildings and services, people interactions and willingness to walk or bike, and advancements of green constructions and technologies creates connected, safe, and more complete sustainable urban environments. In the same way, a final priority result of the ANP-based MCDA model reflected that the compact, polycentric, and diffused scenarios represent different available suitability priorities of sustainable Stockholm urban forms.

The final priority results also suggested that the polycentric scenario was a very close alternative to the compact scenario whereas the diffused scenario was unsuitable even comparing with the polycentric scenario. This agreed with the 1930s Stockholm’s radial urban growth plan which recommended the growth should follow the public transportation systems by forming long fingers of built areas. These have still undeveloped green wedges left in between for easily accessible and ecologically beneficial open spaces (Office of Regional Planning and Urban Transportation 1991). It also matches a fundamental intuition of sustainable urban form as compact, between compact and polycentric, or compact that expands to polycentric form in time due to population increase and expansion constraints.

**GIS-based and ANP based methods**

Both GIS-based and ANP based MCDA methods were compared theoretically and with practical applications using a fictive planning and decision making process of sustainable development of the Stockholm city region considering urban form. A basic difference between the two methods lays on the structure of the decision problems. Decision problems are hierarchical and every element and alternative is considered as independent in the former method whereas they are linked in a network and every element and alternatives are considered as dependent in the later method. These differences are obvious in the problem formulation, decision processing, and output display of this study.

In case of GIS-based MCDA using the AHP method, considerations of criteria independence is not always realistic. This is due to a top-down relationship among the decision levels which leave an option for bias to occur when the criteria and sub-criteria are correlated with each other (Navarro et al, 2008). Oversimplification of criteria and unavailability of GIS data, particularly for socio-economic criteria, can provide a visually pleasing model to help visualization for decision makers, which however that may lead to a non-optimal evaluation. However, even if this study used a considerable amount data that included environmental, social, land-use, and transportation data, still data deficiency and knowledge gaps exist. Still, the overlaying of the suitability map with different scenarios can help planners and decision makers to evaluate criteria both visually and computationally.

In case of the ANP based MCDA method, interdependent considerations of criteria avoid a great deal of compensation problems. Its provision to a group of expert’s judgments in the analysis of carefully selected variables makes the method more efficient, reliable, and realistic. Despite the facts of making more accurate criteria judgments, involvement of different experts provide a working environment for evaluating different scenarios with scarce information, which is one of the method’s strengths. Complex inter-relationships problem formulation of the modeling processes using a network of criteria and alternatives (all called elements) create feedback and interdependence relationships within and between the clusters. This provided a more realistic modeling of the complex settings, which is a key to handling interdependence among elements in sustainable development planning and decision making processes. It provides very efficient analysis and simplified displays of outcomes which benefit communication with decision makers, and illustrates the external risks and hazards faced by the decision maker. However, it is difficult to visualize the final outcomes in spatial maps.

**Conclusions**

The main aim of this study was to distinguish the basic differences between the concepts of GIS-based MCDA using the AHP and ANP based MCDA methods for sustainable planning and decision making processes. At the same time the goal was to provide decision support on sustainable development of Greater Stockholm concerning urban form alternatives. After a close examination of these questions the following conclusions were drawn:

1. The two MCDA methods can be used for sustainability planning and decision making processes, however, the ANP based MCDA method is more realistic than the GIS-based MCDA using the AHP method, since it include feedbacks and interdependences of elements inside the criteria.
2. The structural development of the decision support model (that include identification of all the relationships between clusters, elements, criteria, and alternatives of the network) and narrowing opinions of different experts towards the planning and decision making goals are difficult in an ANP based MCDA method compared to the GIS-based MCDA using AHP.

3. GIS is an important tool for sustainability planning and decision making aid.

4. A compact scenario that over time leads to a polycentric scenario would be the best alternative urban form for a sustainable development of Greater Stockholm. The reason for this is that the compact scenario mainly lay in already existing small and very suitable urbanization portion of the Stockholm region that provide most of the sustainability benefits. The more than three forth overlapping with the polycentric scenario, the reasonable coincidence between the main city and highly suitable urbanization areas, and the original polycentric planning of Stockholm will provide an ideal transition from a compact to a polycentric scenario with time due to natural constraints.

**Recommendations**

This study forwarded recommendation for future works: to fully consider three dimensional problems structure that simulate reality, the integration of GIS and ANP based MCDA will create an environment to utilize synergy of both tools.
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APPENDICES

Appendix I
The following are models for constraints and factors.

\[ a. \text{Constraints model} \]
b. Factors model.
Appendix II

The following are constraint maps

Fig.1. Maps that show constraints; a. Nature of national interest, b. National park, c. Culture reserves, and d. Water
Fig. 2. Maps that show constraints; e. Nature reserves, f. Slope, and g. Protected water
Appendix III
The following are factor maps.

*Fig. 1.* Maps that show factors; *a.* Culture reserve, *b.* Nature reserves, *c.* Nature of national interest, and *d.* Urban Park.
Fig. 2. Maps that show factors; e. Nature2000, f. National park, g. Soil, and h. Protected water
Fig. 3. Maps that show factors; i. Landcover, j. Slope, k. Intermediate roads, and l. Railways
Fig. 4. Maps that show factors; m. Main roads, n. Forest recreation, o. Activities, and p. Concerns
Fig. 5. Maps that show factors; q. Services, r. Cultures, s. Views, and e. Variations.
Fig. 4. Maps that show factors: f. Wetlands, v. Grass, g. Deciduous forest, and h. Coniferous forest