A Multi-objective Decision-Making Framework for Sustainable Urban Development

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By

KHALED NASEF, MCRP, B.Sc.

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AUTHOR: Khaled Nasef, B.Sc. (Cairo University), MCRP (KFUPM)

SUPERVISOR: Professor Brian W. Baetz

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LAY ABSTRACT

Achieving sustainable urban development is a very challenging task for planners. It requires simultaneous integration of a large number of conflicting objectives pertaining to economic, environmental and social dimensions. It also involves multiple stakeholders with opposing views, and a high level of uncertainty. In addition, the decision-making process should be transparent, participatory and understandable by all participants. This research introduces a decision-support framework, underpinned by mathematical modeling techniques, to assist in achieving sustainable solutions for urban development problems. The framework is examined through two case studies. First, it is used to find a sustainable distribution of healthcare centers taking into consideration conflicting objectives including cost, efficiency of service and accessibility. Second, the framework is used to develop planning scenarios for transit-oriented development (TOD) around a transit station. The developed framework has proved to be a flexible and practical approach to assist decision-making in the context of urban sustainability.

ABSTRACT

Planning in the context of urban sustainability is very challenging as it requires simultaneous integration of a large number of conflicting objectives pertaining to economic, environmental and social dimensions. It also involves multiple stakeholders with opposing views, and a high level of uncertainty. In addition, the process should be transparent, participatory and understandable by all participants.

Existing literature has called for exploring new analytical methods to support decision-making for urban sustainability. This research introduces a structured decision support framework underpinned by Multi-objective Decision-Making (MODM) and Multi-attribute Decision Making (MADM). The framework provides systematic guidance to decision-making starting from problem structuring to generating a wide range of alternatives until the selection of the final solution.

The developed framework is tested in two different decision-making situations pertaining to real urban problems. In the first case study, the framework is examined in the situation where the decision-maker is available to interact with the planner at the design stage. The framework is used to find a sustainable distribution of healthcare centers taking into consideration conflicting objectives including cost, efficiency of service and accessibility. The optimal solution is reached through an interactive process with stakeholders.

In the second case study, the framework is examined in the situation where the decision-maker is unavailable for interaction at the design stage. The framework is used to develop planning scenarios for transit-oriented development (TOD) around a transit station. The optimal intensification of land use and land use mix is achieved taking into consideration the conflicting objectives of various stakeholders. Large number of non-dominated alternative solutions has been generated. An interactive tool has been developed by which the stakeholders can identify the alternative that best reflects their preference.

The quality of the outputs for both case studies has shown that the developed planning methodology outperforms conventional approaches. The developed framework has proved to be a flexible and practical approach to assist decision-making in the context of urban sustainability

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LIST OF ABBREVIATIONS

MADM	Multi-attribute Decision-making
MODM	Multi-objective Decision-making
MCA	Multicriteria Analysis
MACED	Mountain Association for Community Economic Development
MOP	Multi-objective Optimization
EO	Evolutionary Optimization
GP	Goal Programming
CBA	Cost-benefit Analysis
MAUT	Multi-attribute Utility Theory
AHP	Analytic Hierarchy Process
SAW	Simple Additive Weighting
DHA	Dubai Health Authority
DMPD	Dubai Municipality Planning Department
GIS	Geographic Information Systems
TOD	Transit-oriented Development
MOE	Measures of Effectiveness
SDSS	Spatial Decision Support Systems

NOTATION

For Chapter 5

Variable, Constant, or index	Description
i	Index for alternative planning zones
j	Index for alternative locations of healthcare centers.
n	Number or potential zones to be served (in this case study there are 15 zones)
m	Number of potential healthcare center alternatives.
S	Target capacity of each healthcare center (per patient)
H_i	Population holding capacity of zone *i*.
F	Target number of health care centers.
D	Target ratio of population assigned to healthcare facility more that 3 kilometres away from there residence.
C_i	Cost index for zone *i*.
M	Very large number.
d_{cap}^-, d_{cap}^+	Negative and positive deviations associated with the target service capacity.
d_{dem}^-, d_{dem}^+	Negative and positive deviations associated with service coverage
d_{num}^-, d_{num}^+	Negative and positive deviations associated with the target number of healthcare centers.
d_{num}^-, d_{num}^+	Negative and positive deviations associated with the target service capacity.
d_{dist}^-, d_{dist}^+	Negative and positive deviations associated with the target ratio of population outside the acceptable distance.
d_{cost}^-, d_{cost}^+	Negative and positive deviations associated with minimum capital cost
X_{ij}	Number of patients living in zone *i* and assigned to a healthcare center located in zone *j*.
$Y_j = 1$	If a healthcare center is allocated in zone *i*, 0 otherwise.
X_{ij}	The number of patients living in zone (i) and assigned to HCC in zone (j)
Y_j	Binary variable (= 1 if HCC is proposed at zone (j) and =0 otherwise)

For Chapter 6

X_i	FAR for each zoning category *i* *(i = 1, 2, …, 7) where:*
i= 1	Residential zoning category type R2 (single-family detached villas)

$i = 2$	Residential zoning category type R7 (multi-storey apartment building) located inside the vicinity area (within 200 radius from the station)
$i = 3$	Residential zoning category type R7 (multi-storey apartment building) located outside the vicinity area..
$i = 4$	Residential/commercial zoning category type RC category (mixed residential and office building) located inside the vicinity area.
$i = 5$	Residential/commercial zoning category type RC category (mixed residential and office building) located outside the vicinity area.
$i = 6$	Commercial and retail zoning category type C located inside the vicinity area
$i = 7$	Commercial and retail zoning category type C located outside the vicinity area
Y_{ir}	Percentage of residential floor space to the overall floor space in RC category. (i = 4, 5)
Y_{ic}	Percentage of offices and commercial floor spaces to the overall floor space in RC category (i = 4, 5)

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INRODUCTION

a-1 Research Motivation

One of the main challenges facing urban planners is to identify and adopt more sustainable alternative plans by balancing economic, environmental and social aspects. This is not a trivial task as it entails quite complex decision-making, which is often accompanied by a number of difficulties (Jeffreys 2002, Azapagic et al 2005, Camagni et al 1998, Wiek and Binder 2005):

First, decision-making in the context of urban sustainability requires the consideration of a large number of objectives and decision criteria pertaining to the economic, environmental and social aspects of urban sustainability;

Second, it involves a number of different stakeholders with conflicting interests and preferences. A solution that meets all objectives and preferences may not exist (e.g. a solution that promotes economic objective may degrade the environment). Therefore, the decision-making process often involves a complex trade-off between competing objectives before a final solution is reached (Xiao et al 2006);

Third, many stakeholders claim to be troubled by the feeling that there is an alternative as yet unidentified or alternative that must surely be better that those so far considered. The need to explore and examine a wide range of high quality alternatives adds to the complexity of decision-making for urban sustainability (Boulager and Brechet 2005);

Fourth, further difficulties emerge due to the need for transparency and communication among all interested parties during the decision-making process;

Finally, Uncertainty in the input data, information, and the outcomes of a choice poses yet another challenge for decision-making (Fondazione Eni Enrico Mattei, 2008). These difficulties are encountered to various degrees in all levels of planning and decision-making for sustainable urban development.

Spatial planning in such a complex decision-making context requires analytical methods that examine trade-offs, consider multiple economic, environmental, and social dimensions, reduce conflicts, explore a wide scope of potential alternatives and incorporate these realities in a transparent and participatory framework (Herath and Prato 2004).

Conventional planning approaches satisfy some of these requirements but fall short in others. ***For example, in all scenario-based approaches***, typically few schemes are identified. Consequently stakeholders may not find the scheme that represents their perspective and therefore feel excluded from the process. (Lam and sun 2000; Herath and Prato 2006).

Many authors have called for new analytical methods and new tools to be developed to support decision-making for urban sustainability (Herath and Prato 2006, Elrefaie 2004, Lam and Sun 2000). Xiao et al (2006) believe that borrowing ideas and methods from other fields will benefit in spatial planning and decision-making.

Multi-criteria Decision-making MCDM, which has been developed in the field of Decision Science, is a valuable and widely-used analytical tool to aid decision-making where there is a choice to be made between large number of competing options. It consists of two categories: *Multi-attribute Decision-making (MADM)* which deals with choosing from among a predefined set of alternatives, and *Multi-objective Decision-making (MODM)* which deals with generating a large number of alternatives using mathematical optimization modeling. These tools have been widely used to support sustainability decision-making related to environmental management (Bell 1975), energy policy analysis (Haimes and Hall 1974, Keeney et al. 1995), farm management (Xu et al. 1995), food security (Haettenschwiler 1994), forest management (Kangas and Kuusipalo 1993), protection of natural areas (Anselin et al. 1989), water management (Keeney et al.

1996), ecosystem management (Prato 1999), and wildlife management (Kangas et al. 1993, Prato et al. 1996b).

This research examines the integration of these analytical tools within the urban planning process to overcome the challenges associated with decision-making in a sustainability context.

a-2 Problem Statement

Planning in the context of urban sustainability involves conflicting objectives pertaining to economic, environmental and social dimensions, multiple stakeholders with opposing views and a high level of uncertainty. Effective planning and decision-making processes in such a complex context have to overcome the following challenges:

1- Simultaneous integration of many objectives with incommensurable measures;
2- The capacity to trade-off between economic, environmental, and social, alternatives to reach a satisfactory balance;
3- Integrating stakeholders values and objectives into the analysis;
4- Generating a wide range of high quality alternatives;
5- Facilitating stakeholder and/or decision maker involvement in the design stage;
6- Facilitating negotiation and communication between stakeholders;
7- Offering a transparent, understandable, clear process reviewable by all participants;
8- Ensuring robustness of the preferred alternative;
9- Incorporating sustainability indicators and benchmarks into the analysis;

Conventional planning approaches may satisfy some of these requirements but fall short in other aspects. Therefore, there is a need for new analytical methods and new planning approaches to support decision-making for urban sustainability

a-3 Research Hypothesis:

Integrating *Multi-attribute Decision-making (MADM*) and *Multi-objective Decision-making (MODM*) tools within the urban planning process will help to overcome the challenges associated with decision-making in the context of sustainability.

a-4 Research Objectives:

The research has two main objectives:

1. To develop a structured decision-support framework that provides systematic guidance to decision-making starting from problem structuring to generating a wide range of alternatives until the selection of the final solution. The framework integrates multi-objective decision-making techniques MODM and multi-criteria decision-making techniques (MCDM) into the urban planning process.
2. To examine the effectiveness of the developed framework in solving different real world planning problems in various decision-making contexts.

a-5 Research Methodology:

The methodology adopted in this research consists of three phases; *assembly of underlying components*, *development of planning framework* and *testing of the developed framework* (figure A-1):

Phase one: Assembly of underlying components

This phase includes conducting three main streams of research as follows:

- The first stream investigates the common challenges associated with decision-making in the context of urban sustainability. It aims at understanding the prerequisites that have to be fulfilled by any successful decision-making process in the context of urban sustainability.
- The second stream is concerned with studying Multi-objective Decision-making MODM as a decision-aiding tool including concepts, methodologies, advantages,

limitations, and solving techniques. It aims at investigating the potentialities of MODM to support decision-making in the context of urban sustainability.

- The third stream studies Multi-attribute Decision-making (MADM) concepts, techniques and methodologies as an evaluation tool aiming at exploring its potentialities to support decision-making in the context of urban sustainability.

Phase Two: Development of planning framework:

This phase aims at synthesizing the findings of phase one and the subsequent development of an integrated MODM/MCDM decision support framework specially tailored to reflect the prerequisites of a successful decision-making process in the context of urban sustainability.

Phase Three: Testing the developed framework (Applied Studies):

At this phase, two applied studies will be conducted using the developed decision support framework in solving two different real urban problems that have been previously addressed by conventional planning approaches. The framework will be evaluated through comparing the results and through investigating to what extent the framework managed to respond to the prerequisites raised in phase 1. The applied studies will follow the methodology presented in Figure (A-2).

a-6 Structure of Research:

This document consists of two parts in addition to this introduction. The first part consists of four chapters and the second part consists of three chapters as follows:

Part one: Building Blocks and Proposed Planning Framework.

Chapter 1: This chapter includes a theoretical background on definitions and concepts of sustainability, with an emphasis on sustainable urban development and the common principles of sustainable urban form. The common challenges associated with decision-making in the context of urban sustainability are outlined. This establishes understanding about the complexities inherent in planning for urban sustainability due to the multi-dimensional, multi-objective and multi-stakeholder nature or urban sustainability problems at any planning level. A list of the general requirements (prerequisites) that should be fulfilled within the decision-making process to deal with such complexities is developed. The need to incorporate a decision analysis tool is then justified and a brief introduction to Multi-criteria Analysis MCA techniques is provided, including its two main categories: Multi-objective Decision-making (MODM) and Multi-attribute Decision-making (MADM).

Chapter 2: This chapter focuses on Multi-objective Decision-making (MODM) and its potential in the context of urban sustainability. It provides a background on mathematical optimization models as a decision-making tool. The chapter then focuses on multi-objective optimization concepts and highlights the role of both the decision maker and the analyst (the planner) in problem-solving within a multi-objective optimization context. The three main MODM approaches (posterior, priori, and interactive) and their advantages and disadvantages with regard to decision-making in the context of urban sustainability is studied. Accordingly, the most appropriate solving techniques are recommended. Finally, this chapter provides a literature review on applications of MODM in urban planning.

Chapter 3: This chapter focuses on Multi-attribute Decision-making (MADM) and its potential in the context of urban sustainability. It provides an overview on alternative evaluation methods commonly used in urban planning domains and highlights the advantages and limitations of each method. The chapter, then, concentrates on MADM as an effective tool for assessing alternatives with multiple and conflicting objectives. The typical MADM methodology is studied together with alternative weighting and scoring techniques and the appropriate techniques, for the context of urban sustainability are recommended.

Chapter 4: In this chapter, a general multi-objective decision-making framework for sustainable urban planning is developed. The framework employs MODM and MADM methods to respond to the prerequisites raised in chapter 1 concerning effective decision-making processes in the context of urban sustainability. The framework provides a step-by-step guidance starting from problem structuring, to generating and evaluating alternatives until a final solution is reached. The limitations and scope of the proposed framework are addressed.

Part Two: Application of the Developed Planning Framework

Chapter 5: This chapter aims at testing the developed framework in a decision-making situation where the decision maker is available to interact with the planner at the design stage, which is quite common in planning practice. The framework has been applied in a real world case study pertaining to achieving sustainable locations for healthcare centers in Dubai, United Arab Emirates. A literature review on various public facility planning approaches is provided to confirm the significance of the proposed approach. A goal programming model is formulated taking into consideration conflicting objectives (cost, efficiency of service, accessibility) as well as sustainability bench marks obtained from the strategic plan of the Dubai Emirate. The optimal distribution of health care centers is reached through an interactive process with stakeholders where various scenarios are tested until a satisfactory proposal is reached. The result is compared against that achieved by a conventional approach to illustrate the added value of the developed decision-making framework.

Chapter 6: This chapter aims at testing the developed framework in a decision-making situation where the decision maker is not available to interact with the planner at the design stage, which is the second decision-making situation addressed by the framework. The framework has been applied in a real world case study pertaining to achieving a sustainable transit-oriented development TOD around metro stations in Dubai, United Arab Emirates. The purpose is to achieve the optimal intensification of land use and the optimal land use mix, taking into consideration the conflicting objectives of various stakeholders. A multi-objective optimization model has been formulated and used to generate twenty non-dominated alternative solutions. An interactive instrument has been developed (in Excel) by which the decision maker can identify the alternative that reflects his preference by defining the relative importance (weight) of each objective. The result is compared against that achieved by a conventional approach to illustrate the added value of the proposed decision-making framework.

Chapter 7: This chapter synthesizes the main conclusions and recommendations of the research. It also highlights potential future research in the area of decision-making and decision support systems for urban sustainability.

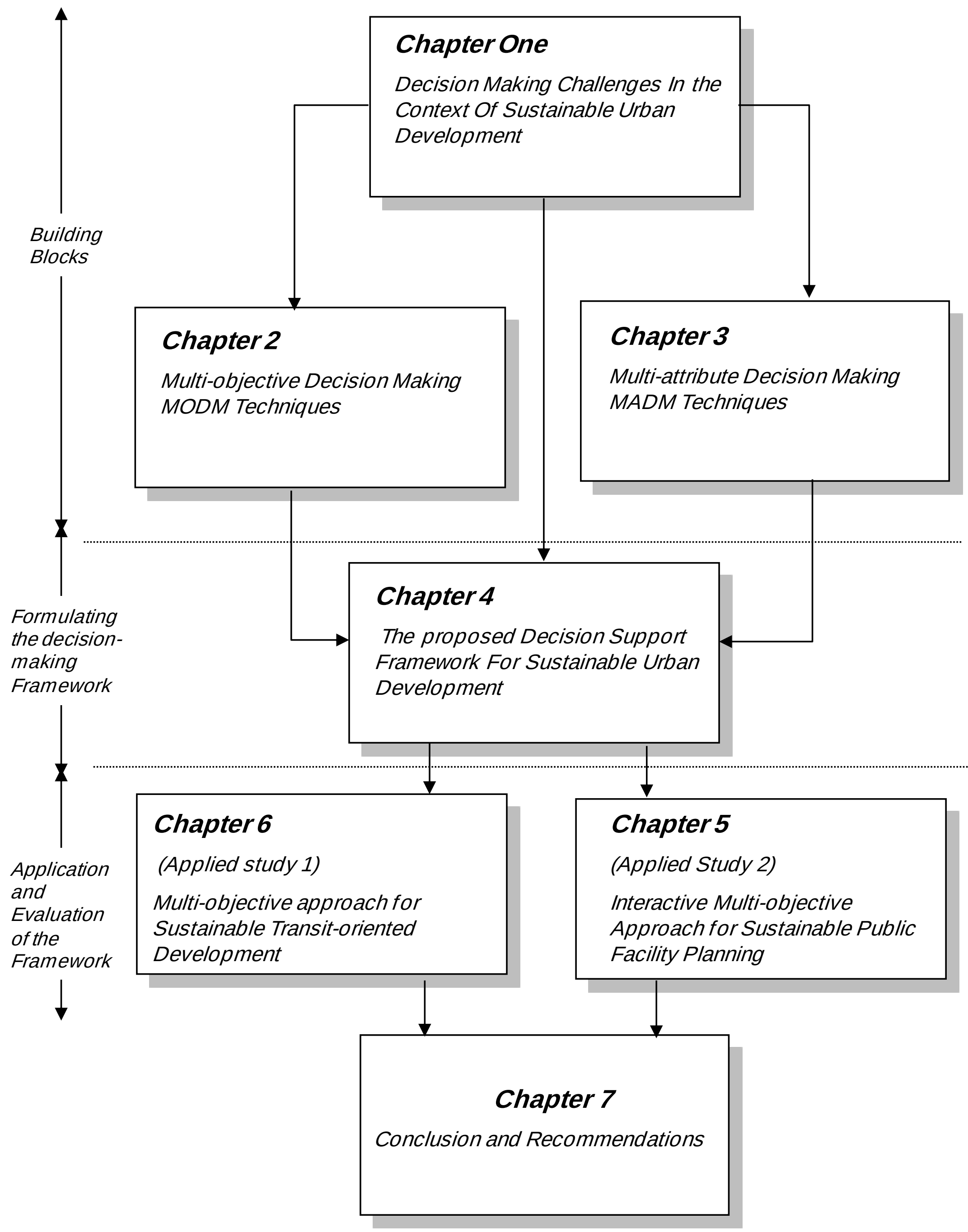


Figure (a-1) Methodology of research.

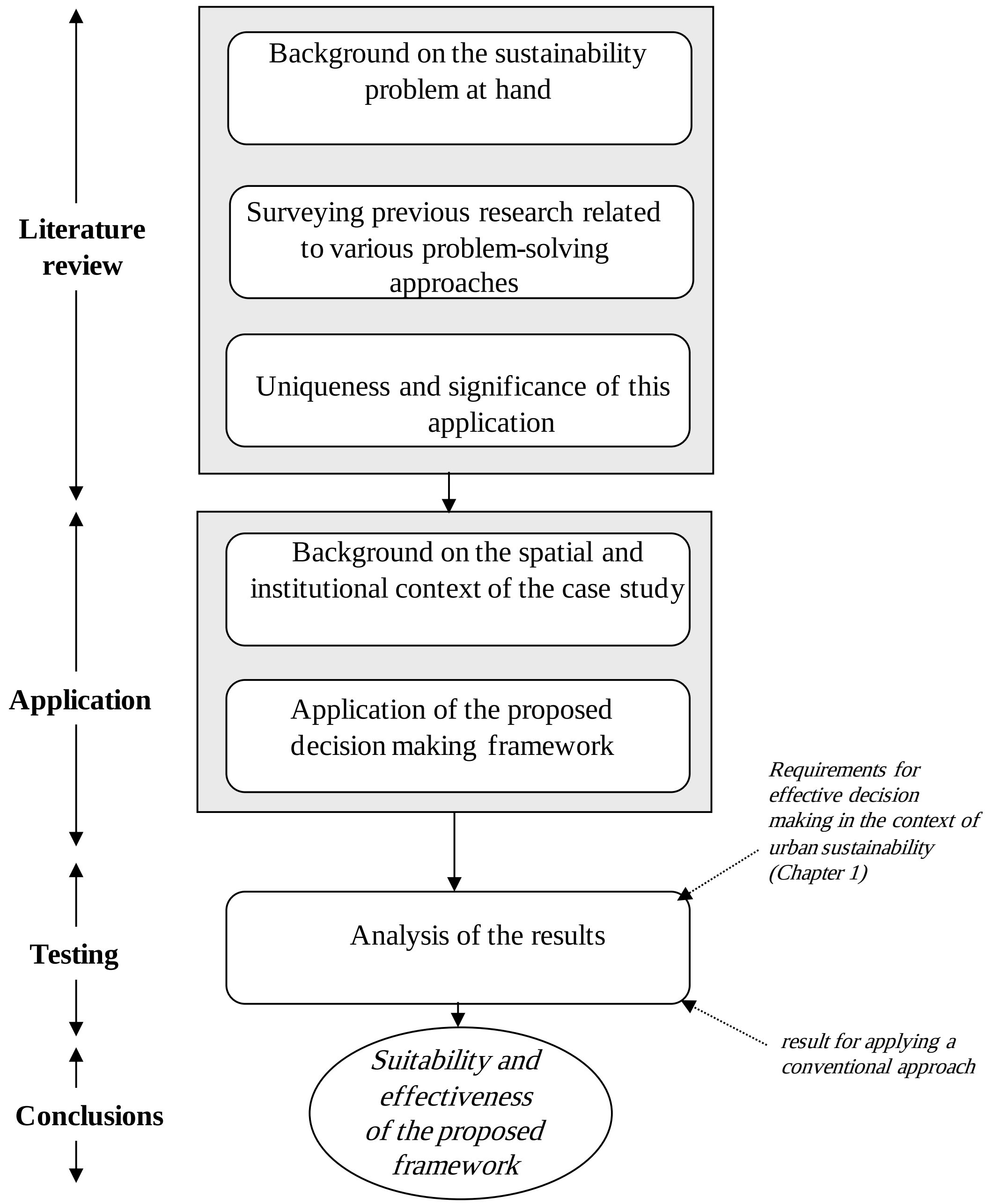


Figure (a-2) Methodology of applied studies.

CHAPTER ONE

DECISION-MAKING FOR SUSTAINABLE URBAN DEVELOPMENT

This chapter includes a theoretical background on definitions and concepts of sustainability with emphasis on sustainable urban development and the common principles of sustainable urban form. Then it focuses on studying the common challenges associated with decision-making in the context of urban sustainability. It establishes an understanding about the complexity inherent in planning for urban sustainability due to the multi-dimensional, multi-objective, multi-stakeholder nature of urban sustainability problems at any planning level. A list of the general requirements (prerequisites) that should be fulfilled within the decision-making process to deal with such complexities is then concluded. The need to incorporate a decision analysis tool is then justified and a brief introduction to Multicriteria Analysis (MCA) techniques is provided, including its two categories: Multi-objective Decision-making (MODM) and Multi-attribute Decision-making (MADM). The integration of these tools for effective decision-making in a decision support framework has been introduced as an initial hypothesis for this research.

1-1 Introduction To Sustainable Urban Development

1-1-1 Definition of urban development

In order to plan effectively for urban development, there is a need to define precisely what the term development means. There is no universal definition of the term development; some definitions are based on economic criteria, some on social conditions, while others are based on political considerations.

Sociologists define development as a process which results in the transformation of social structures in a manner which improves the capacity of the society to fulfill its aspirations. Development implies a qualitative change in the way the society carries out its activities, such as through more progressive attitudes and behavior by the population, the adoption of more effective social organizations or more advanced technology which may have been developed elsewhere (Striano2010).

Geographers tend to define development as the use of resources to relieve poverty and improve the standard of living of a community; the means by which a traditional technology society is changed into a modern, high-technology society, with a corresponding increase in incomes.

Most ***economists*** define development from a growth perspective. Mehmet (1978) and Netson (1958) have contributed to the definition by distinguishing between the terms "economic growth" and "economic development". Growth is a narrower idea and refers to increase of income per capita , as a result of increased capital formation and input utilization. "Development" is much broader in scope and refers to general improvement in the material and social well-being of the society as a whole. While this general improvement incorporates higher income per capita, it also requires reforms in the institutional or quasi-economic framework such as wider accessibility to education, health and welfare facilities, greater political participation in the decision-making process, and more equitable distribution of the benefits of progress, achieved through economic planning.

All the above definitions of development are quite relevant to the ***urban and regional planner,*** who is primarily concerned with the spatial aspects of development. He is interested in how economic development, social development, political development, *etc.* are reflected in a spatial context. This suggests that this definition of development should embrace those of other disciplines. Consequently urban development may be defined as socio-economic changes which are significant and which touch all layers of society. Development entails the activation of a society's socio-economic potentials in a combined effort to overcome problems or indicators of under-development. It also entails human progress as measured by members of the society concerned (Ademiluyi 2009).

1-1-2 Definition of Sustainable development

There is no truly universal definition of sustainable development. At least 300 different definitions are currently in circulation (Dobson 1996). The most cited definition is probably the definition by Bruntland's World Commission on Environment and Development (1987):

> *"Humanity has the ability to make development sustainable – to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs".*

The Bruntland Commission stressed the fact that any future progress toward economic development should be made without depleting existing natural resources or harming the environment. (Kapelan et al, 2005).

1-1-3 Sustainable Urban Development and Sustainable Cities

Following the Earth Summit in Rio de Janeiro in 1992, increasing attention is started to be paid to the sustainable development of urban areas. The fact that more than half of the world's population lives in urban areas and that urban population is growing twice as fast as the total population growth put cities at the forefront of a battle to implement sustainable development (Ibrahim 2002, and Kapelan et al 2005). The vagueness and non-uniqueness of the general sustainability definition is reflected in the definition for sustainable urban development. Again, many definitions are in the circulation. One example of a sustainable urban development definition is the one adopted during the preparatory meetings for the URBAN21 Conference held in Berlin in 2000 :

> *"Improving the quality of life in a city, including ecological, cultural, political, institutional, social and economic components without leaving a burden on the future generations - a burden which is the result of a reduced natural capital and an excessive local debt."*

However, there are many more definitions out there. The Mountain Association for Community Economic Development (MACED) raised the following definition that highlights the three primary aspects of urban sustainability:

> *" Sustainable urban development is the ability to make development choices which respect the relationship between the three "E's"-economy, ecology, and equity:*
>
> ° ***Economy** - Economic activity should serve the common good, be self-renewing, and build local assets and self-reliance;*
>
> ° ***Ecology** - Humans are part of nature, nature has limits, and communities are responsible for protecting and building natural assets;*
>
> ° ***Equity** - The opportunity for full participation in all activities, benefits, and decision-making of a society."*

1-1-4 Fields of policy intervention towards sustainable urban development.

To drive a city towards urban sustainability, existing literatures covers three main fields of policy intervention: *Technology*, *Territorial* and *Life style* related policies. (Ibrahim M., 2002, Camagni el al, 1998) as follows:

Technology is probably the most common area of intervention toward urban sustainability. Advanced technology can bring about two types of changes to make a system more sustainable; *efficiency changes* and *substitution changes* (Hatfield and Karlen,1994). Efficiency changes progress toward sustainability by reducing inputs for the same output and/or reducing wastes. Examples include utilizing energy-saving transportation systems and building designs which consume less energy and produce less waste. Substitution changes can increase sustainability by replacing limited or environmentally troublesome inputs with alternatives that are less troublesome. Examples include replacing fossil fuels with less-polluting and renewable solar energy for various urban uses. Thus, the utilization of advanced less polluting, environmentally friendly and energy-efficient technologies becomes a short-term aim of urban sustainability policy (Camagni et al, 1998).

Territorial related policies aim at achieving optimal structure of urban form and the organization of activities in space that would minimize energy consumption and environmental pollution without limiting economic activity. A systematic identification and analysis of alternative urban configurations and land use patterns from the viewpoint of sustainable development and a critical judgment of such options seem therefore necessary. For example, policies that emphasize compact, mixed-use and transit-oriented land use patterns reduce trip length and vehicle emissions and therefore contribute effectively to the sustainability of the city (Jabareen 2006). Thus, achieving a more sustainable urban form becomes a major long-term goal of urban sustainability and land use policies.

Life style related policies aim at influencing behavioral choices of individuals towards more sustainable and environmentally-oriented attitudes. For example, in developed communities where domestic energy consumption is high, differentiated prices of electric energy at certain times of the day can influence such habits and reduce consumption in peak hours (Camagni et al, 1998)

The territorial policy intervention has been considered as the major challenging task of contemporary urban planning (Godschalk 2004. Ligmann et al, 2005). The emergence of "sustainable development" as a popular concept has revived discussion about the form of cities. Undoubtedly, it has motivated and provoked scholars and practitioners in different disciplines to seek forms for human settlements that will meet the requirements of sustainability and enable built environments to function in a more constructive way than at present. (Jabareen 2006). The next section discusses the widely accepted principles of sustainable urban form.

1-1-5 Principles of Sustainable Urban Form:

Urban form is defined as the spatial pattern of human activities at a certain point in time (Jia, 2006). Generally, urban form is a composite of characteristics related to land use patterns, transportation systems, and urban design (Handy, 1996). Kevin Lynch (1981) defines urban form as “the spatial pattern of the large, inert, permanent physical objects in a city.” Williams et al (2000) characterize a sustainable urban form as the one "that enables the city to function within its natural and man-made carrying capacities, and is user-friendly for its occupants, and promotes social equity".

In fact, there is some controversy regarding even the simplest assumptions about sustainable form (Scheer and Scheer, 2002). However, certain literature such as Leccese et al (2000), Willams et al (2000), Jabareen (2006), Omar (2009), have identified several widely accepted principles that contribute to the sustainability of urban form on various levels of planning, as follows:

A- Compactness:

Compactness of the built environment is a widely accepted strategy through which more sustainable urban forms might be achieved. Compactness also refers to urban contiguity (and connectivity), which suggests that future urban development should take place adjacent to existing urban structures. Intensification, a major strategy for achieving compactness, uses urban land more efficiently by increasing the density of development and activity. The intensification of the built form includes development of previously undeveloped urban land, redevelopment of existing buildings or previously developed sites, and infill development. Jabareen (2006) and (Sherlock 1990) argue that compactness allows more efficient provision of urban services, helps in promoting social interaction, reduces energy consumption and greenhouse gas emissions and reduces commuting one of the most wasteful and frustrating aspects of city living today.

B- Sustainable Transport

Jabareen (2006) and Leccese et al (2000) argue that sustainable urban form must have a form and scale appropriate to walking, cycling, and efficient public transport and must enable access to the facilities and services of the city while minimizing the resulting external costs. Policies for sustainable urban development should, therefore, include measures to reduce the need for movement and to provide favorable conditions for energy-efficient and environmentally friendly forms of transport. Intensifying development around mass transit stations, or "Transit-oriented development" is among the well known measures of sustainability. Newman and Kenworthy (1989) advocate policies to increase the "efficiency" of cities mainly by introducing a new mass rail transit system, restricting automobile-related infrastructure, increasing densities and strengthening the city center.

C- Density:

Density is a critical typology in determining sustainable urban forms. It is the ratio of people or dwelling units to land area. High density and integrated land use not only conserve resources and infrastructure but provide for compactness that encourages social interaction. Density is the single most important factor associated with transit use (Transportation Research Board of the National Academy 1996). As density increases, automobile ownership declines, and automobile travel also decreases. Similarly, transit use, walking and biking all increase with increasing density. (Jabareen 2006).

D- Mixed Land Uses

Mixed-use or heterogeneous zoning allows compatible land uses to locate in close proximity to one another and thereby decrease the travel distances between activities. For the past several decades, urban planning has been “un-mixing” cities by the use of rigid zoning that separates single land uses into different colored parts of the city plan. The result is a city with less diversity in local areas and more traffic, as well as reduced safety and diminished attractiveness of local streets (Jabareen 2006). For a sustainable urban form, mixed use should be encouraged throughout cities (Omar, 2009).

E- Diversity

There are some similarities between diversity and mixed land uses. However, diversity is “a multi-dimensional phenomenon” (Turner et al 2001) that promotes further desirable urban features, including greater variety of housing types, building densities, household sizes, ages, cultures, and incomes. Thus, diversity represents the social and cultural context of the sustainable urban form (Jabareen 2006). Wheeler (2002) argues that "If development is not diverse, then homogeneity of built forms often produces unattractive, monotonous urban landscapes, a lack of housing for all income groups, class and racial segregation, and job-housing imbalances that lead to increased driving, congestion, and air pollution".

F- Passive Solar Design

Specific design measures can reduce the need for energy through generating a microclimate. Yannas (1998) summarizes some design parameters for improving urban microclimate and achieving environmentally sustainable cities: (1) *built form*—density and type, to influence airflow, view of sun and sky, and exposed surface area; (2) *street canyon*—width-to-height ratio and orientation, to influence warming and cooling processes, thermal and visual comfort conditions, and pollution dispersal; (3) *building design*—to influence building heat gains and losses, and use of transitional spaces; (4) *urban materials and surface finish*es—to influence absorption, heat storage, and emission; (5) *vegetation and bodies of water*—to influence evaporative cooling processes on building surfaces and/or in open spaces; and (6) *traffic*— reduction, diversion, and rerouting to reduce air and noise pollution and heat discharge.

G- Greening, parks and open spaces

Green urbanism, beside making the city a more appealing place also (1) contributes to maintenance of biodiversity through the conservation and enhancement of a distinctive range of urban habitats and ecological diversity; (2) amelioration of the physical urban environment by reducing pollution, moderating the extremes of the urban climate, and contributing to cost-effective sustainable urban drainage systems; (3) improving the image of the urban area and therefore the quality of life; and (4) increasing the economic attractiveness of a city and fostering community pride. Greening also has health benefits and an educational function as a symbol or representation of nature (Jabareen (2006).

H- Moderate parcel and building sizes

Omar (2009) argues that moderate parcel sizes impel small-scale changes that are less expensive, easier to implement, and require less disruption to the physical environment and social fabric than large-scale change. There is more coherent flexibility and adaptability of parcels that are a moderate scale. Moderate size buildings are also more sustainable. Relatively large buildings are usually less energy-efficient, create urban temperature sinks, require more sophisticated technology to operate, and are built from materials that require high energy in manufacturing and transport.

Despite the fact that these principles of urban form might seem to be more sustainable than others, Williams et al (2000) concluded that urban sustainability cannot be achieved by applying such principles as fixed standards. They stressed that the focus should be on formulating and practicing an effective decision-making process to ensure identifying and choosing the right solution for any given circumstances. This is the main motivation of this research.

However, decision-making in the context of urban sustainable development is described by being a complex issue accompanied by many difficulties (Jeffreys 2002, Azapagic et al 2005, Camagni et al 1998, Wiek and Binder 2005, Boulager and Brechet 2005). Urban sustainability is a multi-faceted phenomenon fraught with conflicts and uncertainties (Finco A., and Nijkamp 1999). Effective decision-making for urban sustainability requires the consideration of a large number of objectives pertaining to the economic, environmental and social aspects of urban sustainability. It also involves different stakeholders with conflicting interests and preferences. A solution that fully meets all objectives and preferences might not exist. Therefore, it is required to explore a wide range of high quality alternatives and to examine trade-offs between the competing objectives before a final solution is reached (Xiao et al 2007). Further difficulties emerge due to the need for transparency and communication among all interested parties during the decision-making process. Uncertainty in the input data, and the outcomes of a choice poses yet another challenge for decision-making (Fondazione Eni Enricso Mattei, 2008).

The next section discusses in more detail the challenges associated with decision-making in the context of urban sustainability.

1-2 Decision-making In The Context Of Urban Sustainability

This section aims at addressing the challenges associated with decision-making in the context of urban sustainability. However, it is important to start with highlighting the basic definitions and concepts of decision-making in general terms.

1-2-1 Definition of decision-making:

Two main definitions are suggested by (Harris, 2008)

1- Decision-making is *the study of identifying and choosing alternatives based on the values and preferences of the decision maker(s)*. Making a decision implies that there are alternative choices to be considered, and in such a case we want not only to identify as many of these alternatives as possible but also to choose the one that best fits with our goals, objectives, desires, or values. This definition is particularly important in the context of urban planning as it stresses that decision-making is not a separate function of choosing among alternatives but it is intertwined with the generation of a wide range of alternatives.

2- Decision-making is *the process of sufficiently reducing uncertainty and doubt about alternatives to allow a reasonable choice to be made from among them.* This definition stresses the information-gathering function of decision-making. It should be noted here that uncertainty is *reduced* rather than eliminated. Very few decisions are made with absolute certainty because complete knowledge about all the alternatives is seldom possible. Thus, every decision involves a certain amount of risk. If there is no uncertainty, you do not have a decision; you have an algorithm--a set of steps or a recipe that is followed to bring about a fixed result.

1-2-2 Decision-making Challenges In the Context of Urban Sustainability

This section discusses in more detail the common difficulties associated with decision-making and planning in the context of urban sustainability . It highlights the common challenging characteristics of urban sustainability problems and the prerequisites for effective decision-making to overcome such challenges (figure 1-3). In general, regardless of the geographical scale (local, city, regional, etc) or the problem domain (land use, transportation, etc.), when addressing sustainability planners are confronted with the following characteristics:

1-2-2-1 Multi-faceted / Multi-objective Problems:

Achieving urban sustainability is a multi-faceted problem in which environmental, economic and social aspects have to be considered simultaneously. Decision-making in such a context involves dealing with multiple objectives and incommensurable units for measuring the achievement of each objective (Herath G. and Perto T., 2006). Urban planners strive to achieve a balance between these objectives (Ibrahim, 2002). The multi-objective multi-disciplinary nature of urban sustainability problems is described in several sources (Vedia F. et al., 1993, Balling R. et al., 1999, Henn and Patz, 2007 and Alshuwaikhat H. M., 2006).

Requirements for effective decision-making:

Therefore, an effective decision-making process for sustainable development should be capable of ***integrating*** and ***simultaneously analyz***ing a large number of objectives (related to environmental and socio-economic aspects) with incommensurable measures of effectiveness (Kapelan, 2005).

1-2-2-2 Conflicting and Competing Objectives

In addition to addressing a large number of objectives, the fact that many of these objectives are competing and conflicting adds to the difficulty of planning for urban sustainability . Campbell (1996) provides a good description of the inherent conflicts between the economic, environmental and equity goals of sustainable development. To illustrate these conflicts Campbell created the "Planner's Triangle," which shows a goal at each point and conflicts occurring along the axes as a result of contradictions between them (Figure 1-1). According to Campbell, the *property conflict* occurs between economic growth and equity, as competing claims arise over the use of property between private interests and the public good. The *resource conflict* arises between environmental protection and economic growth. There is an ongoing conflict over scarce resources, which is often seen as either a means of promoting economic growth or contributing to ecological value. Finally, the *development conflict* between social equity and environmental preservation arises from competing needs to improve the lot of poor people through economic growth while protecting the environment through growth management. These competing goals, Campbell claims, cannot be reconciled due to scarce resources which are necessarily directed toward one of the goals at the expense of the other. Campbell considers the center of the "Planner's Triangle" to represent sustainable development, a point which can only be reached when the goals of economic growth, environmental protection, and social equity are balanced.

To focus on the sustainability of urban areas, Godschalk (2004) expanded the "Planner's Triangle" by adding "livability" as a fourth goal pertaining to urban sustainability. Livability cares for the quality of public spaces, movement systems, building design and man-made environment. By adding livability to the sustainable development triangle, Godschalk created a three-dimensional figure—the *sustainability/livability prism* (Figure 1-2). The four points of the prism represent the three primary sustainability goals of equity, economy, ecology, together with livability goals. In addition to the development, resource, and property conflicts suggested by Campbell, the inherent conflicts between livability and the three primary goals of sustainability arise on each new axis of the prism. The *"growth management conflict"* between livability and economic growth arises from competing beliefs in the extent to which unmanaged development, beholden only to market principles, can provide high-quality living environments.

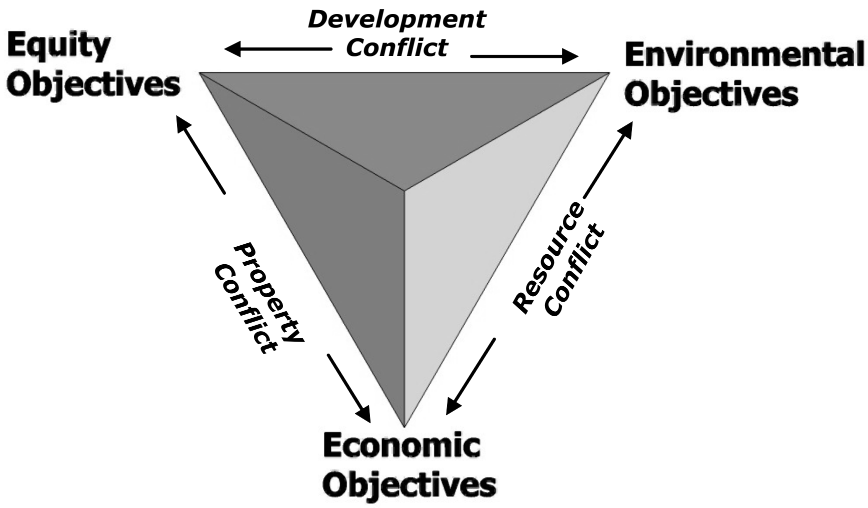


Figure (1-1) The planner's triangle shows the conflicts between sustainability aspects (source: Campbell 1996)

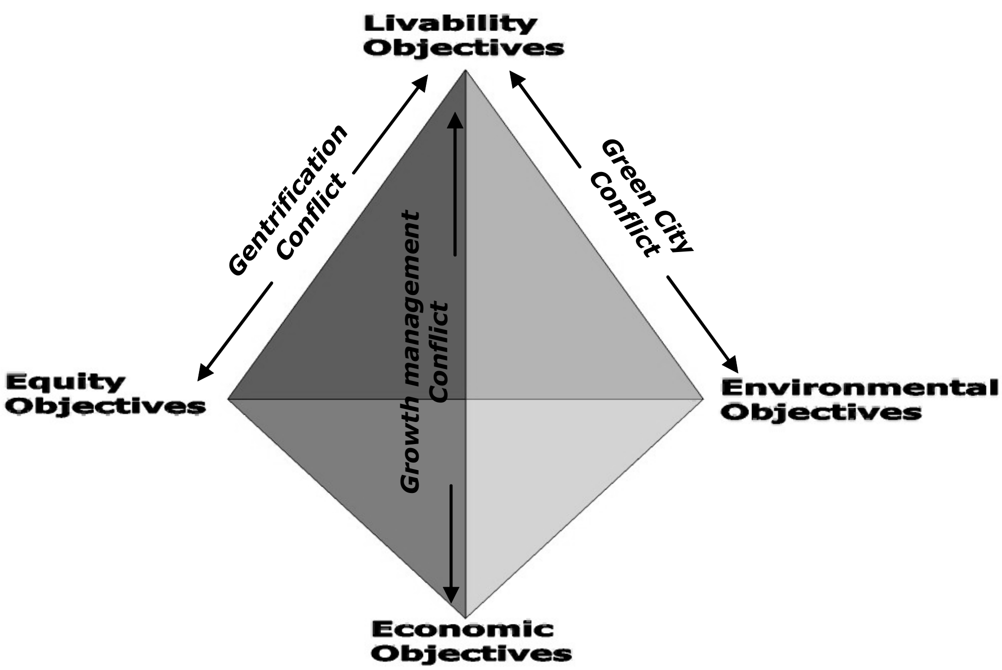


Figure (1-2) The sustainability/livability prism showing the conflicts in the context of sustainable urban development- adding in the livability aspect (source: Godschalk 2004)

The *"green cities conflict"* between livability and ecology arises from competing beliefs in the primacy of the natural versus the built environment. The *"gentrification conflict"* between livability and equity arises from competing beliefs in preservation of poorer urban neighborhoods for the benefit of their present populations versus their redevelopment and upgrading in order to attract middle- and upper-class populations back to the central city. Godschalk argues that the sustainability of any development depends on its success in responding to the four goals and resolving the six conflicts.

Requirement for effective decision-making:

In such a context of conflicting objectives, there is no single solution that can satisfy all objectives at the same time because increasing one benefit typically decrease other benefits (Herath G. and Perto T. 2006). Therefore, decision-making for sustainable urban development ***must involve a trade-off between these conflicting objectives*** until a satisfactory solution is achieved (Stewart et al 2001, Camagni et al 1998, and Finco and Nijkamp 1999).

1-2-2-3 Multi-stakeholder Problem:

Planning for urban sustainability also involves also dealing with a large number of stakeholders with multiple and even conflicting values and interests (White L., 2009). It is well recognized that broad-based stakeholders' involvement and participation is crucial to successful planning for sustainable urban development (Habitat, 2002). Dumreicher et al (2000) consider sustainability as "a local, informed, participatory, balance-seeking process.

Definition of Participation:

Amler B. et al (1999) defined participation as "an interactive and co-operative process of analyzing, planning and decision-making in which all stakeholders take part. It is a process which allows all participants to formulate their interests and objectives in a dialogue, which leads to decisions and activities in harmony with each other, whereby the aims and interests of other participating groups are taken into account as far as possible".

Participatory Decision-making

Participatory Decision-making is a creative process to give ownership of decisions to the whole group, finding effective options that everyone can live with.

Importance of Participation:

- Public participation aims at establishing and maintaining a high degree of trust, transparency, and a sense of shared responsibility for all involved in the planning process (Malczewski 2004);

- Participation is also seen as a critical component to legitimize bureaucratic decisions, improve and expand the information base for making decisions, and enhance accountability by opening up decision-making to public scrutiny. Public participation helps to identify and explicitly incorporate the different stakeholder needs and demands and therefore formulate alternatives that are more acceptable to them (Herath and Prato 2006).

Requirement for effective decision-making:

An effective decision-making process for urban sustainability should promote stakeholder participation as integral part of planning and decision-making (Arnstein, 1971). This implies that the decision-making process in the context of urban sustainability should respond to the following requirements:

1- The process should be able ***to integrate stakeholder values and objectives*** into the analysis (Ibrahim, 2002);
2- The process should be able ***to generate and analyze a wide spectrum of feasible alternative solutions*** to the problem at hand rather than a limited set of alternatives (Stewart et al., 2004). This is particularly important because many stakholders claim to be troubled by the feeling that there is an, as yet unidentified, alternative that must surely be better that those so far considered. The development of techniques for identifying as many alternatives as possible is receiving considerable attention. (Buede 2009, Friend and Hickling 1987);

3- The process should ***facilitate stakeholder involvement into the design stage*** (formulating alternatives). According to (Herath and Prato 2006), when excluded from the formulation stage, stakeholders have a limited role in identifying issues, and developing and prioritizing alternative management options. Public participation at this late stage may be little more than a ratification of decisions that have already been made;
4- The process should ***facilitate negotiation and communication between stakeholders*** to achieve consensus on a compromise solution. This is particularly important in the context of multiple decision makers (Laskar 2003);
5- The process should be ***transparent, understandable, and allows for an audit trail*** by all participants in the process**.** This will increase the level of trusts and a sense of shared responsibility (Malczewski 2004 and Azapagic 2005)

1-2-2-4 Uncertainty in the context of Sustainable Urban Development.

Decision-making for urban sustainability is further complicated by uncertainty in the input data and the outcomes of a choice poses yet another challenge for decision-making (Fondazione Eni Enrico Mattei, 2008).
In the context of urban sustainability two types are of uncertainty particularly important: model and parameter uncertainties. The former refer to the assumptions made and choice of particular preference (e.g. choice of sustainability criteria and indicators, scoring and weighting of various criteria, evaluation of alternatives, consequences of a particular choice, etc.), and the latter to the lack of knowledge about the parameters and working environment (e.g. empirical data on environmental impacts, design variables, etc.) used to support the decision-making (Azapagic and Perdan 2005).

Requirements for effective decision-making:
In view of uncertainties, an effective decision-making process for urban sustainability should respond to the following requirements:

1- The process should possess ***the capacity to ensure the robustness of the preferred alternative***- with respect to any change in input parameters- before a final decision is made (Azapagic and Perdan 2005).

2- The process should enable the planner to ***generate a wide range of high quality alternative solutions without a clear statement of stakeholder preferences***. (Balling et al, 1999, 2000). This is particularly important in the context where stakeholders (and decision maker) are not able – or not willing- to formulate their views about the relative importance of various competing objectives ahead of the design stage. In such a case it is the responsibility of the planner to generate comprehensive set of plans that represent various potential differences in stakeholder preferences (Kennedy et al, 2008).

1-2-2-5 Indicators in the context of sustainable urban development

Decisions in the context of urban sustainability are increasingly being made using indicators of sustainable development. Sustainable development indicators translate sustainability issues into quantitative or qualitative measures used to evaluate the economic, environmental and social performance of alternative solutions. (Azapagic, 2005) The development of sets of sustainability indicators and targets is very complex because there are many components (social, economic and environmental) to measure and there is no single index that sufficiently measures these factors (Alshuwaikhat 2006). Numerous studies have been conducted world-wide to develop common sustainability indicators. However, Ibrahim (2002) argued that the most influential and reliable indicators have been those that were developed with input from local stakeholders.

In the context of sustainability decision-making, where there are often a large number of sustainability issues and related indicators, the challenge is to reduce the list of indicators to a number that can be handled by decision-makers. At the same time indicators must be measurable, understandable, non-redundant and provide enough information to allow decision-makers to choose among scenario options (Weng 2005).

Requirement for effective decision-making:

A effective decision-making process for urban sustainability should ***facilitate the utilization of performance indicators and target values*** in developing and evaluating alternative course of actions (Alshuwaikhat 2006 and Weng 2005).

1-3 Prerequisites For Effective Decision-making Process For Urban Sustainability

According to Simon (1977) a typical decision-making process consists of three main stages: *Intelligence* (What is the problem?), *Design* (What are the alternatives?), and *Choice* (Which alternative is the best?). Figure (1-4) synthesizes the prerequisites for effective decision-making for urban sustainability on top of these three stages. The prerequisites pertaining to each decision-making stage are defined. This figure is particularly important as it is can be evaluate any planning process with regard to its effectiveness in the context of urban sustainability . It is also a milestone for the decision-making framework proposed in this study.

1-4 Limitations Of Conventional Planning Approaches

Conventional planning approaches in the field of urban sustainability satisfy some of these prerequisites but fall short in others. ***In most scenario-based approaches*** the planner analyzes the problem, stakeholders are involved, and then short-lists a few number of alternatives to be assessed by stakeholders and decision-makers. Despite the fact that such approaches have the advantages of being simple, convenient, and easy to operate, their shortcomings are very obvious as they do not satisfy the important prerequisite of exploring a wide range of alternatives. Only very limited schemes are identified with no guarantee that the optimal one is being explored. In addition, some stakeholders may not find the scheme that represents their perspective and therefore feel excluded from the process (Lam and sun 2000, Herath and Prato 2006).

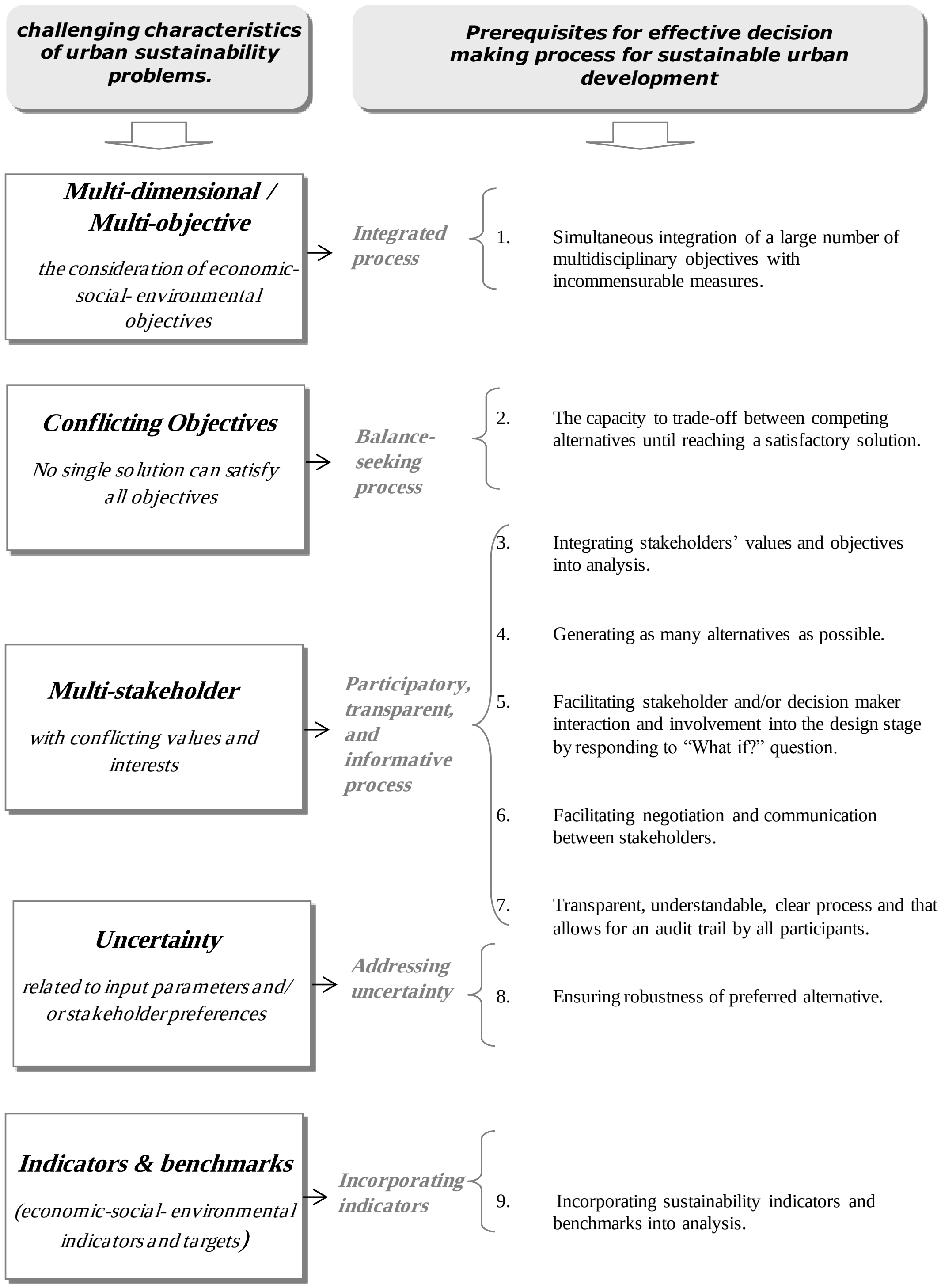


Figure (1-3) Decision-making challenges in the context of urban sustainability.

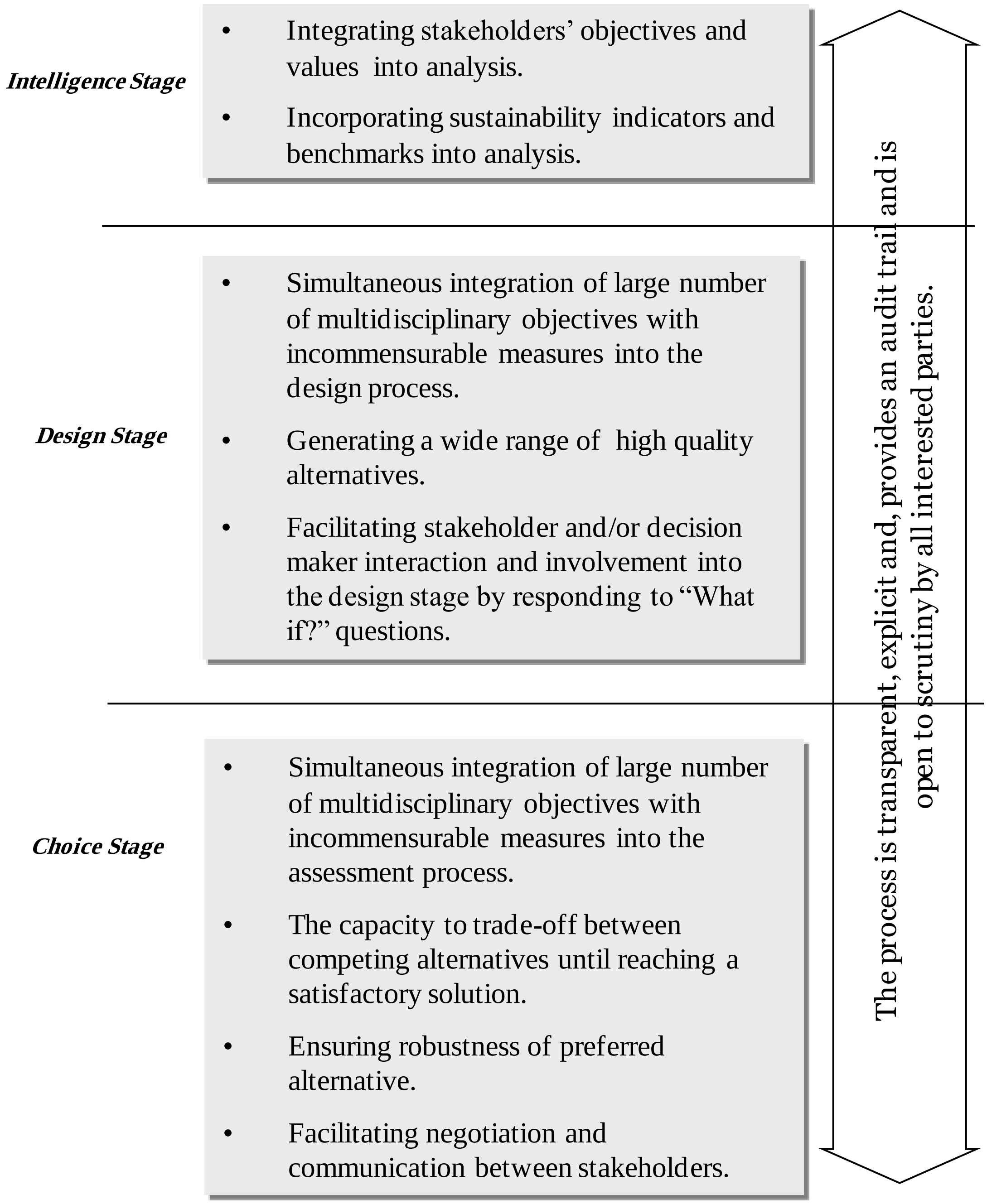


Figure (1-4) Prerequisites for an effective decision-making process in the context of urban sustainability.

Approaches that foster ***advocacy planning*** or "plan with people" where plans are developed during open discussions may have the advantage of fully integrating public values and objectives. However, such approaches are generally not suitable if the problem is too complex to be tackled by lay persons, which is the case in many day-to-day planning problems (Wiek and Binder 2005).

Therefore, many resources have called for new analytical methods and new tools to be explored to support decision-making for urban sustainability (Herath and Prato 2006, Elrefaie 2004, Lam and Sun 2000). Xiao et al (2006) believe that borrowing ideas and methods from other fields will benefit spatial decision-making. The field of decision science has a long history in developing methods and tools that support decision-making in various situations. The next section discusses one of these tools, Multi-criteria Decision-making (MCDM), which will be a fundamental element for this research.

1-4-1 The need for analytical decision-making tools for complex problems

From the preceding discussion it can be concluded that decision-making for urban sustainability is a complex problem; multi-dimensional, involving multi-stakeholders and presenting exactly the type of problem that behavioral decision research shows human (either expert or lay) are typically quite poor in solving unaided. (Lincov 2004).

According to Holloway (1979) "*there are four factors that can make a problem complex enough to make some sort of decision aid attractive:1- Large number of factors. 2- More than one stakeholder 3- Multiple attributes (objectives) and 4- uncertainty" If one or more of these characteristics is present, the problem becomes complex*".

Due to cognitive limitations, most people when confronted with such complex problems will attempt to use intuitive or heuristic approaches. This approach aims at reducing the cognitive load by simplifying the problem until it is more manageable.
However, there is a substantial amount of empirical evidence that human intuitive judgment and decision-making can be far from optimal, and it deteriorates even further

with complexity and stress (Druzdzel and Flynn, 2002). Research on human judgments shows that, during the simplification process, important information may be lost, opposing points of view may be discarded and elements of uncertainty may be ignored. In addition, the decision is inclined to be biased to alternatives that can more readily be linked to what is familiar (the 'representativeness heuristic'), and to be unduly influenced by recent, memorable, or successful experience (the 'availability heuristic'). In short there are many reasons to expect that, on their own, individuals will often experience difficulty making informed, thoughtful choices in such complex decision situations (Lincov 2004).

Because in many situations the quality of decisions is important, aiding the deficiencies of human judgment and decision-making has been a major focus of decision science throughout history. Disciplines such as statistics, economics, and operations research have developed various analytical methods for making rational choices. These methods are especially valuable in situations in which the amount of available information is prohibitive for the intuition of an unaided human decision maker and in which precision and optimality are of importance (Druzdzel and Flynn, 2002).

1-4-2 Decision science techniques

Decision science, also referred to as decision analysis, operations research, system engineering, and management science, has a long history. Put simply, it is the application of scientific methods to every day decision-making. Decision science seeks to apply logical reasoning to decision problems in a structured way, thereby making the decision process explicit and repeatable. It also offers a means to look inside a particular decision and make explicit how and why it was made. Decision science has had many applications in engineering, the military and business management. Although there is evidence that formal decision-making methods in military strategy date back thousands of years, the field of decision science is commonly assumed to have originated during WW II, when scientific methods were applied to strategy in anti-submarine warfare by

T.C.Koopmans (Bailey, 2005). There is a multitude of formal decision-making methods depending on the type of the problem addressed; either single objective problems or multi-objective problems (MOP) where a large number of conflicting objectives exist. The methods that deal with multi-objective problems are called Multi-criteria Decision-making MCDM methods.

1-5 Multi-criteria Decision-making (MCDM)

1-5-1 Reasons for the Growing Interests in the MCDA Field.

Multiple-criteria decision-making (MCDM) is perhaps one of the most important and active area of research in the field of management science (Kasanen et al 2000, Keefer et al 2004). Wallenius et al (2008) compared the growth path of MCDM from 1992 to 2006 with the growth of science in general. While the number of MCDM publications grew exponentially 4.2 times, the number of publications included in the Science Citation Index had only doubled.

There are many reasons for the increasing interest in this field. ***First***, and most importantly, is the increasing recognition that most decision problems are inherently multi-objective and multi-dimensional. A ***second***, but related, reason is the presence of numerous stakeholders in many problems and the societal implications of their decisions. Finally, a ***third*** reason for increasing interest in MCDA is the enormous improvement over the last two decades in the speed, storage, and flexibility of computing facilities required to process MCDM. On the other hand, the decision support applications became user-friendly and often built around spreadsheets , such as Excel. The massive growth of the Internet also offered intriguing possibilities for web-based MCDM applications (Wallenius 2008 and Evans 1984).

1-5-2 Definitions of MCDM

Multi-criteria decision analysis (MCDA), sometimes called **multi-criteria analysis (MCA)**, is a discipline aimed at supporting decision makers who are faced with making numerous and conflicting evaluations. MCDA aims at highlighting these conflicts and deriving a way to come to a compromise in a transparent process**.**

Malczewski (2000) *defined Multi-criteria decision-making (MCDM)* as *"a set of mathematical tools aimed at supporting decision makers in a wide variety of disciplines such as economics, geography, biology and geology among others"**;***

International Society on Multiple Criteria Decision-making defines MDMA as "*the study of methods and procedures by which concerns about multiple conflicting criteria can be formally incorporated into the management planning process";*

Multi-criteria analysis is generally defined as "a decision-aid and a mathematical tool allowing the generation and comparison of different alternatives or scenarios according to many criteria, often conflicting, in order to guide the decision maker towards a judicious choice" (Roy 1996).

Multi-criteria decision-making (MCDM) refers to making decisions in the presence of multiple and conflicting criteria. Problems of MCDM may range from our daily life such as the purchase of a car to those affecting entire nations as in the judicious use of resources for the preservation of national security. However, even with this diversity, all MCDM problems share the following common characteristics (Lu, et al 2007):

- ***Multiple criteria***: each problem has a number of criteria which can be objectives or attributes;
- These criteria are in ***conflict*** with each others;
- ***Incommensurable units***: criteria may be of different units of measurement.

MCDM approaches are often distinguished according to the problems they address with respect to the number of alternatives decision-makers have to choose from. A problem can be either "discrete" with a finite set of predefined alternatives or "continuous" with an infinite number of feasible alternatives. Accordingly, MADM can be broadly classified into two categories (Figure 1-5):

Multi-Attribute Decision-making (MADM): concerned with choosing from a finite set of predefined alternatives (e.g. selecting the best location for a factory from a set of five alternative sites). MADM requires that both the alternatives and the evaluation criteria be known prior to analysis. MADM then provides a systematic and structured framework and tools to incorporate the decision maker's preferences, generate an aggregated score that measures the overall performance of each alternative and ranks the alternatives accordingly. The output is a list of ranked alternatives with the optimal alternative at the top of the list.

Multi-Objective Decision-making MODM (also called Multi-objective Optimization MOO): concerned with choosing from an infinite number of alternatives. (e.g. finding the optimal floor space for a new real estate project; theoretically could be any number). In such a case, only the objectives and constraints will be known prior to analysis. In MODM the problem is formulated as a mathematical optimization model with a set of objective functions (to be maximized or minimized) and constraints. The model is then used to generate a set of large number of efficient (non-dominated) solutions to be presented to the decision maker who will select the solution that best suits him. Or, alternatively, the optimal solution will be generated through interactive process with the decision maker who has to provide his preference with respect to the relative importance of each objective (Cohon,1978).

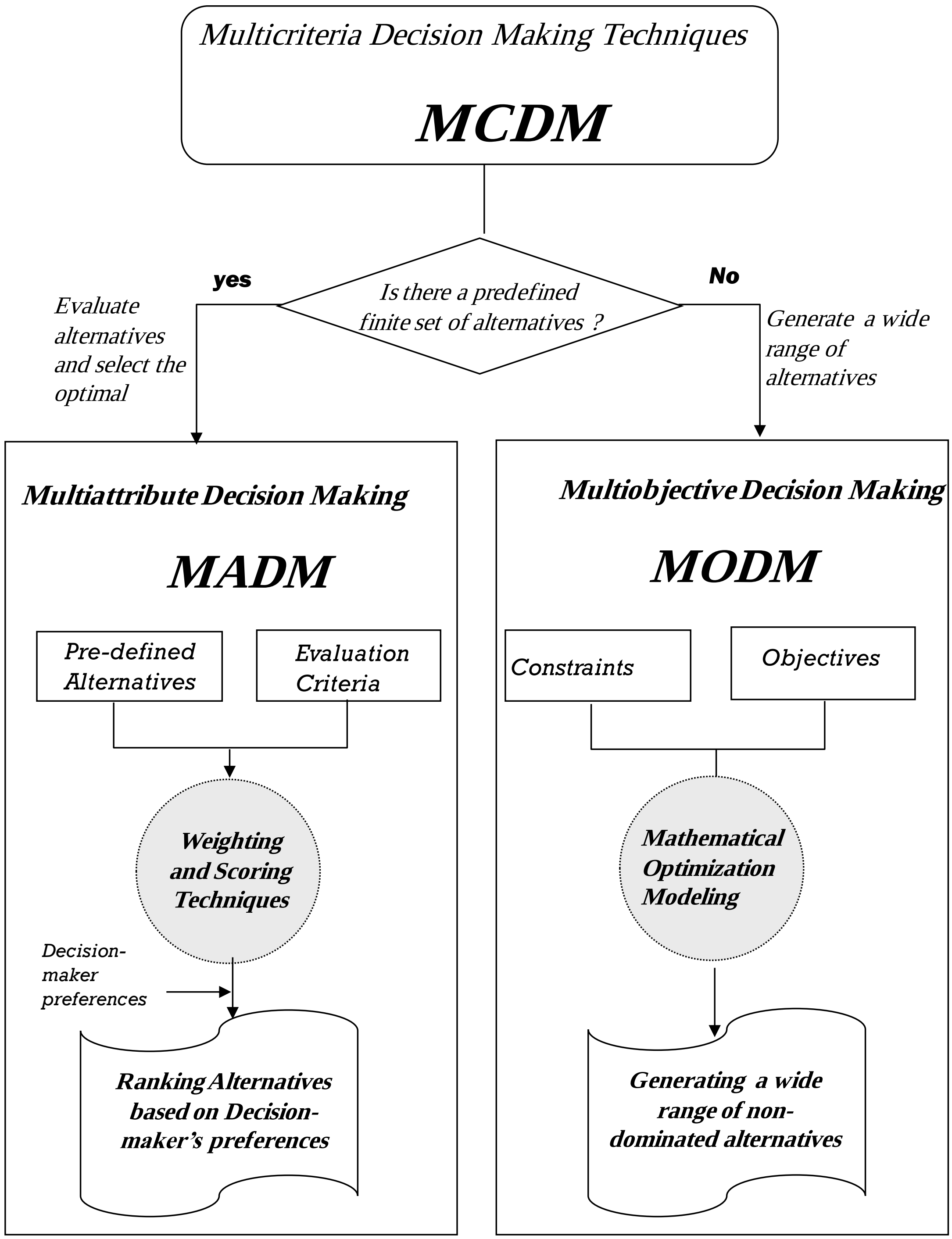


Figure (1-5) Categories of Multi-criteria Decision-making including the function, input, output of each category

1-6 Formulating the initial research hypothesis:

From the previous discussion on the prerequisites for effective decision-making in the context of urban sustainability (Figure 1-4) and the characteristics of MCDM techniques (Figure 1-5), it can be initially hypothesized that combining MODM and MADM in a structured framework as in (Figure 1-6) can provide a significant assistance in urban sustainability decision-making by responding to the prerequisites presented in Figure (1-4). This initial hypothesis is based on the following:

- Both MODM and MADM are based on theoretical sound backgrounds and have been tested in numerous applications (Azapagic 2005 and Malczewski 2000);
- Both MODM and MADM deal with problems with large number of conflicting and incommensurable objectives (Lu et al 2007);
- Both MODM and MADM provide a systematic and transparent approach for problem solving that can be reviewed by all participants in the decision-making process (Azapagic 200 and, Bailey 2005);
- MODM can provide a large number of feasible solutions based on multi-disciplinary sustainability objectives (social, economic, and environmental) (Cohon, 1978);
- MODM provides solutions interactively therefore can respond to "what if?" questions (Cohon, 1978);
- MADM can be used to evaluate this large number of alternatives after incorporating the decision maker's preferences who can then trade-off between objectives by changing the weights (Bailey 2005)

In chapter 2 and 3 MODM and MADM techniques will be studied in detail to explore their capacity to support decision-making in the context of urban sustainability. In Chapter 4, the final research hypothesis will be formulated by providing a detailed decision support framework that integrates MODM and MADM to respond to the prerequisites presented in figure (1-4)

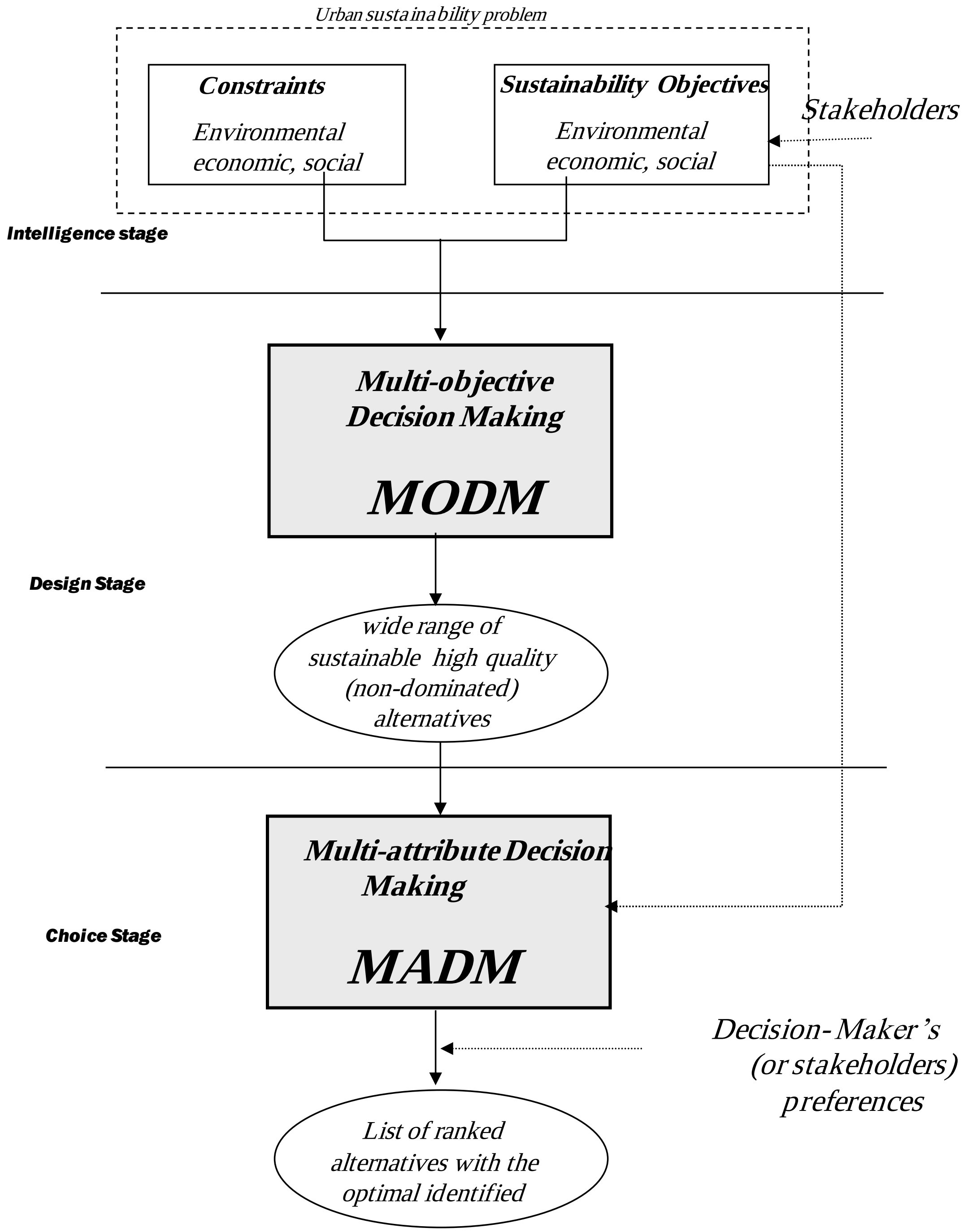


Figure (1-6) initial research hypothesis (integrating MODM and MADM into decision-making process for urban sustainability

1-7 Summary and Conclusions

- The fact that more than half of the world's population live in urban areas puts cities at the forefront of a battle to implement sustainable procedures. Previous attempts to standardize urban sustainability in terms of fixed characteristics of urban form such as: compactness, density, etc have been criticized. The focus should be on formulating and utilizing an effective decision-making process to ensure identifying and choosing the right solution for any given circumstance.
- Problems related to urban sustainability are complex and characterized by being multi-disciplinary, involving multiple and conflicting objectives, multiple stakeholders with various priorities, and a high level of uncertainty;
- For effective decision-making in such a complex context, the decision-making process should be integrated, participatory, balance seeking, and capable of addressing uncertainty. It should satisfy the following prerequisites :
  1. Simultaneous integration of many objectives with incommensurable measures;
  2. The capacity to trade-off between alternatives to reach a balance;
  3. Integrating stakeholders values and objectives into analysis;
  4. Generating a wide range of high quality alternatives;
  5. Facilitating stakeholder and/or decision maker involvement in the design stage;
  6. Facilitating negotiation and communication between stakeholders;
  7. Transparent, understandable, clear process reviewable by all participants;
  8. Ensuring robustness of preferred alternative;
  9. Incorporating sustainability indicators and benchmarks into analysis;
- As conventional planning approaches cannot satisfy all these requirements, the existing literatures call for exploring new tools and techniques.
- Multi-criteria Decision-making MCDM techniques, developed by the field of management science, aims at assisting decision-making with multiple conflicting objectives. It consists of two categories: Multi-attribute Decision-making MADM which deals with choosing from among a predefined set of alternatives, and Multi-objective Decision-making MODM which deals with generating a large number of alternatives using mathematical optimization modeling. This research hypothesizes

that a hybrid MODM/MADM approach will effectively support decision-making for urban sustainability .

CHAPTER 2

MULTI-OBJECTIVE DECISION-MAKING TECHNIQUES FOR URBAN SUSTAINABILITY

This chapter focuses on Multi-objective Decision-making (MODM) and its potentiality in the context of urban sustainability. It provides a background on mathematical optimization models as a decision-making tool, then focuses on multi-objective optimization concepts and highlights the role of both the decision-maker and analyst (the planner) in problem solving with multi-objective optimization. The three main MODM approaches (posterior, priori, and interactive) and their advantages and disadvantages with regard to adding decision-making in the context of urban sustainability are studied. Accordingly, the appropriate solution techniques are recommended. Finally, this chapter provides a literature review on applications of MODM in urban planning.

2-1 Introduction on Mathematical Optimization:

2-1-1 Models as tools for decision-making

Decision-making often involves the exploration of situations that do not exist. Analyzing such situations requires a model or abstraction of reality rather than reality itself. A model is a simplified representation or abstraction of reality. Models are used to portray the important aspects of reality while eliminating other aspects, which may cause difficulties in a particular situation. Models make the structure of the problem explicit. Examining a simple model may show general principles of how the system in question behaves and may lead to a deeper understanding of the problem. This behavior might be hidden behind the mass of details resulting from a more complex model. (Ford, 1999)

The main reason to rely on any model in a decision-making process is to provide a quantitative assessment of the effects of management decisions on the system being considered. A model also provides a relatively objective assessment as opposed to subjective opinions of system behavior. Thus, models should be used in support of decision-making (Cohon 1978). To model means to build a representation of something. Often the model is not an exact match of reality, but only an abstraction. There are many ways models can be created; **mathematical models, mental models**, **physical models**, **computer models**, or some combination of the above.

We use models all the time, but we work mostly with informal models. The images we carry in our minds are simplified representations of a complex system; they are something called "Mental Models." Fullan (2007) describes mental models as "*deeply ingrained assumptions, generalizations, or even pictures or images that influence how we understand the world and how we take action*." We use mental models constantly to interpret the world around us, and we usually do not realize that we are doing so (Ford, 1999).

Mathematical (quantitative) models are the most abstract form of modeling and an essential component of decision-making. Making decisions on issues with important consequences has become a highly complex problem due to the many competing forces under which the world is operating today; an intelligent utilization of mathematical modeling is essential for good results (Mutey, 2003). The mathematical model can serve the following purposes: (1) to find an optimal solution to a planning or decision problem; (2) to answer a variety of what-if questions; (3) to establish an understanding of the relationships among the input data items within a model; and (4) to attempt to extrapolate past data to derive meaning (Mutey, 2003).

2-1-2 Mathematical modeling

Mathematical modeling is the process of creating a mathematical representation of some phenomenon in order to gain a better understanding of that phenomenon. It is a process that attempts to match observation with symbolic statements. During the process of building a mathematical model, the modeler will decide what factors are relevant to the problem and what factors can be de-emphasized. Once a model has been developed and used to answer questions, it should be critically examined and often modified to obtain a more accurate reflection of the observed reality of that phenomenon. In this way, mathematical modeling is an evolving process; as new insight is gained, the process begins again as additional factors are considered. "Generally the success of a model depends on how easily it can be used and how accurate are its predictions." (Murty, 2003). There are two main thrusts in mathematical modeling for decision-making: simulation and optimization.

Simulation: Simulation is a methodology for performing experiments using a model of a real world system.

Optimization: is a normative approach to identify the best solution for a given decision problem. An optimization method is a modeling method that seeks to find the beast (often maximum profit or minimum cost) solution to a well-defined problem. A well-defined problem is one which has been structured in a way that the optimization method can utilize. Common to all optimization models is a quantity (quantities) to be minimized or maximized. This quantity is often termed the objective function. Optimization problems typically have a set of constraints imposed on the decision variables. If the problem involves a single objective it is referred to as single objective optimization problem. When more than one objective is to be optimized simultaneously, the problem is called a multi-objective optimization problem (Amin, 2008).

2-1-3 Mathematical optimization process

Optimization is a collective process of finding the set of conditions required to achieve the best result in a given situation.

> *Optimization is just another type of modeling and the same applies to optimization models. Optimization tools should be used for supporting*

decisions rather than for making decisions, i.e. should not substitute for decision- making process. (Savic 2004, pp 7)

We may want to get the largest production from a given set of raw materials, the greatest profit from a fixed investment, and so on. Optimization is a formal presentation of these ideas. (Render, Stair, and Hanna, 2012). Problem solving with optimization involves the following steps:

1- Define the problem of interest and gather relevant data;
2- Formulate a mathematical model to represent the problem;
3- Solve the model to derive solution;
4- Implement the solution.

2-1-4 Components of an optimization model

The most critical part of the process is the formulation of the mathematical model. The mathematical model of the proposed problem is the system of equations and related mathematical expressions that describe the essence of the problem. Thus, if there are n related quantifiable decisions to be made, they are represented as ***decision variables*** (say, x1, x2, …..xn) whose respective values are to be determined. The appropriate measure of preference (e.g. profit) is then expressed as mathematical function of these decision variables. This function is called the ***objective function***. Any restrictions on the values that can be assigned to those decision variables are also expressed mathematically, typically by means of inequality equations. Such mathematical expressions for the restrictions are often called ***constraints.*** The constants (namely the coefficients and the right-hand sides) in the constraints and the objective function are called the ***parameters*** of the model. The mathematical model might then say that the problem is to choose the values of the decision variables so as to maximize (or minimize) the objective function, subject to the specified constraints (Fredrick, 2001).

2-2 Multi-objective Decision-making MODM:

Multi-objective Decision-making MODM, also called Multi-objective Optimization MOO, without loss of generality, can be defined as a technique for simultaneously minimizing or maximizing several non-commensurable and often conflicting objectives. Although single-objective optimization problems may have a unique optimal solution, this is not the case for many realistic multi-objective optimization problems (MOPs). Typically, MOPs have no unique, perfect solution but rather a set of non-dominated, or non-inferior, alternative solutions, also known as the Pareto-optimal set.

2-2-1 General formulation, definitions, and concepts :

In MODM the decision problem is formulated with mathematical equations taking the following structure: Maximize (or minimize) two or more conflicting ***objective functions*** subject to a set of ***constraints*** which define feasibility. The objective functions and constraints are mathematical functions of ***decision variables*** and ***parameters***. Decision variables *(Xi)* are those aspects of a system which are controllable, while parameters are given values (not controllable). The general form of a multi-objective optimization problem with *n* decision variables and *m* constraints and p objectives is:

Objective functions: **Minimize (or maximize)** $\mathbf{Z}(x_1, x_2, \ldots, x_n)$

$$= \left[\mathbf{Z}_1(x_1, x_2, \ldots, x_n),\ \mathbf{Z}_2(x_1, x_2, \ldots, x_n),\ \ldots,\ \mathbf{Z}_p(x_1, x_2, \ldots, x_n) \right]$$

Constraint functions: **Subject to:** $\mathbf{g}_i(x_1, x_2, \ldots, x_n) \leq \mathbf{0} \qquad i = 1, 2, \ldots, m$

$$Xi \geq \mathbf{0} \qquad j = 1, 2, \ldots, n$$

In solving a mathematical optimization model, the analyst is attempting to discover the best values for the decision variables. A collection of values for each decision variable is called ***a solution*** to the mathematical program. A solution which satisfies all the constraints is called a ***feasible solution***. The solution that does not satisfy any of the constraints is called an ***infeasible solution.*** In general there are an enormous number of feasible solutions. The collection of all feasible solutions comprises the ***design space***. The role of the objective function is to provide a basis for the evaluation of the feasible solutions to find the optimal solution.

2-2-1 Single objective optimization Vs. Multiple objective optimization.

The optimization model that includes only one objective function is called a single objective optimization model. In the case of a single-objective optimization problem the feasible solution which gives the best (lowest or highest) value of the objective function is called the ***optimal solution***. There is only one unique optimal solution for a single objective problem. Optimality plays an important role in single objective problems. It allows the analyst and decision-maker to restrict their attention to a single solution. There are many techniques to solve the single objective optimization such as ***Linear Programming*** (Magnanti, Hax and Bradley, 1977). However, in the case of multi-objective problems **no single optimal solution** exits. Usually, in case of conflicting objectives, it is impossible to optimize all objectives simultaneously. What is optimal in terms of one of the objectives is usually non-optimal for other objectives. Instead of one optimal solution, a multi-objective problem typically has a set of **Pareto optimal solutions** (also called non-dominated solutions). Therefore, incorporating the decision-maker's preferences is necessary to find the optimal solution from among the Pareto optimal set of solutions (Cohon, 1978).

2-2-3 Pareto Optimality concept:

The concept of Pareto optimality was first introduced by the Italian economist Vilfrodo Pareto. A feasible solution to a multi-objective problem is called a **Pareto optimal solution** (also named: **non-dominated**, non-inferior, or efficient solution) if there exists no other feasible solution that will yield an improvement in one objective without causing a degradation in at least one other objective (Cohon 1978, Lu et al 2006).

Illustrative example from the domain of urban planning

To illustrate this important concept let us consider a hypothetical example related to the urban planning profession: An urban planning agency is required to select the best alignment for a new light-rail system to serve the population of several urban centers Figure (2-1-a). For such alignment to be sustainable it has to satisfy numerous environmental, economic and social concerns. For the purpose of this illustrative example we will consider only two objectives:

- *Economic objective:* to minimize the length of the transit line (so as to reduce the construction cost).
- *Social objective*: to minimize the number of un-served population (assuming equal population numbers of at each center).

As a constraint, the new light-rail should serve at least 4 urban centers. Obviously there is a huge (almost infinite) number of possible alternative alignments within the solution space however, none of them can satisfy both objectives at the same time. The alignment that passes through all population centers will minimize the number of un-served population but the economic objective will deteriorate. On the other hand, an alignment that takes a short cut may minimize the length at the expense of increasing the number of un-served population.

Figure (2-1-b) represents the objective values of various alternatives. Alternatives A, B, and C, are non-dominated, alternative D is dominated (as alternative A serves the same number of population with lower cost) while alternative E is infeasible as it does not satisfy the constraint. There is no alternative that is better than any of the non-dominated alternatives with regard to *all* objectives. Trying to enhance one objective in any non-dominated alternative will definitely cause the other objective to deteriorate. However, for dominated alternative such as D it is possible to enhance the economic objective at the same social cost by moving to alternative A, for example. It should also be noted that any of the non-dominated solutions performs better than any dominated solution for at least one objective. The infinite number of non-dominated solutions constitute the ***Pareto Frontier,*** which is located at the boundary of the solution space. The optimal

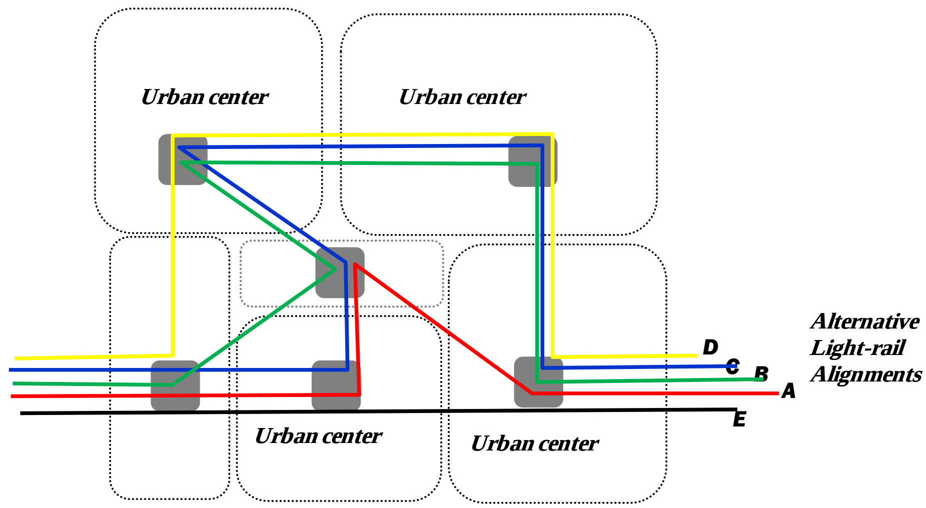


Figure (2-1-a) Illustrative example of light rail alignments.

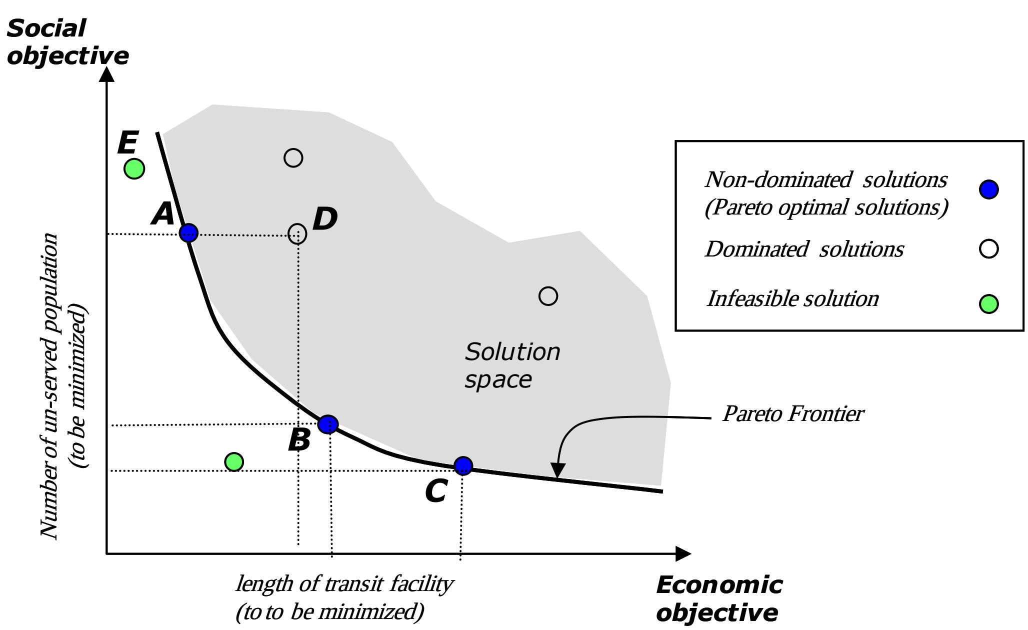


Figure (2-1-b) Objective values for various alternatives.

solution of any multi-objective optimization problem could be any point on the pareto frontier, depending on the decision-maker's preference. For example, if the decision-maker prefers to reduce the cost of the light-rail system, alternative F could be optimal. However, if he seeks a balance between the economic and social objectives any point in the middle of the pareto frontier (such as B) could be optimal. In other words, by moving from point to point on the pareto frontier the decision-maker can ***trade-off*** between the two objectives until he finds the one that satisfies his preference.

The ultimate goal of any multi-objective optimization technique is to find the Pareto optimal solution that satisfies the preferences of the decision-maker. Therefore, the interaction with the decision-maker to reveal the relative importance of each objective is crucial. (Rosenthal 1985). Thus, the final MOP solution(s) results from both *optimization* (by the optimization method) and *decision* (by the decision-maker who has to decide on the relative importance of the competing objectives) (Veldhuizen and , Lamont 2000).

2-2-4 The advantages of MODM for urban sustainability planning:

Cohon (1978) defines planning as "the process by which the planner perceives a problem, defines it, collects data about it, formulates it and generates and evaluates alternatives for solving it, leading to the end of the process when a decision-maker chooses an alternative for implementation.. Thus planning is defined as the sum total of the activities of analysts and decision-makers from problem perception to project implementation." Cohon claimed that Multi-objective optimization should be the focal point for planning activities for the following reasons:

1- Multi-objective optimization provides an orderly, systematic and structured approach to problem solving which is likely to be more efficient and effective than an informal approach;
2- It promotes more appropriate roles for the participants of the planning process; the planner (the analyst) develops the model and generates alternatives without imposing his preferences, the stakeholders' suggest objectives to be considered by

the planner in developing the model, and the decision-maker is the one who is decides and selects the final solution;

3- Multi-objective optimization allows for a wider (theoretically infinite) number of alternatives to be identified.

4- With models, the planner's perception of a problem will be more realistic. They will spend more time and effort to understand all relationships since mathematical formulation requires all system relationships to be clearly stated.

Therefore, we can conclude that MODM (or alternatively named Multi-objective optimization) can help in responding to some of the prerequisites for effective decision-making for urban sustainability development as raised in chapter 1. In particular, It provides a structured and participatory approach to generate a wide range of alternatives.

2-3 Main Multi-objective Decision-making Approaches:

To achieve the goal of finding the final Pareto optimal solution three approaches have been distinguished in the literature according to the timing the decision-maker articulates his preferences (the relative importance of objectives) ie. priori, after or during the optimization process as follows (Cohon, 1979 and Xiao et al 2007):

Priori articulation of preferences: (Decide → *Optimize*)

This approach requires the decision-maker to decide the relative importance (the weight) of each objective before the optimization is conducted. The weights are then integrated into the mathematical model which will be solved to generate one Pareto optimal solution.

Posterior articulation of preference: (*Optimize → Decide*)

This approach does not require the decision-maker to decide on his preferences prior to the optimization process. Instead, this approach depends on methods to generate the entire Pareto optimal solutions (or a comprehensive set of solutions that are evenly distributed on the Pareto frontier). The set of non-dominated solutions are subsequently presented to the decision-maker who should trade-off between solutions to make a final decision. Therefore, this approach is also called the generation approach. Balling (1999) called this approach the "Planning by shopping" paradigm, as the decision-maker is allowed to explore (shop around) all possible designs, form a preference after viewing the designs and select what he prefers (Figure 2-2).

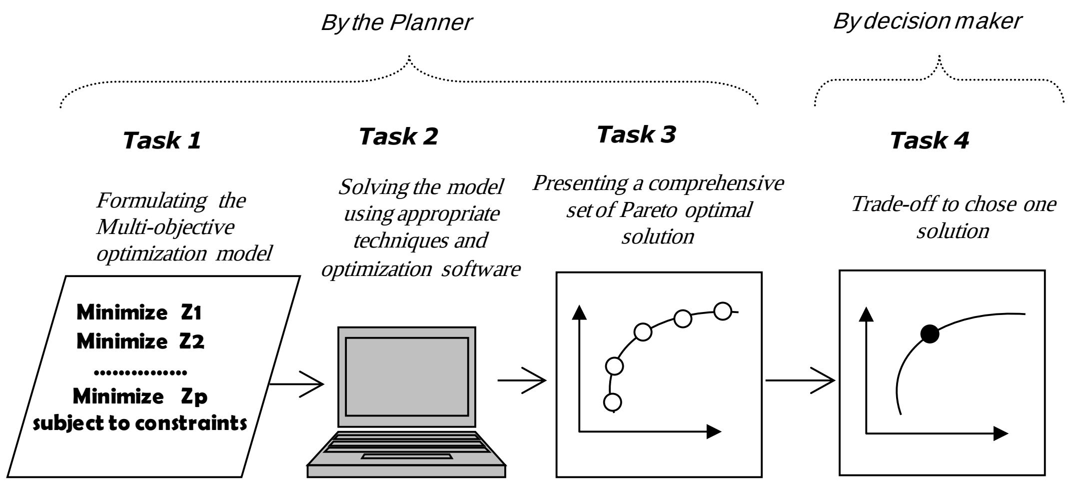


Figure (2-2). Process for the posterior approach.

<u>*Progressive* articulation of preferences: (Optimize ↔ Decide)</u>

This approach realizes that, due to the complexity of real world problems, the decision-maker is usually unable to decide 'a priori preference. Therefore this approach promotes an interactive iterative process in which the decision-maker progressively refines his preferences during each iteration of the process. Decision-makers are presented with a (typically small) subset of non-dominated solutions. The decision-maker therefore gains a better understanding of the problem and adjusts his preferences. The model is solved again to generate another set of non-dominated solutions. This process is repeated until the decision-makers are satisfied.

There are many solution techniques for each of the above mentioned approaches. However, the decision on which approach to be applied depends on many factors such as: the level of involvement of the decision-maker in the process, the complexity of the problem at hand and, the time available for the process and the available computation capacity. The next section discusses the appropriateness of various approaches for decision-making in the context of urban sustainability.

2-4 Selecting the Appropriate MODM Approach For Decision-making in The Context of Urban Sustainability:

As concluded from the previous chapter, decision-making in the context of urban sustainability requires an *integrated*, *participatory*, *balance-seeking*, and *informative* process. Accordingly the following assessment can be concluded:

1- The *priori approach* does not satisfy these prerequisites. It assumes that the decision-maker has a complete knowledge of the problem and can precisely decide on the relative importance of each objective. In addition it only provides one solution based on the *priori* preferences.

2- *The posterior approach* is very appealing in the context of urban sustainability for the following reasons:

- It is informative: due to the capability of generating a broad range of efficient alternatives (theoretically all possible non-dominated solutions) rather than a limited number of alternatives as in conventional planning methods. Therefore, the decision-maker will be more informed and will gain valuable insight into the problem (Balling 1999, Kennedy 2008);
- It is participatory: as the large number of generated alternatives will make it possible for many stakeholders to find "niche" solutions that are beneficial to their view of the problem and its resolution (Xiao, 2007);
- The generation of pareto set does not require prior knowledge of the decision-maker's preferences. Therefore, it works very well in the context where the decision-maker(s) is not accessible to the planner which is the case in many planning practices (Cohon, 1978);

- This approach also helps to screen the dominated alternatives out of analysis. Therefore, the decision-maker need only focus on the non-dominated and more efficient solutions;
- The existence of a large number of non-dominated solutions will impose a substantial cognitive burden on decision-makers who must somehow select a solution from the multitude of alternatives (Xiao, 2007). However, this research provides an interactive and user friendly instrument that will help the decision-maker to navigate through the solution space and trade-off between alternatives.

3- *The Progressive approach* is also very appealing for urban sustainability for the following reasons:
   - It is participatory: as it encourages intensive involvement of the decision-maker in the process of searching for alternative solutions;
   - It also responds to "what if?" questions and fits within the interactive context of a public hearing;
   - It is informative as it is a learning process where the decision-maker obtains a better understanding of the problem as the process evolves;

In the light of the above mentioned assessment, the following section will focus on the solution methods of both the posterior and the progressive approaches.

2-5 Selecting the Appropriate MODM Solution Methods:

2-5-1 Selecting a posterior solving method

There are several techniques for solving the multi-objective programming problem and generating a representative set of the Pareto frontier. Two main streams of techniques are revealed in the literature: The classical optimization techniques (also called scalarization techniques) and the evolutionary optimization (EO) techniques (Andersson J. 2000).

***Classical optimization techniques*:** These techniques depend on converting the multi-objective problem into a single objective optimization problem which can be solved by any commercial optimization software. The single run of the software will yield a single non-dominated solution. Among the well-known classical methods are the weighted sum methods and the E-constraint method. A comprehensive review of classical methods for multi-objective optimization can be found in Cohon (1978), Miettinen (2008), and Andersson 2000).

The evolutionary optimization techniques (EO) : These techniques take advantage of advanced artificial intelligent methodologies such as Genetic Algorithms to enumerate the Pareto frontier all together in a single run. An EO begins its search with a population of solutions usually created at random within a specified lower and upper bound on each variable. The EO procedure enters into an iterative operation of updating the current population to create a new population by the use of four main operators: selection, crossover, mutation and elite-preservation. The operation stops when one or more pre-specified termination criteria are met (Deb 2008). Advancements in computer capacity have helped these techniques to gain popularity and to be applied in many applications. However, these techniques require considerable knowledge in computer programming which makes it less appealing to many professionals (Andersson 2000). Therefore this research will focus on the classical optimization techniques.

2-5-1-1 ε-Constraint Method

For the purpose of this research, the ε-Constraint Method has been selected for solving the multi-objective optimization problem. Cohon (1978) argued that ε-Constraint Method is probably the most intuitively appealing classical method of the posterior approach. Cohon (1978) and Miettinen (2008) highlighted the following advantages:

1- It can generate Pareto optimal solutions regardless of the shape of the areto frontier. Some methods such as the Weighted Sum cannot find non-dominated solutions in case of non-convex shaped frontier;
2- It can produce well distributed points (solutions) on the Pareto frontier;

3- It is relatively easy to be applied.

Solution procedures for the ε-Constraint Method:

The main idea behind this method is to select one objective function to be optimized while converting the remaining functions to constraints bounded by some feasible parameters. To do this, the following steps should be applied (Mashrur et al, 2002):

1- Formulate a mathematical model:

The mathematical model is expressed as a mathematical function that represents the problem. The model is used to generate the value of decision variables and maximize or minimize the objective function subject to the specified constraints. If there are n-related decisions to be made, they are represented as *decision variables* (x1,x2,…,xn) whose respective values are to be determined.

The appropriate measures of effectiveness (defined in step 4), such as cost and travel time, are then expressed as a mathematical function of these decision variables. This function is called the *objective function*.

Example: If the problem at hand requires defining the size of land to be allocated for residential projects in three cities and the objective is to minimize the cost, and the constraint is that the total developed land should not exceed certain size (Z) Therefore:

Measure of effectiveness = total cost

Cost parameters = C1, C2, C3 (land cost at each city)

Decision variables = X1, X2, X3, (size of developed land at each city)

Object function Min (X1C1 + X2C2 + X3C3)

Constraint $X1+X2+X3 \leq Z$

It is always preferable to use such simple models where all the relations between variables are known, and the model will give accurate results. It is always preferable to use linear models (objectives and constrains are linear functions) which can be solved by many commercial software (including the well known Excel).

2: Construct a Pay-off Table

A payoff table (Table 4-1) consists of all objective values, when each objective is optimized, subject to the constraints, using optimization software such as Excel Solver. The first row in the table shows that the result Z1(*V1*) represents the objective values for the first optimization run (R1), optimizing objective Z1. This process (optimization run) is repeated for a number of times equal to the number of objectives, Z1, Z2,.., Zp. For example, if the total number of objectives is three (Z1, Z2, and Z3), the optimization should be run three times to construct a pay-off table. The purpose of developing a pay-off table is to help formulate the constraint model in the next task by determining the lower and upper bounds for the constraint e value.

Table (2-1) The pay-off table.

	Z1	**Z2**		**ZP**
R1	Z1(R1)	Z2(R1)		Zp(R1)
R2	Z1(R2)	Z2(R2)		Zp(R2)
Rp	Z1(Rp)	Z2(Rp)		Zp(Rp)
Max	Max Z1(Rk)	Max Z2(Rk)		Max Zp(Rk)
Min	Min Z1(Rk)	Min Z2(Rk)		Min Zp(Rk)

3: Transform a Multi-objective Problem into a Single Objective Problem (Constraint Model)

This task involves considering one objective as primary and transforming other objectives as constraints. The general formulation of the multi-objective problem presented below with *p* objectives and *m* constraints will be transformed into a constraint model that has only a single-objective problem. The objective is called the primary objective where the h^{th} objective was arbitrarily chosen to be optimized as follows:

Maximize	$\mathbf{Z}_h\ (X_1, X_2,\ldots,X_n)$		
subject to:	$\mathbf{g}_1\ (X_1, X_2,\ldots,X_n)$	$\leq 0,$	
	$\mathbf{g}_2\ (X_1, X_2,\ldots,X_n)$	$\leq 0,$	
	$\ldots,\mathbf{g}_m\ (X_1, X_2,\ldots,X_n)$	≤ 0	
	$\mathbf{Z}_k\ (X_1, X_2,\ldots,X_n)$	$\leq \boldsymbol{\varepsilon}_k$	$k = 1,2,\ldots,h-1, h+1,\ldots,p$
	$X_j \leq 0,$	$j = 1,2,\ldots,n$	

The minimum and maximum values (for each column representing $Z_1(X_k)$, $Z_2(X_k)$,…, $Z_p(X_k)$ in the pay-off table) are derived from the pay-off table. By selecting a different number of constraint values, $\boldsymbol{\varepsilon}_k$, the non-dominated solutions generated will represent a different satisfaction level of objectives.

5: Solve the Constraint Model using Optimization Software for Every Combination of Values for the $\boldsymbol{\varepsilon}_k$.

The mathematical models (constraint model) with every combination of constraint values, $\boldsymbol{\varepsilon}_k$ are solved in this task to generate a set of non-dominated solutions. The model may be solved by using a commercially available optimization software packages, such as Excel Solver. The output from Step 5 is a large set of non-dominated solutions. The size of the set depends on the number of combinations selected.

2-5-2 Selecting a progressive and interactive solution method.

For the purpose of this research the Goal Programming method (GP) has been selected to facilitate decision-making in the context where the decision-maker is available for interaction during the design stage. The reason behind this choice can be summarized as follows:

1- Goal programming is perhaps the oldest and most widely used method within the MCDM paradigm and regarded by many researches as one of the most effective strategies for solving multi-objective problems (Ho and Dey 2006, and Abdelaziz, 2007);

2- Goal programming also offers a high degree of computational efficiency as it stays within the efficient linear programming environment and can be solved using commercially available software (Malczewski and Jackson 2000);

3- The most appealing feature of goal programming is its practicality for supporting decision-making for urban planning. This is due to the fact that, Goal Programming operationalizes the '*saticficing*'[1] behavior which has a widespread use by decision-makers, particularly in the field of urban planning. (Bell 1976, and Azapagic and Perdan 2005 and El-Iraqi 2006).

4- Goal programming aims at finding a feasible solution that is closest to target levels. This is particularly valuable in decision-making for urban sustainability where indicators and benchmarks are sought to be achieved.

General formulation of the Goal Programming Model:

The Goal Programming method supports multi-objective decision-making by trying to achieve a solution that comes as close as possible to target levels. Target levels (called also aspiration levels) are acceptable levels of achievement for each objective considered by the decision-maker. The decision-maker should also provide the priority level (relative importance) of each objective**.** The objective function of Goal programming attempts to minimize the deviation from these target levels**.** The general Goal Programming model can be introduced as follow (El-Iraqi 2006, Soliman 2002, and Ho and Dey 2006) :

1- Notation on the 'Satisfying
'Satisficing' (a combination of the words "Satisfactory" and "Sufficient") is a philosophy of decision-making which was first introduced by the economist Herbert Simon (1979). Simon observed that in today's complex organizations there are too many conflicts, uncertainty and incomplete information. In such an environment the decision-maker does not really try to optimize anything. Just the opposite, he tends to set certain target levels for the objectives and is willing to accept a solution that comes as close as possible to these target (El-Iraqi, 2006).

Minimize $\mathbf{Z} = \sum_i Pi\,(d_i^+ + d_i^-)$

Subject to: $\sum_j a_{ij} X_j \le b\text{i}$ for all i

$\sum_j a_{ij} X_j - (d_i^+ + d_i^-) = b\text{i}$ for all i

X_j , d_i^+ and d_i^- ≥ 0

Where
Pi = priority level of goal i;
$b\text{i}$ = target value of goal i
d_i^+ = over-achievement of goal i
d_i^- = under-achievement of goal i
X_j = decision variable
a_{ij} = coefficient

Two methods for solving Goal Programming can be found in the literature (Hillier and Lieberman 2004). They differ in the way the relative importance of objectives is revealed by the decision-maker:

- The pre-emptive method in which the decision-maker has to define the priority level of each objective (P1, P2, ….Pn) goal with priority level P1 followed by P2, and so on.
- The Weighting method: in which the importance of objectives is represented by weights.

According to Tamiz and Jones (1995) the pre-emptive method accounts for more than 60 % of all goal programming applications listed in the literature. They also argue that prioritizing objectives may be more meaningful and comprehended by the decision-maker than setting absolute weights. Therefore this research has adopted the pre-emptive method.

The solution procedures for the pre-emptive method can be summarized as follows (Soliman 2002, Ho and Dey 2006):

1- Formulate the Goal Programming Model as shown above;
2- The decision-maker decides on the target and the priority level of each objective;
3- The objective with the highest priority will be considered first. Until it is satisfied with no further improvement the deviation variable ($\boldsymbol{d}^+$, $\boldsymbol{d}^-$) of this objective is derived by the objective function. The optimization can be done using any linear programming package;
4- The next most important goal is then considered taking the optimized deviation variables of the first objective as a constraint;
5- Steps 2 and 3 are repeated until the last objective is optimized;
6- The decision variables X_j associated with the last single objective solved are considered as optimal solutions.
7- After the solution is obtained and investigated, the decision-maker may ask to refine the priority levels, the target values, or any of the parameters. The above steps can be repeated until a satisfactory solution is obtained.

2-6 Literature review on Multi-Objective optimization applications in an urban planning domain.

This section provides examples of recent urban planning-related applications where optimization is used as a tool for decision-making and problem solving. The purpose of this review is to demonstrate the powerful capacity of this tool for solving a wide spectrum of complex spatial planning problems.

2-6-1 Neighborhood design applications:

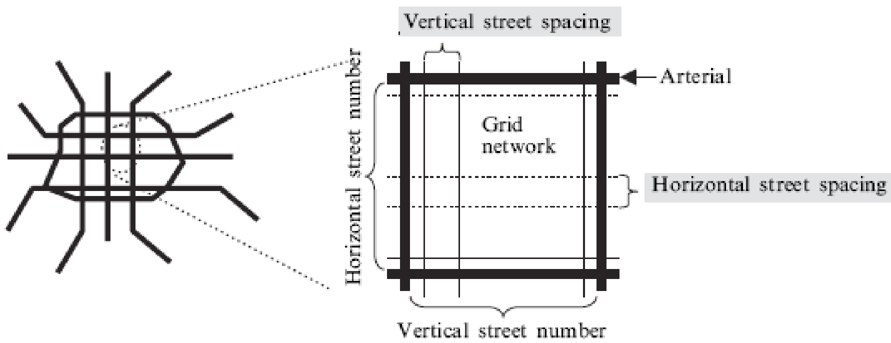


Figure (2-3) Neighborhood road design application (Lin and Shen 2006)

Lin and Shen 2006 developed a multi-objective optimization model for designing local streets systems in residential neighborhoods. The model defines the optimal spacing between the roads (Figure 2-3). The model considers three objectives: increasing accessibility to and from the area, facilitating mobility within the area and increasing traffic safety. Three constraints have been considered: satisfying travel demand and abiding by regulations with regards to noise level and effective evaluation in case of disaster. The decision variable is the horizontal and vertical spacing between the center line of parallel roads in the grid local street system. The model was tested on an area in Taipei, the planning outcome produced by the model was concluded to be theoretically better and more feasible than the planning result obtained by planner intuition.

2-6-2 Urban energy conservation applications:

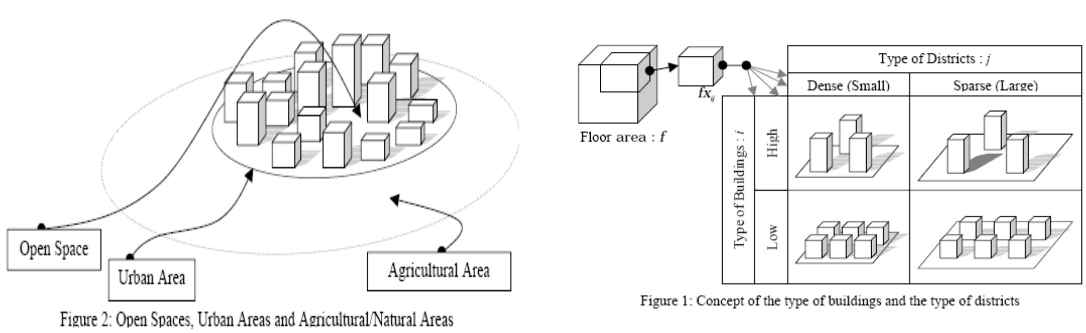


Figure (2-4). Urban energy conservation application (source: Makowaski K., 2000)

Makowaski K., 2000, has demonstrated a multi-objective optimization application to improve urban land-use planning in order to decrease energy consumption while maintaining a desirable lifestyle. Decision variables are the shares of floor area allocated to a certain type of building and at a certain type of district (Figure 2-4). Building types vary in the height described as the ratio of the building area to the floor area. District types vary in the density described as the ratio of the district area to the floor area. In the primary model, three criteria will be considered: minimizing the energy consumption for transportation and construction of buildings, maximizing the area of open spaces in the city, and maximizing the area of natural and agricultural land-use outside the city. The model captures that a more dense urban fabric usually reduces construction and transportation cost and also preserves agricultural area. However, the amount of urban spaces required to maintain the quality of life is degraded. The model has been applied in Tokyo to assist the decision-maker in achieving a trade-off between these conflicting objectives.

2-6-3 Public facility allocation applications:

Amin S., 2008 has integrated GIS with multi-objective optimization to locate illiteracy classes in Fayoum City, Egypt. Five contradicting variables have been considered: minimizing the total number of allocated classes, minimizing the total cost of allocation, minimize the total transportation cost, minimizing the total travel distance, and minimizing the total travel time. The author applied an evolutionary optimization method to generate various Pareto optimal locations.

2-6-4 Land development applications:

Gabriel et al, 2006 used multi-objective optimization together with GIS to investigate potential land development scenarios seeking a sustainable urban growth (Figure 2-5) . They tried to find the most appropriate land parcels to be developed taking into consideration: maximizing urban area compactness, minimizing impact on environmentally sensitive areas, maximizing developers profit, and minimizing imperviousness change. The authors optimized each objective first and then reached a compromise solution.

Figure (2-5). Modeling compactness objective. (Source: Gabriel et al, 2006)

This brief review reveals that multi-objective optimization is indeed a powerful tool for addressing a wide variety of complex urban planning problems. Integrating GIS with multi-objective optimization expands the capacity of this tool in spatial planning. It is also clear that all the objectives that have been addressed in these applications are quantitative in nature. However, in urban planning and resource management, the objectives may be described by qualitative statements without 'crisp', well-defined boundaries, such as "install best available technology" or "carry out best management practice". Techniques such as "fuzzy membership functions' and "probability distributions" can be incorporated into optimization models to quantify such 'fuzzy' objectives (Loucks et al 2005). Despite the growing interest in applying optimization in urban planning, Lasker (2003) argues that there are very few examples that address the integration of multi-objective optimization within the overall planning process. This is one of the motivations for this research.

2-7 Summary and Conclusions:

- Optimization is an approach for problem solving which aims at identifying the best solution for a given decision problem. Multi-objective Decision-making (also called Multi-objective optimization) is defined as a technique for simultaneously minimizing or maximizing several non-commensurable and often conflicting objectives. Since there is no single solution that satisfies all the objectives, therefore the aim of MODM is to find a comprehensive set of non-dominated solutions, while the role of the decision-maker is to provide his preferences.
- A feasible solution to a multi-objective problem is called a Pareto optimal solution or non-dominated solution, if there exists no other feasible solution that will yield an improvement in one objective without causing a degradation in at least one other objective. The optimal solution to any MODM problem should be one of the non-dominated alternatives.
- MODM provides two solution approaches depending on the time when the decision-maker can provide his preferences:
    - The progressive approach, which promotes an interactive iterative process in which the decision-maker progressively refines his preferences during each iteration until reaching the solution that meets his satisfaction. ***Interactive Goal Programming method*** is promising in the context of decision-making for urban sustainability.
    - The posterior approach, which does not require the decision-maker to interact during the analysis. Instead, the planner will generate a wide range of non-dominated alternatives to be presented later to the decision-maker for selection. ***The E-constraints*** method is found to be promising for this approach.
- MODM is essential in planning for sustainable development for the following reasons: it provides a systematic approach for problem solving, it defines clearly the role of the planner (developing the model), decision-maker (providing value judgments regarding the relative importance of objectives), and stakeholders (providing the list of objectives to the planner) and it can generate a wide range (theoretically infinite) of high quality alternatives (non-dominated alternatives) for consideration.

CHAPTER 3

MULTI-ATTRIBUTE DECION MAKING (MADM) TECHNIQUES FOR SUSTAINABLE URBAN DEVELOPMENT

This chapter focuses on Multi-attribute Decision-making (MADM) and its potentiality in the context of urban sustainability. It provides an overview of alternative evaluation methods commonly used in the urban planning domain and highlights advantages and limitations of each method. The chapter then concentrates on MADM as an effective tool for assessing alternatives with multiple and conflicting objectives. The typical MADM methodology is studied together with alternative weighting and scoring techniques and the appropriate techniques for the context of urban sustainability are recommended.

3-1 Introduction (Evaluation in planning):

Evaluation is the group of actions concerning choosing one or more alternatives (or policy measures) from a set of mutually exclusive alternatives or producing their complete ranking. Evaluation is considered to be an integral part of any decision-making process (Mattei, 2008). Evaluation is a major task of planners to impose some order on the problematic situations in which they are involved. In order to track this goal they must take all kinds of distinctions, classifications, and other judgments into account. Therefore, it is essential that they have tools which enable them to perform this task in a responsible way. A very important subset of these tools are the methods and techniques which assist the planner, as objectively as possible, to inventory, classify and conveniently arrange the information needed for a choice, in order that the various participants in the planning process (e.g., policy makers) are enabled to make this choice as responsibly as possible. These joint activities will be called the **evaluation procedure**. (Elrefaie 2004). Lichfield and Whitbread (1975) stressed that evaluation is *not* decision-making. Instead it assists decision-making by highlighting the differences between alternatives and providing information for subsequent deliberation. Therefore they defined evaluation as:

"the process of analyzing a number of plans or objects with a view to searching out their comparative advantages and disadvantages and the act of setting down the findings of such analysis in a logical framework."

Evaluation is an important and intrinsic part of environmental planning, although its systematic use is often neglected. Natural scientists, on the other hand, are skeptical about its value because it appears unscientific, while bureaucratic and formalistic planners generally try to use evaluation schemes without critical adaptation to the given case. This procedure then leads to results that are, consequently, unscientific and therefore susceptible to criticism (Kaule, 2000).

3-2 Overview On Other Evaluation Approaches in Planning Domain:

Before discussing MADM techniques it is beneficial to scan through alternative evaluation techniques commonly applied in planning practice. In addition to MADM, two main evaluation approaches can be distinguished in the planning process: Monetary-based approach and Participatory approach (Erefaie 2004, Fulop 2004).

3-2-1 Monetary Evaluation Approach:

The most well known method in this approach is ***Cost-benefit analysis (CBA)***. Agencies often rely on a simple cost-benefit analysis to evaluate projects, intending to supply a framework for a monetary assessment of potential projects However, *this approach is criticized by* its limitation with regard to environmental and social impacts. It is often difficult, with a lot of uncertainties, to describe such impacts in monetary terms. Moreover, many people are philosophically opposed to evaluate biologically important areas in terms of money. Another shortcoming of this approach is its failure to account for equity considerations. The emphasis is on aggregate economic effects, not on which groups gain and lose if a project is implemented. Critiques of the resulting decisions, based on this approach, are common. Government planners have been accused of making judgments that favor project development by overestimating benefits and underestimating costs (Elrefaie 2004).

3-2-2 Explicit Participation Approach:

This is an evaluation approach situated on the boundary of explicit and implicit evaluation. It focuses on permanent discussion between, or among, the stakeholders concerned. In this case all essential aspects of choice are emphasized and brought into the discussion. The planning process, based upon this idea, consists, in fact, of the continuing active participation of social groups and governmental agencies. In this method procedures should be applied such that the choice is made by mutual agreement with all parties involved. It's easy to see that this approach is especially suitable for planning process on a local level. (i.e., neighborhood planning). A recent application of this approach is discussed in (Amando et al, 2010). *This explicit participatory approach is criticized by* being in some cases impractical as it may be difficult to find the proper person who can and be willing to participate actively. In addition, the results can be influenced, perhaps unconsciously, by the values and view points of the planner/expert who facilitates the discussion. (Voogd,1982).

The limitation of the above mentioned approaches has stimulated efforts to search for other suitable and more scientific approach such as the Multi-Attribute Decision-making MADM.

3-3 Overview On Multiple Attribute Decision-making MADM

MADM deals with decision problems with multiple criteria and a finite set of alternatives. It is regarded as one of the most scientifically grounded evaluation methods with a strong foundation in decision theory (Linkov et al 2004). Multi-attribute decision-making techniques can partially or completely rank the alternatives therefore the single most preferred alternative can be identified or a short list of a limited number of alternatives can be selected for subsequent detailed appraisal. It has emerged as a major approach for solving natural resource management problems and integrating the environmental, social, and economic values and preferences of stakeholders while overcoming the difficulties in monetizing intrinsically non-monetary attributes. Quantifying the value of ecosystem services in a non-monetary manner is a key element in MCDM (Herath and Prato, 2006).

MCDM provides framework for decision-making and set of methods aiming at avoiding inconsistencies underlying judgment and choice, and making decisions more compatible with the normative axioms of rationality. Furthermore, if combined with deliberative techniques, MADM renders policy processes transparent and informative of the perspectives or viewpoints of all stakeholders. This is translated into a higher acceptance of the policies (Mettei, 2008). Elrefaie (2004) and Herath and Prato (2006) highlight the following reasons for choosing MCDM in planning which make it also an attractive evaluation approach in the context of urban sustainability:

1- MCDM best meets the conditions for contemporary planning such as; to promote ***participation*** in a multiple decision-maker's environment, to promote ***accountability*** and the ability to justify and interpret outcomes based on easy to illustrate and ***transparent*** principles;
2- MCDM does not offer a rigid set of rules but instead a ***flexible framework*** which may be adaptable to various circumstances without a change in the basic nature of the approach.

3-3-1 MADM techniques:

Two general types of MADM analysis methods are distinguish in the literature: ***Elementary***, ***Value and utility-based*** methods. Elementary methods do not require explicit evaluation of quantitative trade-offs between criteria. The value and utility-based and approaches, on the other hand, assume that decision-makers are able to articulate and 'quantify' their preferences. To facilitate this process, the value-based approaches use scores and weights to construct a 'model' of decision-maker's preference in the form of value or utility function. More details on these methods can be found in Hwang and Yoon (1981) and Linkov et al (2004).

3-3-2 Elementary Methods:

These elementary approaches are simple and no computational support is needed to perform the analysis. These methods are best suited for problems with a single decision-maker, limited alternatives and criteria that are rarely characteristic in urban planning decision-making (Linkov et al 2004):

- *Pros and cons analysis*: It is the easiest method of qualitative comparison between alternatives where the good and bad things are listed to select the best alternatives. This requires no mathematical skills and can be implemented rapidly but is suitable only for simple problems with few alternatives (2 to 4) and few criteria (1 to 5). ***SOWT analysis*** is a form of this method (Fulop 2004);
- *Maximin and maximax methods*: The maximin method is based upon a strategy that tries to avoid the worst possible performance, maximizing the minimal performing criterion. The alternative for which the score of its weakest criterion is the highest is preferred. The maximin method can be used only when all criteria are comparable so that they can be measured on a common scale, which is very rare in the urban planning domain (Fulop 2004);
- *Conjunctive and disjunctive methods*: These are screening methods to exclude alternatives that do not meet certain performance criteria;
- *Lexicographic method:* The criteria are ranked in the order of their importance. The alternative with the best performance score on the most important criterion is chosen. If there are ties with respect to this criterion, the performance of the tied alternatives

on the next most important criterion will be compared, and so on, till a unique alternative is found (Linkov et al 2004)

3-3-3 Value and Utility-Based Methods:

These methods are the core of MCDM The procedures and results obtained from MCA can be improved with the interaction of stakeholders. The intention in these methods is to generate a numerical score which can quantify the overall performance of each alternative to be able to produce a preference order for the alternatives, based on decision-makers' value judgments (Belton and Stewart 2002). Although there are numerous methods, ***Multi-attribute Value theory MAVT***, ***Analytic Hierarchy Process method***, and the ***outranking methods*** are the most commonly addressed in the literatures. A recent review by Malczewski (2006), reveals that these three methods and related svariation count for almost 67% of the applications between the years 1990-2004. The typical process includes the following steps (Herath, 2006):

1- Define objectives;

2- Choose the criteria to measure the objectives;

3- Specify alternatives;

4- Transform the criterion scales into commensurable units;

5- Assign weights to the criteria that reflect their relative importance;

6- Select and apply a mathematical algorithm for ranking alternatives;

7-Choose an alternative.

The fundamental starting point of all methods is the performance matrix (or the analysis matrix) which records the performance of each alternative with respect to each criteria. However, the way of weighting the criteria and how the weights are aggregated varies between methods. As indicated in Table (3-1), the goal of MAVT is to find a simple expression for the net benefits of a decision. Through the use of value functions, the MAVT method transforms diverse criteria into one common scale of utility or value. However, AHP uses a quantitative comparison method that is based on pair-wise comparisons of decision criteria, rather than utility and weighting function. The method uses an underling scale with values, from 1 to 9 for example, to describe the relative preferences for two criteria. The result of the pairwise comparisons is a reciprocal quadratic matrix as shown in Figure (3-1). Table (3-1) shows a comparison among the three main methods including advantages and disadvantages. More details about MCDM techniques are to be found in Keeney and Raffia (1976) and Belton and Stewart (2002).

Table (3-1) Comparison of critical elements, strengths and weaknesses of Several MCDA Methods: MAUT, AHP, and Outranking methods (Linkov et al 2004).

Important elements	Strengths	Weaknesses
Multi-attribute utility/value theory (MAUT/MAVT)		
• Expression of overall performance of an alternative in a single, non-monetary number representing the utility of that alternative; • Criteria weights often obtained by directly surveying stakeholders.	• Easier to compare alternatives whose overall scores are expressed as single numbers; • Choice of an alternative can be transparent if highest scoring alternative is chosen; • Theoretically sound — based on utilitarian philosophy; • Many people prefer to express net utility in non-monetary terms.	• Maximization of utility may not be important to decision-makers; • Criteria weights obtained through less rigorous stakeholder surveys may not accurately reflect stakeholders' true preferences; • Rigorous stakeholder preference elicitations are expensive.
Analytic hierarchy Process AHP		
• Criteria weights and scores are based on pairwise comparisons of criteria and alternatives, respectively.	• Surveying pairwise comparisons is easy to implement.	The weights obtained from pairwise comparison are strongly criticized for not reflecting people's true preferences; Mathematical procedures can yield illogical results. For example, rankings developed through AHP are sometimes not transitive.
Outranking methods		
One option outranks another if : • "it outperforms the other on enough criteria of sufficient importance (as	• Does not require the reduction of all criteria to a single unit. • Explicit consideration of possibility that very poor	• Does not always take into account whether over-performance on one criterion can make up for underperformance on

reflected by the sum of criteria weights)" and; • it "is not outperformed by the other in the sense of recording a significantly inferior performance on any one criterion"; • Allows options to be classified as "incomparable".	performance on a single criterion may eliminate an alternative from consideration, even if that criterion's performance is compensated for by very good performance on other criteria.	another; • The algorithms used in outranking are often relatively complex and not well understood by decision-makers.

1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance

2,4,6,8 may be used for interpolation

	C1	C2	C3	C4
C1	1	4	7	5
C2	1/4	1	1/3	9
C3	1/7	3	1	5
C4	1/5	1/9	1/5	1

Figure (3-1) The AHP pairwise comparisons matrix and scale (source: Fondazione Mattei, 2008).

Deciding which method to use would be dependent on the trade-offs between ease of use, accuracy, degree of understanding on the part of the decision-maker, the theoretical foundation underlying a given method, number of alternatives that can be handled as well as the availability of computer software (Malczewski. 2006). After reviewing the advantages and disadvantages of various MCDM methods, MAVT method has been selected as an evaluation mechanism for the purpose of the applications included in this study for the following reasons:

1- MAVT is one of the most scientifically grounded methods with a strong foundation in decision theory (Lincov et al 2003);
2- The method is easy to use in evaluating alternatives (Mashrur, 2002);

3- The method is understandable and practical. According to Azopagic (2005), it is practicable and justifiable to use additive scoring instead of more sophisticated methods such as MAVT, providing that the definition of criteria and the scoring methods used are fully understood and agreed on by decision-makers;
4- Scores and weights are explicit and are developed based on established techniques. They can be cross-referred to other sources and changed if necessary (Mashrur, 2002);
5- Using weights in comparing criteria is sometimes easier and less time consuming than pair wise comparison. This rules out AHP;
6- MAVT proved to be practical in dealing with spatial data.

3-4 General Framework of MADM:

Figure (3-2) shows the basic methodology for conducting Multi-attribute Decision Making. The decision process starts with problem structuring during which the problem to be solved is explored and available information is collected. The possible options (alternatives) are defined and criteria aiming at evaluation of their performance are identified. The subsequent steps are as follows:

A- The analysis matrix:

In the next step, the performance of each alternative with regard to each criterion is identified. As a result the analysis matrix is constructed. In the matrix each row belongs to a criterion and each column describes the performance of an alternative. The score a_{ij} describes the performance of alternative $\mathbf{A}_j$ against criterion $\mathbf{C}_i$.

B- The Normalized analysis matrix:

In order to help the decision-maker to perceive the relative level of achievement for each objective, the performance values have to be measured on an equal scale. In other words, the values have to be normalized. One of the well known methods to do this - that will be applied later in this study- is the *score range* method which transforms the objective values into 0 to 1 scale using the following linear functions (Prato, 2006, Fondazione Mattei, 2008):

$X_{ij}* = X_{ij} - X_{j\ (min)} \ / \ [X_{j\ (max)} - X_{j\ (min)}]$ *for criteria to be minimized*

$X_{ij}* = X_{j\ (max)} - X_{i\ j} \ / \ [X_{j\ (max)} - X_{j\ (min)}]$ *for criteria to be maximized*

Where

X_{ij} = the is the performance of alternative (*i*) for criteria (*j*) .

$X_{j\ (max)}$, $X_{j\ (min)}$ are the lowest and largest performance values for criteria (*j*)

$X_{ij}*$ = the normalized value

C- Modeling criteria weight:

Decision problems involve criteria of varying importance to the decision-maker. At this stage the decision-maker has to interfere in the process. The criterion weights usually provide the information about the relative importance of the considered criteria. There are many techniques commonly used in MADM for assessing the criterion weights such as *direct decision and input, ranking and rating methods, pairwise comparison (the Analytic Hierarchy Process), partial weight ratio and swing weights methods*. Table (3-1) presents a comparison between some of these methods. Related research (Feng et al 2008, 2006) recommend the ***swing weights method*** for a wide range of applications and acknowledge its correct theoretical foundation, flexibility and easiness to be programmed in Excel. Therefore it has been selected for application in this research.

By using the swing weights method, the objectives are placed in rank order by importance and raw weights are assigned to the objectives on a 0–100 basis, where 0 is the least important and 100 is the most important. Then the raw weights are normalized to add up to 1 (or 100%) and each objective thus receives a calculated normalized weight (= the raw value / the sum total of all raw values). Finally, the ***evaluation matrix*** is constructed to accommodate these values (more information on criteria weighting methods can be found in (Baker et al 2001).

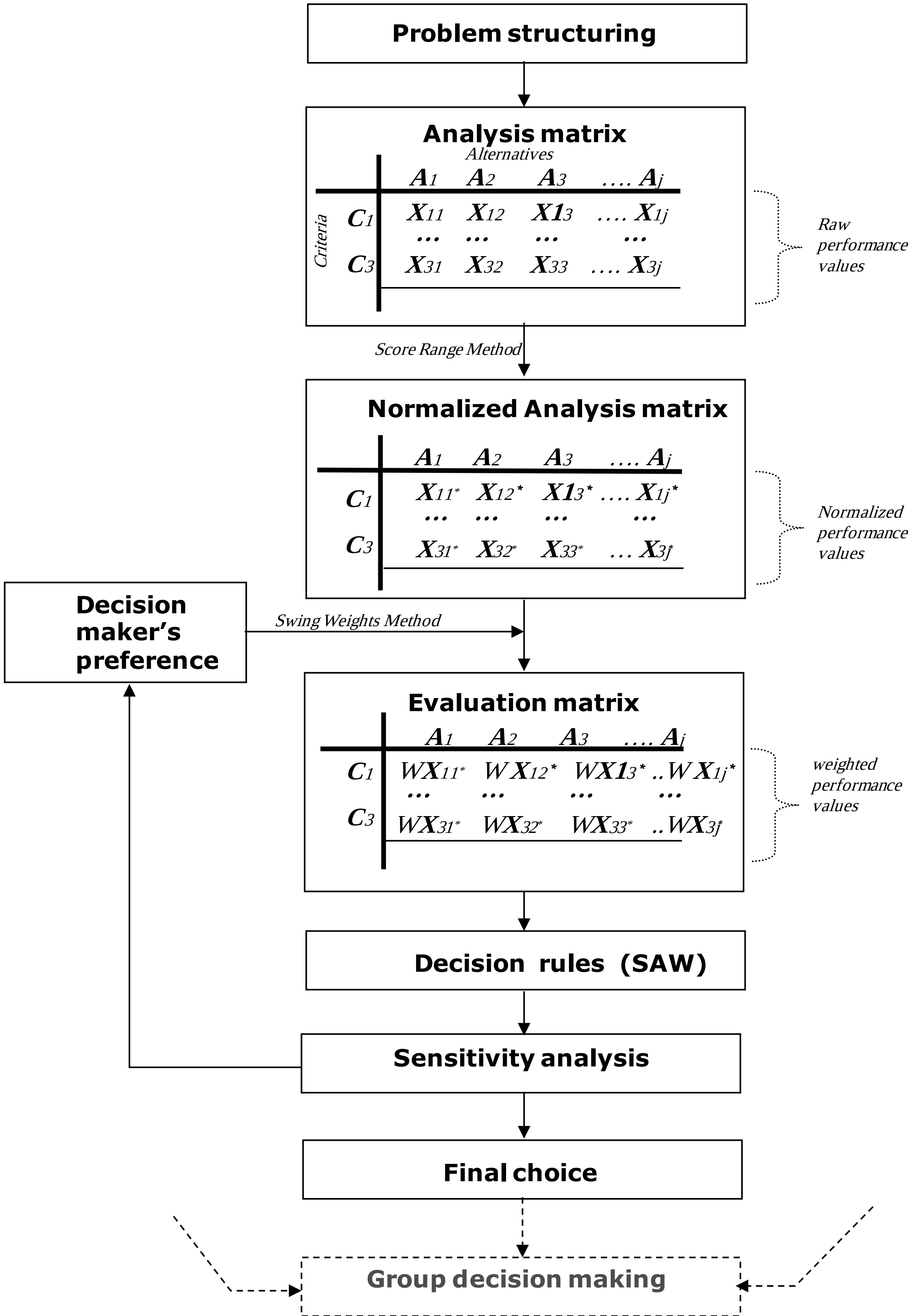


Figure (3-2) Typical MADM process.

D- Decision rules

The main aim of a multi-attribute decision analysis is to come up with a single value that describes the overall performance of each alternative, to facilitate the ranking process. Decision rules aggregate partial preferences describing individual criteria in a global preference and then rank the alternative. There are numerous decision rules addressed in literatures such as:

- ***Simple additive weighting (SAW)*** is one of the most popular decision methods because of its simplicity. It assumes additive aggregation of decision outcomes, which is controlled by weights expressing the importance of criteria. It can be derived for each alternative simply by multiplying its normalized scores by the corresponding criteria weight;

  $$\boldsymbol{S}_i = \sum W_j^* X_{ij}^* \quad \text{for all } (j)$$

  Where W_j^* is the weight of criteria j, and X_{ij}^* is the normalized score of alternative (i) for criteria (j), $\boldsymbol{S}_i$ is the final score of alternative (j);
- ***Order weighting average*** (***OWA)*** is used because of its potential to control the trade-off level between criteria and to consider the risk-behavior of the decision-makers;
- ***The Ideal point method*** orders a set of options on the basis of their separation from the ideal solutions. The option that is closest to the ideal positive solution and furthest from the negative ideal solution is considered to be the best one.

Comparative analysis is done by Saparauskas (2004) over features such as consistency, ease of understanding, flexibility and other features have recommended SAW for evaluation of urban sustainability. For the purposes of this research SAW was selected for implementation in the proposed decision-making framework.

E- Sensitivity analysis:

Subsequent to obtaining a ranking of alternatives, *sensitivity analysis* should be performed to determine robustness. Sensitivity analysis is defined as a procedure for determining how the recommended course of action is affected by changes in the inputs of the analysis. To be more specific, it aims at identifying the effects of changes in the inputs (geographical data and the decision-maker's preference) on the output (ranking of alternatives). If the changes do not significantly affect the outputs, the ranking is considered to be robust. But if the current result is found to be unsatisfactory, we may use information about the output to return to the problem formulation step. The sensitivity analysis can be thought of as an exploratory process by which the decision-makers achieve a deeper understanding of the structure of the problem. It helps to illustrate how the various decision elements interact to determine the most preferred alternative and which elements are important sources of disagreement among decision-maker or interest groups.

3-5 Summary and conclusions:

- This chapter reviewed the evaluation techniques commonly used in urban planning highlighting advantages and disadvantages of each. Cost benefit analysis CBA is limited with regard to environmental and social valuation, other elementary methods such as pros and cons analysis, SOWT analysis, maximin and maximax and lexicographic methods are best suited for problems with few alternatives and single decision-maker.
- Multi-attribute Decision-making MADM provides a transparent, structured, and systematic process for ranking a finite set of alternatives in presence of multiple conflicting and incommensurable objectives. MCDM provides tools to assist the decision-maker in weighting the objectives and other tools to aggregate the final score of each alternative.
- The MADM process typically starts with defining the objectives and the alternatives, developing performance matrix which quantifies the performance of each alternative with regard to each criterion, normalizing performance values to an equal scale, weighting objectives based on the decision-maker's preferences, aggregating the weighted performance values to develop an overall performance score for each alternative, and finally sorting alternatives based on their scores. Sensitivity analysis is usually done to ensure the robustness of the final solution.

- MADM is superior on other evaluation techniques for the following reasons: it can deal with a large number of incommensurable objectives, it is open, explicit and can be cross-referenced by all participants, it can provide important means of communication, within the decision-making body and sometimes, later, between that body and the wider community, it provides theoretically sound methods to facilitate weighting objectives and aggregating the overall scores, finally it is flexible for application in any types of problems.
- After comparing the three main MADM approaches, the Multi-attribute value theory MAVT approach has been selected for the purpose of this study. MAVT the Swing Weight Methods for weighting objectives, and the Simple Additive Weight method for aggregating the final scores. The justifications for this selection are provided.

CHAPTER 4

THE PROPOSED DECISION SUPPORT FRAMEWORK FOR URBAN SUSTAINABILITY

1- Synthesizing the Findings of Previous Chapters
2- The Purpose of the Proposed Framework
3- The Main Stages and Process
4- Detailed Steps of Multiobjective Decision-Making Framework
5- Limitations of the Proposed Framework
6- Re-formulating the Research Hypothesis
7- Summary and Conclusion

In this Chapter the main research hypotheses are reformulated and refined by providing a general multi-objective decision-making framework for urban sustainability planning. It provides a step-by-step guidance for urban planners starting from problem structuring to generating a wide range of alternatives until the selection of the final solution. The framework employs MODM and MADM methods to respond to the prerequisites raised in Chapter 1 concerning the effective decision-making process in the context of urban sustainability. The framework also highlights the role of all the participants: the planner, the decision-maker, and the stakeholders in the decision-making process.

4-1 Synthesizing the findings of previous Chapters:

This section synthesizes the main findings of the previous Chapters which will be of importance in formulating the proposed decision-making framework.

In Chapter 1. The main prerequisites for effective decision-making in the context of sustainable urban development have been identified. They can be classified into two groups: prerequisites for the design stage, and prerequisites for the selection stage.

In Chapter 2: Multi-objective Decision-making MODM provides effective methods for generating a wide range of non-dominated alternatives in the presence of multiple and conflicting objectives. The planner's role is to formulate the problem as a multi-objective optimization model which is used to generate the alternatives. The decision-maker's role is to provide his preference regarding the relative importance of objectives in order to select the optimal alternative that corresponds to his preference.

MODM provides two solutions approaches, depending on the time when the decision-maker can provide his preferences:

- The progressive approach, which promotes an interactive iterative process in which the decision-maker progressively refines his preferences during each iteration until reaching the solution that meets his satisfaction. ***The Interactive Goal Programming method*** is promising in the context of decision-making for urban sustainability in this interactive context.
- The posterior approach, which does not require the decision-maker to interact during the analysis. Instead, the planner will generate a wide range of non-dominated alternatives to be presented later to the decision-maker for selection. ***The E-constraints*** method was found to be most promising for the non-interactive context.

In Chapter 3: Multi-attribute Decision-making MADM provides a transparent, structured, and systematic process for ranking a finite set of alternatives in the presence of multiple conflicting objectives. MCDM provides tools to assist the decision-maker in weighting the objectives and other tools to aggregate the final score of each alternative. Chapter 3 provides a justification for selecting the ***Swing Weights*** method to facilitate the weighting process and the ***Simple Additive Weighting*** *SAW* method for aggregating the final scores.

4-2 The Purpose of the Proposed Framework:

The framework, which is underpinned by both Multi-objective Decision-making MODM and Multi-attribute Decision-making MADM, is designed to provide systematic guidance to decision-making in the context of urban sustainability where there are multiple and conflicting objectives and multiple stakeholders with opposing views. The framework has been adopted to respond to the prerequisites raised in Chapter 1 for effective decision-making in the context of urban sustainability. The framework is not problem-specific. That is to say it is general and flexible and can be adopted and tailored to aid decision-making in a variety of urban-related sustainability planning problems. Example applications will be provided in the next Chapters. However the following should be noted:

1- The framework is not intended to replace the decision-maker but rather to assist him in taking an informative, justifiable, and participatory decision and utilizing state-of-the-art decision aiding tools.

2- The framework acknowledges the fundamental roles of 3 major components "people, tools, and process":

- **People**: includes the *planner* who conducts the analysis (the modeling) without imposing any preferences or judgment, *the decision-maker* who provides value judgments regarding the relative importance of objectives and is therefore responsible for the final decision, and *stakeholders* who provide their environmental, social, and economic concerns. In some cases stakeholders are also the decision-maker;
- **Tools**: include MODM tools (Goal programming methods, e-constraint methods to facilitate generating alternatives, and MADM tools (Swing weights method, and Simple additive method) to facilitate choice among alternatives. It should be noted that these methods have been selected because they combine simplicity with efficiency. They can be modeled in EXCEL without any sophisticated programming. However, they can be replaced with more advanced decision analysis methods to enhance the functionality without altering the main process. For example, an evolutionary method such as Genetic Algorithm could replace the e-constraint method in order to enumerate the entire Praetor frontier in one single run. However, this will require certain technical expertise from the planner.
- **Process:** includes an overall structure connecting the main stages of the framework and guiding "people" to the appropriate tool for each decision-making situation, as will be explained in the next section. There is also an internal process inside each stage. It is important to mention that all processes are iterative in nature.

4-3 The Main Stages And Process:

The proposed framework is constructed based on the three traditional main stages of decision-making identified by Simon (1979), which are typically followed when decisions are made: *Intelligence* (What is the problem?), *Design* (What are the alternatives?), and *Choice* (Which alternative is the best?). Figure (4-1) illustrates the three stages, the tools and the decision-making challenges addressed at each stage.

Stage 1: The Problem-Structuring Stage:

At this stage the problem is initially stated, stakeholders are identified and consulted with regard to sustainability objectives and constraints. Various knowledge elicitation techniques (brain storming, interviews, etc...) can be employed to elicit knowledge from stakeholders. This stage ends up with translating objectives into quantitative sustainability indicators (measures of effectiveness), with which the performance of potential alternatives will be evaluated. Then the planner has to check the type of problem at hand whether it is a discrete or a continuous problem:

- *The problem is discrete* if there is a finite number of predefined alternative solutions (eg. What is the optimal site for a facility from among three potential alternative sites?). Most strategic and policy level decisions normally deal with a limited number of discrete alternatives (Azapagic, 2005). In such a case, the alternatives should be defined outside the framework. Other techniques such as scenario planning can be employed. The framework can then serve as a tool to evaluate the alternatives (in Stage 3).
- *The problem is continuous* if the number of alternative solutions could be infinite (eg, what is the optimal distribution of future population over certain developmental regions?). Despite that the number of populations and regions are finite, there are infinite number of possible distribution scenarios. Most operational and tactical level decisions usually deal with a large number of possible alternatives (Azapagic 2005).

If the problem is continuous the user will go to stage 2 to generate alternatives, otherwise the user will go to stage 3 to evaluate the pre-defined alternatives at hand.

Stage 2: The Design Stage:

At this stage, non-dominated alternatives are generated using Multi-objective Decisions-Making (MODM) techniques. Two decision-making situations are addressed at this stage:

1- In the case where the decision-maker is available for interaction an interactive approach is applied (Interactive Goal Programming method) to generate alternatives. The decision-maker provides their aspiration level (target) and the priority level of each objective. Sustainability bench marks can also be considered as targets. A solution will be generated by the model. If it satisfies the decision-maker then a final solution is achieved. Otherwise, the decision-maker should modify his preferences (target values and priorities) and another solution will be generated until he is satisfied. This interactive process is significant for the following reasons:
   - It suits a workshop or decision conference environment which is quite common in decision-making for urban sustainability;
   - It provides a tool by which alternative plans can be generated in real-time in response to "what if?" questions raised by a live audience. Hence, easily reaching a consensus. Such a tool is recommended by literature in the field of urban sustainability (Stewert, 2007 and Smart Growth Network, 2002);
   - It is in line with the "Satificing" philosophy by Simon (1979) who suggested that in an institutional environment, the decision-maker tends to set an aspiration target and to accept any solution that will come as close as possible to this target;

2- If the decision-maker is not available then the planner's responsibility is to generate a wide spectrum of high quality alternatives to be presented to the decision-maker at a later stage. In this case a posterior Multi-objective Decision-making MODM is applied (E-constraints method) to generate a large set of non-dominated alternatives. This is particularly important to make sure that all possible solutions will be looked at during the assessment stage.

Stage 3: Assessment stage:

At this stage, Multi-attribute Decision-making MADM techniques are used to evaluate and rank alternatives based on the preferences of the decision-maker. They can trade-off between various environmental, economic, and social objectives to achieve a satisfactory balance. Before final acceptance, a sensitivity analysis is conducted to make sure that the solution is robust and is not sensitive to minor changes in the input parameters.

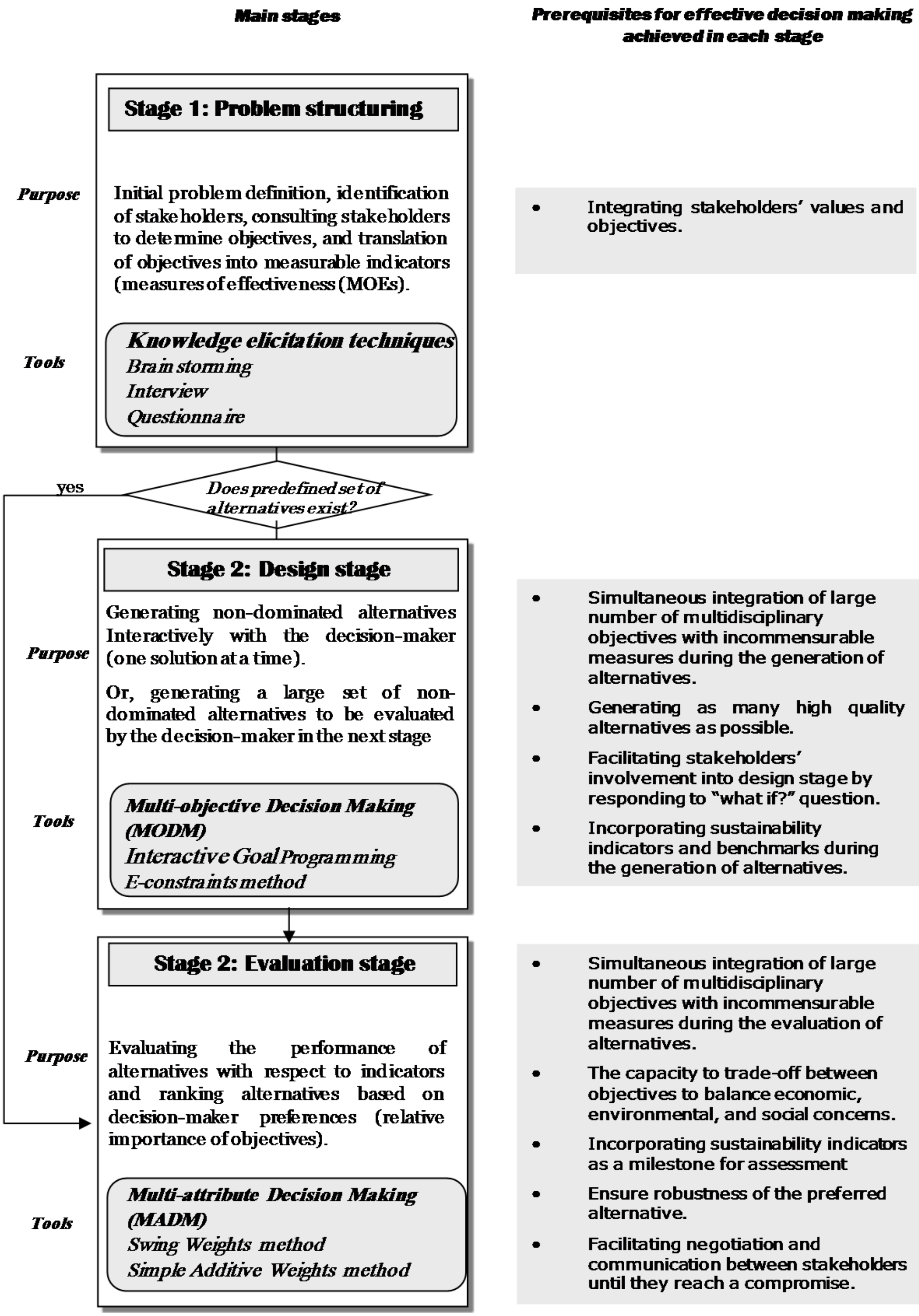


Figure (4-1). The main stages and components of the proposed decision-making framework and the challenges addressed in each stage.

4-4 Detailed Steps of the Proposed Multi-objective Decision-making Framework.

The following paragraphs explain the detailed tasks involved in the proposed decision-making framework. In Figure (4-2) the tasks are numbered. As explained in the previous section, the framework is designed to address three decision-making situations corresponding to the availability of pre-defined alternatives (discrete or continuous problem) and the availability of the decision-maker during the design stage. Tasks 1 to 4 and 8 are common to all decision-making situations. However, other tasks are specific to particular situations as follows:

Table (4-1). Decision-making situations addressed by the proposed framework

Decision-making situation		**Note**	**Tasks involved**
Situation 1	Continuous problem (there is an infinite number of possible alternatives) and the decision-maker is available (or willing) to interact during the design stage.	Operational and tactical decisions in a charrette workshop environment.	1-2-3-4-7-8
Situation 2	Continuous problem (there is an infinite number of possible alternatives) and the decision-maker is not available (or not willing) to interact during the design stage.	Operational and tactical decisions in consultant-client environment.	1-2-3-4-5-6-8
Situation 3	Discrete problem (there is a set of predefined alternatives).	Strategic and policy making decisions.	1-2-3-4-6-8

.

Task 1: Problem Statement:

A decision-making problem exists, when a planner or a decision-maker (DM) perceives a discrepancy between the current and desired states of a system, and when (i) the DM has alternative courses of action to be considered; (ii) the choice of action can have a significant effect on this perceived difference; and (iii) DM is motivated to make a decision, but he is uncertain which option should be selected (Fondazione Mattei, 2008). This task should be done by both the planner and decision-maker to insure a common understanding of the problem. The problem statement should also specify a broad goal to be achieved. Misunderstanding the problem definition and the broad goal is a major stumbling block for successful decision-making.

Task 2: Identifying Stakeholders:

Identification and involvement of stakeholders is regarded by many resources as the most important step in decision-making in the context of sustainable development (Azapagic 2005). The key for a successful decision-making process is to identify both internal and external stakeholders, as appropriate for the type of decision-making and to be sure that all points of views are represented. According to Wiek and Brinder (2005), in complicated problems that require deeper professional insight most stakeholders are experts (e.g., academic, researcher, jurists) who are trained in the required field. Involving experts ensure transparency of the assessment with respect to the "state of the art" in the related scientific field. To insure a healthy decision environment the following principles should be maintained (Habermas 1990, Dearing 2008):

- Inclusion of all those affected;
- Equally distributed and effective opportunities to participate in the decision-making process;
- Equal rights to influence decisions;
- Equal rights to propose alternatives, decision criteria and other aspects that influence decision-making;
- A situation that allows all participants to develop, in the light of sufficient information and good reasons, an articulate understanding of the problem under investigation.

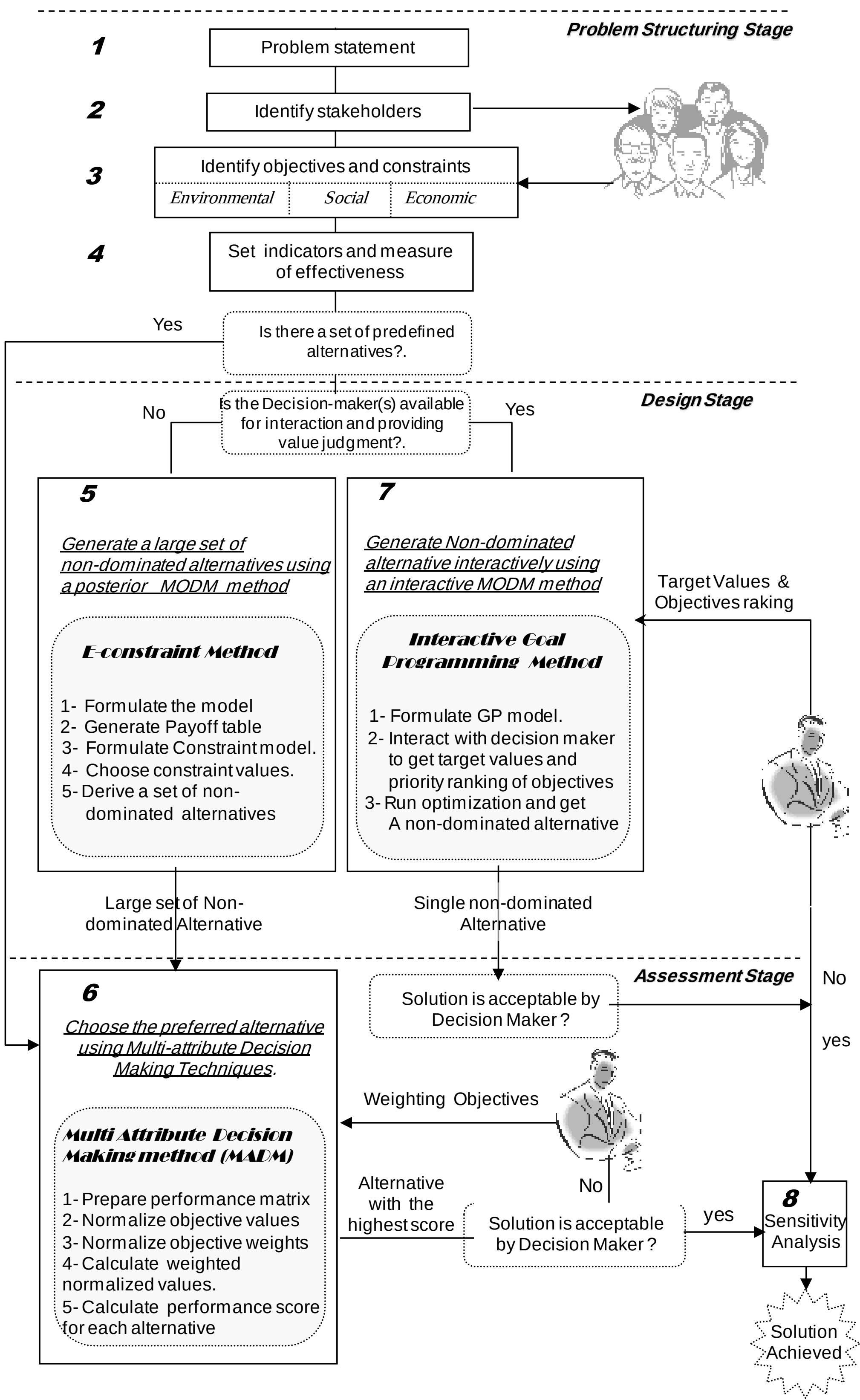


Figure (4-2) The detailed steps of the proposed multi-objective decision-making framework.

Task 3: Identifying objectives and constraints:

This task involves the preparation of an exhaustive list of objectives and constraints with regard to the problem at hand. An objective is a statement about the desired state of the system under consideration. The objectives should be specific and cover the main goal. To be useful in decision-making, these 'top level' objectives have to be disaggregated into 'lower level' criteria; for example, 'management of natural resources' can be described by consumption of fossil fuels, mineral resources and loss of biotic species. The desegregation process should continue until a measurable level of all objectives are reached (Mashrur, 2002).

Each group of stakeholders flags the issues that are important to it, as well as finds out which issues matter to the other groups, without trying to elicit any preferences yet. The initial list of issues will probably be longer than is practically possible to handle, but at this stage, no attempt should be made to pare it down. (Azapagic, 2005).

Knowledge elicitation techniques such as brainstorming, interviews, questionnaires, and focus groups can be employed, depending on the type of problem and the stakeholders. A comprehensive list of knowledge elicitation techniques together with their advantages and disadvantages are available in Proctor (2009).

Task 4 Setting Indicators and Measures of Effectiveness (MOEs):

Decisions in the context of urban sustainable development are increasingly being made using sustainability indicators. Sustainable development indicators translate sustainability objectives into quantitative or qualitative measures of economic, environmental and social performance. Therefore, some resources have used the term "Measures Of Effectiveness MOEs" to refer to performance indicators (Mashrur, 2002). In the context of sustainability decision-making, where there are often a large number of sustainability indicators, the challenge is to reduce the list of indicators to a number that can be reasonably handled. In preparing the short list of indicators the following should be considered:

- **Value relevance**: decision-makers must be able to relate each indicator to the 'top level' goals they are trying to achieve and to express their preferences or values in relation to these goals;
- **Understandability**: decision-makers must have a shared understanding of concepts and indicators to be used in the decision-making process;
- **Measurability**: if possible, the indicators should be measurable and quantifiable; however, in some cases this is not possible (e.g. ethical considerations) so that appropriate MCDA modeling techniques have to be chosen to deal with qualitative criteria;
- **Non-redundancy**: ideally, each indicator should measure a different factor so that none of the indicators is included in the analysis more than once. To avoid double counting, if possible, similar indicators should be combined into a single indicator;
- **Judgmental independence**: indicators should be independent of each other so that a preference for one indicator does not depend on the level of another;
- **Balancing completeness and conciseness**: it is important to capture all relevant issues and identify related indicators; without an over detailing of the problem.

The output of this step is a list of objectives and corresponding indicators. Quantitative objectives can be transferred easily to quantitative indicators. However, qualitative objectives may need some effort to be converted into quantitative indicators. A good example of developing performance indicators to measure alternative policy actions is provided in Figure (4-1) (Lautso et al 2004).

The previous steps are common to all decision-making situations. The next stage depends on the type of problem (continuous or discrete) and the availability of the decision-maker for interaction during the decision stage as explained in Table (4-1)

Situation 1**: **<u>The case of a continuous problem and where the decision-maker is not available for interaction during the design stage:</u>

Step 5: Generate a large set of non-dominated alternatives using a posterior MODM method. (*e.g E-constraint method*)

As the problem is continuous, there are an infinite number of possible alternatives. It is the planner's responsibility to generate a comprehensive set of non-dominated alternatives to be presented to the decision-maker at a later stage. Therefore, a posterior multi-objective decision-making MODM methods should be used. ***The E-constraints*** method has been recommended for this purpose. The process has been explained in details in Chapter 2 and can be summarized in the following steps:

1- Formulate a mathematical model;

2: Construct a Pay-off Table;

3: Transform a Multi-objective Problem into a Single Objective Problem (Constraint Model);

5: Solve the Constraint Model using Optimization Software for Every Combination of values for the ε_k.

<u>The output of Step 5 is a large set of non-dominated solutions. The size of the set depends on the number of combinations selected.</u>

Step 6: Ranking alternatives using Multi-attribute Decision-making (MADM)

This is the first step in the assessment stage. Having a set of alternatives ready for evaluation and selection, this Multi-attribute Decision-making MADM technique will be used to generate an aggregated score for each alternative and to rank the alternatives accordingly. The ranking will be based on the weights assigned by the decision-maker to each objective. The Swing Weights Method is used to elicit weight values from the decision-maker, while the Simple Additive Weight method will be used to aggregate the final scores. The process has been explained in detail earlier in this research. The decision-maker can trade-off between objectives by changing the weights and exploring the impact on the final scores of objectives. This will continue until the decision-maker finds the acceptable balance between objectives. To facilitate the trade-off process, this study introduces an interactive tool by which the decision-maker can navigate through the alternatives. This tool will be applied in the following Chapters.

This step ends up with an alternative being defined as optimal based on the weights assigned by the decision-maker.

Step 8 Sensitivity analysis.

This step aims at testing to what extent any change in input parameters will change the final solution. It is an important step to assure the robustness and feasibility of the final choice. Most optimization and statistical software, including Excel, provide a sensitivity analysis facility by generating a range of input parameters and testing whether the output will change accordingly.

Situation 2: The case of a continuous problem and the decision-maker is available for interaction during design stage.

Step 7: generating non-dominated solution using an interactive Multi-objective Decision-making method *(interactive Goal Programming method)*.

If the problem is continuous and the decision-maker is available for interaction during the design stage, a Goal Programming model will be formulated and used to develop alternative solutions during an interactive and iterative process as explained in Chapter 2. As shown in figure (4-2) the process includes the following steps:

1. Formulate the goal programming model;
2. Interact with the decision-maker to obtain his preferences with regard to the target value and priority level of each objective;

3. Solve the model and get an alternative solution and present it to the decision-maker;
4. If the decision-maker is satisfied then go to Step 8 (sensitivity analysis). Otherwise, the decision-maker should modify his preferences and the process should be repeated.

The output of this step is a single solution that is accepted by the decision-maker. The robustness of this solution should be tested by performing sensitivity analysis as explained in Step 8

Situation 3: In case of a discrete problem (there is only a finite set of potential alternatives)

In this case, the alternatives have to be generated outside this framework. Other techniques such as scenario planning (Scearce et al, 2004) can be applied. For ranking alternatives and obtaining and selecting a final solution Steps 6 and 8 should be applied as previously explained..

4-5 Limitations Of the Proposed Framework:

The proposed framework holds the following limitations:

1- Multi-objective decision-making (MODM) is based on mathematical modeling. Therefore it is more oriented toward addressing operational and tactical type of problems rather than strategic problems. According to Bradley et al (1977) Mathematical modeling is suited particularly well for supporting tactical decisions. This category of decisions, dealing with allocation of resources through a middle-range time horizon, lends itself quite naturally to representation by means of mathematical models. Typically, tactical decisions generate models with a large number of variables and constraints due to the complex interactions among the choices available to the decision-maker;

2- Multi-objective decision-making MODM is oriented toward solving continuous type of problems with an infinite number of possible alternatives. Solving discrete types of problems is best approached by other techniques such as scenario planning.

3- The framework is oriented to deal with uncertainty only in the input values, which can be addressed by sensitivity analysis. In other words, it deals with deterministic problems where there is only one output for a given input. In case of probabilistic or stochastic problems, where there are many possible outputs for a given input other techniques such as fuzzy set analysis can be applied which is considered outside the scope of this study.

4- There are some technical limitations in the selected methods. For example, with Interactive Goal Programming there is no guarantee that the achieved solution is non-dominated. The analysis stops when a satisfactory solution is achieved (Malczewski and Jackson, 2000). The E-constraint method, guarantees a non-dominated solution. However, the solution may differ depending on which objective is considered more important.

5- One limitation of the existing framework is the inability to factor in the preferences of multiple decision-makers. Further research should be conducted to include multiple decision-makers in the modeling framework. This addition would allow the proposed model to receive different inputs from a number of decision-makers with different agendas. The organization would then be able to produce a decision outputs based on these varied inputs and preferences.

4-6 Reformulating the Research Hypothesis:

At this stage, having a clear decision-making framework incorporating both Multi-objective Decision-making MODM and Multi-attribute Decision-making MADM, the research hypothesis can be reformulated as such:

The proposed decision-making framework, incorporating the capacity of both Multi-objective decision-making MODM techniques and Multi-attribute Decision-making (MADM) technique, can satisfy the prerequisites for successful decision-making in the context of planning for urban sustainability.

4-7 Summary and Conclusion

- In this Chapter, Multi-objective Decision-making (MODM), and Multi-attribute Decision-making (MADM) techniques are combined in a general framework aiming at guiding a decision-maker in the context of planning for urban sustainability. The framework responds to the prerequisites raised in Chapter 1 for effective decision-making for urban sustainability.
- The framework is flexible and can be applied for a variety of urban problems. It acknowledges the role of the planner, stakeholders, and decision-maker within the planning process. The framework consists of three main stages: Problem structuring stage, Design stage, and Assessment stage.
- At the first stage (problem structuring stage) the problem is stated, stakeholders are identified and sustainability objectives and indicators are formulated.
- The design stage deals with continuous problems (where there are an infinite number of possible alternatives) and can address two decision-making situations:
    - If the decision-maker is available and willing to interacted then a Goal Programming model is formulated and used to generate alternatives interactively. This is particularly suitable in charrette workshop environment where it is required to respond to "what if?" question in real time;
    - If the decision-maker is not available for interaction then e-constraint model is used to generate a large set of non-dominated alternatives to make sure that all possible alternatives will be addressed by the decision-maker in the assessment stage.
- At the assessment stage, a Multi-attribute Decision-making technique is used to evaluate and rank alternatives based on the preferences of the decision-maker. The user can trade-off between various environmental, economic, and social objectives to achieve a satisfactory balance. Sensitivity analysis is finally done to insure the robustness of solution.
- The framework holds the following limitations: it is oriented toward tactical and operational level of decisions rather than strategic problems. Alternatives for discrete problems should be generated outside the framework, but they can be assessed within it.

CHAPTER 5

INTERACTIVE MULTI-OBJECTIVE APPROACH FOR DECISION-MAKING IN PUBLIC FACILITY PLANNING APPLICATION

This chapter describes the application of the developed decision-making framework to the situation where the decision-maker is available to interact with the planner at the design stage. The framework has been applied to a real-world case study pertaining to the determination of facility locations for health-care centers in Dubai, United Arab Emirates. A literature review on conventional public facility planning approaches is provided to confirm the significance of the proposed approach. A goal-programming model is formulated to take into consideration conflicting objectives (costs, efficiency of service, accessibility) as well as sustainability benchmarks obtained from the strategic plan of Dubai Emirate. The optimal distribution of health care centers has been obtained through an interactive process with stakeholders where various scenarios are tested until reaching a preferred distribution. The proposed solution outperforms that achieved through a conventional non-mathematical approach as it provides better accessibility and more effective service. It is also robust and insensitive to future changes in population or capacity thresholds.

5-1 The Importance of Public Facility Planning For Achieving Urban Sustainability

Determination of where to locate public facilities such as schools, hospitals, fire stations, etc, is probably the most important long-term decision made by local governments and the most powerful tool a community has to shape its future toward sustainability. (Eric & Decker 2000).Public facility location has a direct impact on the economic, social and environmental aspects of urban sustainability. Facility location decisions involve large sums of capital resources and their *economic* effects are long term. Investment in public facilities guides urban growth by influencing the efficiency by which jurisdictions provide public services and the ability of these jurisdictions to attract households and other economic activity. On the other hand, the *environmental* consequences of these decisions may include externalities such as traffic congestion, and pollution (Current et al. 2002). In Addison, planning for public facilities directly affects the public perception on *equity and social Justice*, one of the key principles of urban sustainability (Ademiluyi 2009). In a survey addressing public opinion with regard to the importance of various urban planning elements to be taken into consideration, the planning and location of community facilities constitutes the most highly ranked priority amongst eleven items (Amando el al, 2009).

<u>It can be concluded that spatial distribution of public facilities has a significant influence on the economic, social, environmental, and livability aspects of urban sustainability and on achieving a sustainable urban form.</u>

<u>5-2 Literature Review on Public Facility Planning Approaches</u>:

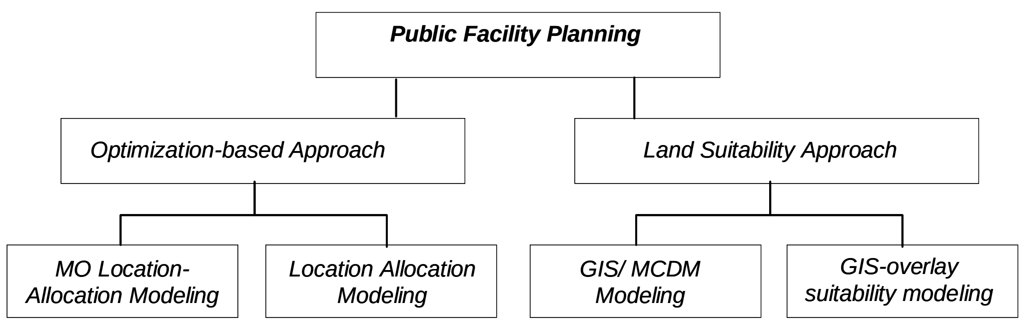


Figure (5-1). Public Facility Planning Approaches

Since the early 1960s, considerable effort has been devoted to public facility planning by researchers from a wide variety of fields (spatial planning, operations research, management science, regional economics, and civil engineering). This resulted in the emergence of several modeling approaches to facilitate decision-making for public facility planning. The objectives of public facility modeling is to define where to locate a facility of a given type among a given set of potential sites, and *what the capacity* should be. According to the modelling involved, two main approaches can be found in the literature (Rebeiro, 2002): Land suitability approaches and optimization-based approaches (Figure 1-5). Applications reveal that these conventional approaches satisfy some of the early mentioned prerequisites for efficient decision making in the context of urban sustainability but fall short in others. For example, GIS-based overlay suitability modeling (Marks et al 1992, Murad 2001 and Church 2002) lacks a well defined mechanism for incorporating stakeholder preferences regarding the relative importance of selection criteria into the GIS-based procedures (Malczewski 2004). Integrating multicriteria decision-making techniques such as AHP may help to overcome this limitation (Sten, et al 1991, Mehrez et al 1996, Vahidnia et al, 2009 and Al-Shuwaikhat & Nasef, 1996). However, lacking the capacity to allocate demand among facilities remains as a major drawback. Optimization-based models such as the p-median model (Gould & Lienbach, 1966 and Oppong 1996) and the maximal coverage model (Bennett et al. 1982) have been used to make location-based decisions on a single criteria so that either the average travel distance is minimized or the demand covered is maximized. In reality however, most location decisions are complex problems and require the consideration of multiple and often conflicting objectives which raises the infeasibility of standard single objective optimization approaches.

Dissatisfaction with traditional optimization approaches has prompted a marked interest in multiobjective optimization approaches during the last two decades. However, relatively few applications can be found in the literature where multiobjective optimization has been used for public facility location planning particularly for the allocation of healthcare facilities. (Badri et al 1998, Pantouvakos & Manoliadz 2008, Amin 2008, Farhan 2008). In their review of healthcare-related applications, Rahman and Smith (2000) noticed that very limited studies were actually implemented. They argued that a successful implementation requires the integration of multiobjective optimization models within a participatory decision-making process that facilitates the involvement of stakeholders, acquisition of their knowledge and experience, and effective communication and interaction among them throughout the planning process.

The remainder of this chapter provides a contribution to healthcare facility planning considering the following:

- It introduces an interactive goal programming model for locating health care facility considering multiobjectives.

- It responds to recommendations by recent literatures (e.g. Rahman S., and Smith D., 2000) to integrate the goal programming model within the planning process taking into account stakeholders preferences. It also facilitates the interaction and communication with decision maker to trade-off between various objectives until an optimal solution is reached.
- It provides a real world application on an area that has been subject to conventional facility planning. Using the same input parameters and set of objectives, there is a unique opportunity to discuss the added value by the proposed decision making framework.

5-3 Application of the proposed decision making framework:

This case study application aims at examining the proposed multiobjective framework in a real-world problem pertaining to achieving the sustainable location of healthcare centers in Dubai, United Arab Emirates that will balance environmental, social and economic objectives. The optimal locations have been reached through an interactive process with the decision maker(s). The results have been compared against those achieved from a conventional approach to examine the added value of the proposed decision-making framework.

5-3-1 Background

Dubai City is divided into 8 planning districts. This case study examines the application of the proposed decision making framework to the second district to the north of Dubai City (Figures 5-2 and 5-3). This district is further subdivided into 15 planning zones, from which 12 zones are predominantly middle-class residential. The remaining 3 zones are dedicated to warehouses with some low income and labor housing. During the last decade, the study area has witnessed a notable increase in population density, accompanied by a severe shortage in community facilities including healthcare services. Dubai Municipality estimates the ultimate population holding capacity of the study area to be 175000 residents.

The study area is currently served by 3 healthcare centers, providing medical services to the public. However, this number is far below what is required to serve the residents. According to DHA standards one center is required for every 30,000 individuals. This means that, unless new centers are constructed, the existing centers will soon be overloaded with almost double the efficient capacity. Therefore, DHA together with Dubai Municipality started to look for proper locations for new healthcare centers. A proposal has been developed as discussed in the next section.

5-3-2 The current proposal for location of the new healthcare centers

Dubai Government recognized the importance of community facility planning for achieving sustainable urban structure. One of the important vision benchmarks for Dubai urban planning by the year 2020 is:

> "80% of the residents can meet their principle health, education, recreation, and retail needs within a 3 km radius of where they work or live." (Dubai Urban Development Framework DUDF study, 2008).

Defining the location of health facilities, together with other public facilities, is mainly the responsibility of Dubai Municipality Planning Department DMPD. In response to the shortage of healthcare centers in the 2nd district the DMPD has proposed 3 new healthcare centers. To select these new sites DMPD followed a typical site selection decision-making process which consisted of the following steps:

(1) *Problem definition*: includes calculating the demand based on predefined standards and identifying the number of required facilities. For the study area, and according to DHA standards, it was estimated that 3 additional centers are needed to fulfil the projected demand.

(2) *Defining site criteria and objectives*: the following objectives have been considered: Easy access, covering all the demand, minimizing land costs, and minimizing the distance travelled to centers. These criteria are in line with DHA principles.

(3) *Applying a GIS-based suitability technique:* The department utilizes spatial analysis capability in GIS to investigate land availability and classifying the sites based on location criteria. GIS functions such as road buffering, overlay, database query have been applied to reach candidate sites.

(4) *Seeking approval from pertaining authority:* The attained locations are normally presented to related governmental authorities, in this case DHA, for final approval.

However, the adopted process holds most of the shortcomings of the GIS-based overlay approach: Lack of a well-defined mechanism to incorporate value judgments or perform trade-offs between objectives, lack of a way to allocate demand to proposed sites and lack of a way to quantify the proposal performance with regard to Dubai 2020 Vision benchmarks. Most importantly the process does not involve the stakeholders or decision-makers into the design (site selection) process.

5-3-3 The purpose of the case study:

This case study aims at examining the proposed multiobjective decision making framework in the context of decision making where the decision maker can (and willing to) provide preferences and value judgment prior to generating alternatives (priori articulation of preferences). The frame work has been applied in a real world case study pertaining to achieving a sustainable location of healthcare centers in Dubai, United Arab Emirates that will balance environmental and economic objectives. The optimal locations have been reached through an interactive process with decision maker(s). The result has been compared against that achieved by a conventional approach to prove the research hypothesis regarding the added value of the proposed decision making frame work. The decision making process follows the shaded path in Figure (5-4). In this case study, an interactive process is conducted between the analyst (the researcher) and decision makers (DMPD officials, and DHA official) where decision makers progressively provide their preferences and get responses from the model terms of alternative solutions. The next section explains, step-by-step, the application of the proposed framework including a detailed discussion on the interactive process.

Figure (5-2). Location of study area within the Dubai Urban Area.
(Source: Dubai Municipality)

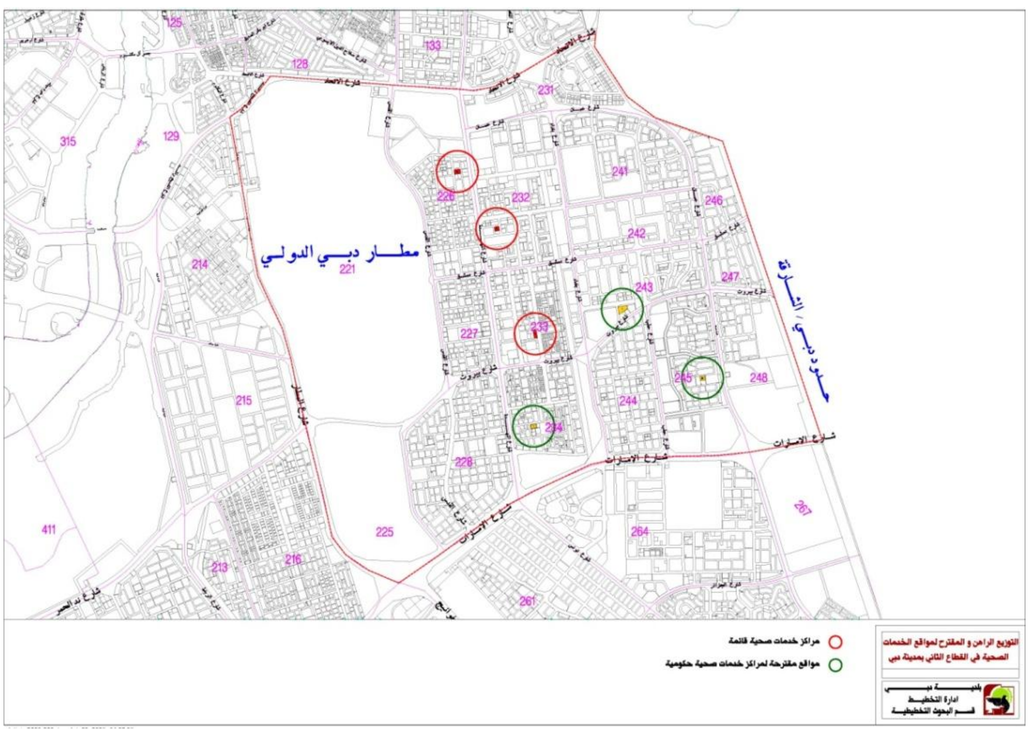


Figure (5-3). Study area and locations of existing and proposed healthcare centers according to DMPD plan (existing centers surrounded by red circles and proposed centers surrounded by green circles). (Source: Dubai Municipality)

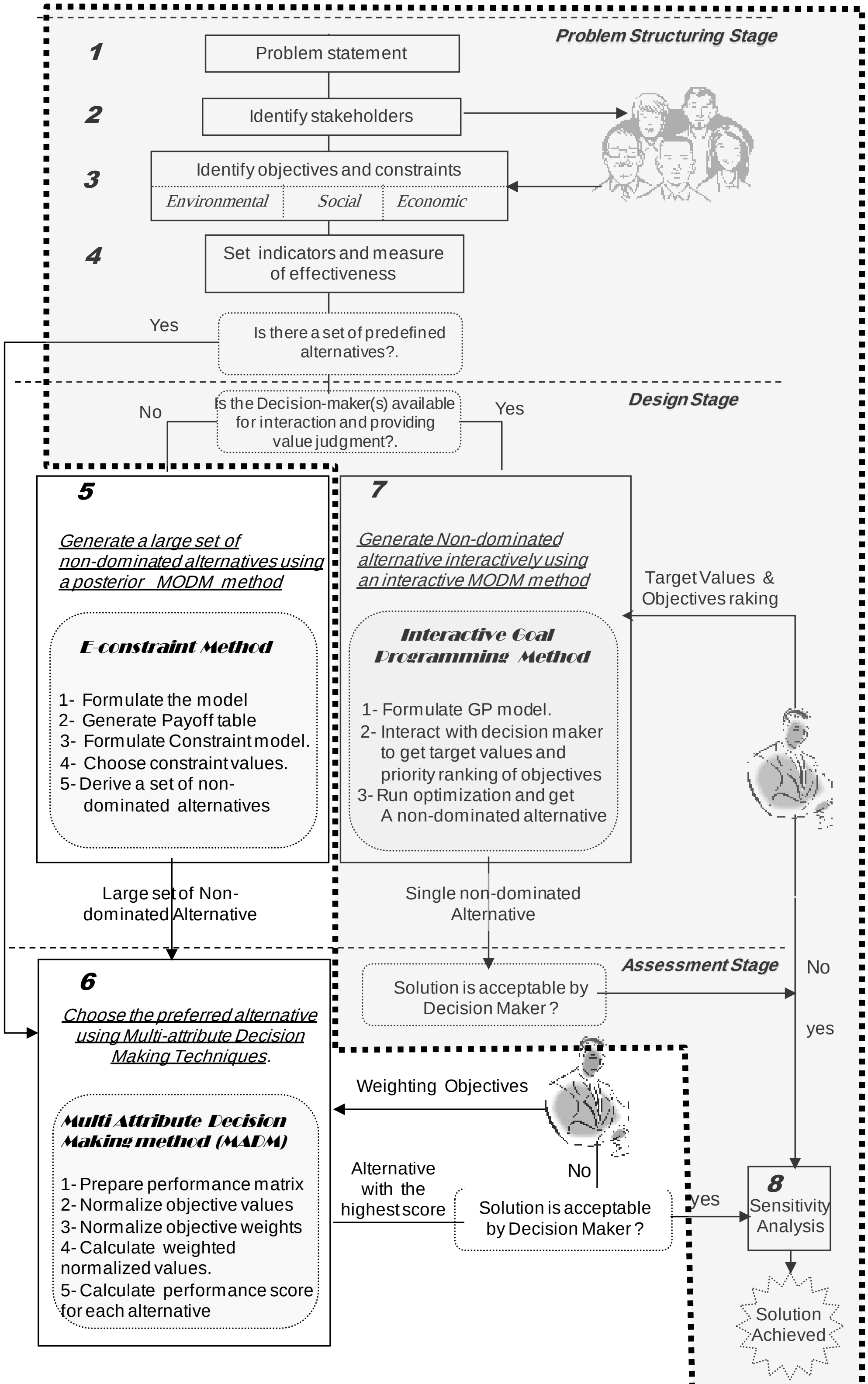


Figure (5-4). Decision-making path for the case study.

5-3-4 Details of decision making process:

In this section the decision making framework steps are followed and explained in detail as shaded in Figure (5-4)

<u>Step 1: Problem Statement:</u>

Due to increasing population density in district 2 in Dubai, the area is suffering from shortage in healthcare centers. It is required to provide a sustainable distribution of healthcare centers by providing answers to the following questions:

(1) How many new healthcare centers should be constructed.
(2) In which zone should these centers be located.?
(3) What is the assignment pattern from each population zone (demand), to each center (supply), including the existing centers?

<u>Step 2: Identify Stockholders:</u>

Three stakeholders are directly concerned with the problem of healthcare facility location:

1- Dubai Health Authority (DHA): DHA is responsible for constructing and operating healthcare facilities in Dubai;
2- Dubai Municipality Planning Department (DMPD): as mentioned is the agency responsible for land-use planning and defining locations for community facilities in Dubai;
3- Residents of District 2: They are the direct users of healthcare centers. However, it is assumed that DHA also presents this group of stakeholders.

<u>Step 3: Identify objectives and constraints:</u>

The following objectives have been identified by stakeholders. (The same objectives have been considered by DMPD for developing the current proposal):

Goal 1: Maximize efficiency of healthcare centers in providing service;

Goal 2: To provide medical services for all residents of district 2

Goal 3: To provide the service in a cost-effective manner;

Goal 4: To maximize accessibility to healthcare centers;

Goal 5: To minimize capital cost.

These goals represent various social, economic and environmental sustainability concerns: Goal (1) represent a social concern of providing the best possible healthcare service by allocating a number of patients to each center that will not exceed the standard threshold. Goal (2) represents an equity concern, while Goal (4) is directly related to convenience. Goal (3) and Goal (4) represent the economic concerns of minimizing operational and capital costs. Reducing the travel time to centers (Goal 4) contributes to enhancing urban environment by reducing traffic congestion, pollution and other adverse impacts associated with mobility.

<u>Step 4: Set indicators and measures of effectiveness (MOEs):</u>

MOEs provide scales to measure the performance of each alternative on all of the objectives specified in step 2. MOEs are defined by consulting urban sustainability benchmarks and indicators as well as planning standards (Table 5-1).

Table (5-1). Measures of effectiveness (MOEs).

Goal no.	**Measures of effectiveness (MOEs)**	**Note.**
Goal 1	Number of residents assigned to each center. (The capacity of each center).	According to DHA standards, the ideal capacity should be as close as possible to 30000 resident/center.
Goal 2	The population served by all centers.	The sum total of all assignments should be as close as possible to the total population of the study area.
Goal 3	Total number of centers in service.	For cost effectiveness, the population should be served by a minimum number of centers.
Goal 4	Number of population that has to travel more than 3 km to visit the center.	According to DUDF benchmarks, it is desirable that at least 80% of population be within a 3 km radius of a public facility.
Goal 5	Total of land cost and construction.	According to DHA, construction and preparation cost is 12 million Dhs/center (3.24 US Dollar). Land cost varies from one zone to another.

<u>Step 5: Formulating the model and generating alternative scenarios.</u>

1- Formulating Goal Programming Model

A- Notations and Symbols.

The proposed model uses the symbols represented in the following table.

Variable, Constant, or index	Description
i	Index for alternative planning zones
j	Index for alternative locations of healthcare centers.
n	Number or potential zones to be served (in this case study there are 15 zones)
m	Number of potential healthcare center alternatives.
S	Target capacity of each healthcare center (per patient)
H_i	Population holding capacity of zone *i*.
F	Target number of health care centers.
D	Target ratio of population assigned to healthcare facility more that 3 kilometres away from there residence.
C_i	Cost index for zone *i*.
M	Very large number.
d_{cap}^{-}, d_{cap}^{+}	Negative and positive deviations associated with the target service capacity.
d_{dem}^{-}, d_{dem}^{+}	Negative and positive deviations associated with service coverage
d_{num}^{-} , d_{num}^{+}	Negative and positive deviations associated with the target number of healthcare centers.
d_{num}^{-} , d_{num}^{+}	Negative and positive deviations associated with the target service capacity.
d_{dist}^{-} , d_{dist}^{+}	Negative and positive deviations associated with the target ratio of population outside the acceptable distance.
d_{cost}^{-} , d_{cost}^{+}	Negative and positive deviations associated with minimum capital cost
X_{ij}	Number of patients living in zone *i* and assigned to a healthcare center located in zone *j*.
$Y_j = 1$	If a healthcare center is allocated in zone *i*, 0 otherwise.

B- Decision Variables:

The model consists of two decision variables to represent the existence of healthcare center (HCC) in a particular zone, as well as the number of patients assigned from each zone to each of the proposed HCC as such:

X_{ij} : The number of patients living in zone (i) and assigned to HCC in zone (j)

Y_j : Binary variable (= 1 if HCC is proposed at zone (j) and =0 otherwise).

C- Goal Equations:

Goal 1: To abide by the service capacity of each HCC:

This objective can be formulated in a group of equations , one for each proposed HCC. The equation guarantees that the assigned population to each HCC will not exceed the preferred service coverage of each center (S = 30,000 person as per DHA standard):

$$\sum_{i=1}^{n} X_{ij} + d_{cap}^{-} - d_{cap}^{+} = S \qquad \text{for each } j = 1,2,3, \ldots, m$$

Goal 2: To cover the demand on health care from each planning zone:

A group of equations should be formulated, one for each planning zone. The equation should guarantee that the number of patients assigned from each zone to all HCC is equal to the holding capacity of this zone (H_i):

$$\sum_{i=1}^{n} X_{ij} + d_{dem}^{-} - d_{dem}^{+} = H_i \qquad \text{for each i.} = 1,2,3, \ldots, n$$

Goal 3: To minimize the number of proposed HCC:

The goal is to provide the required service with the minimum number of centers.

In this case the right hand side of the following equation should be set to zero ($F = 0$). However, if the decision maker is looking to attain a certain target number of centers then (F = the target number):

$$\sum_{j=1}^{m} Y_j + d_{num}^{-} - d_{num}^{+} = F$$

Goal 4: To minimize distance traveled to each center:

As mentioned, the target is to ensure that at least 80% of the population travels not more than 3 kilometres to any center. The right hand side of the following equation represents this benchmark. D is the proportion of population violating this benchmark. Therefore D = 0.2. It should be noted that this equation will only contain those zones located more than 3 kilometres away from each others:

$$\sum_{i=1}^{n}\left(X_{ij} \Big/ \sum_{i=1}^{n} H_i \right) + d_{dist}^{-} - d_{dist}^{+} = D$$

Table (5-2) represents the average distance between each pair of zones in km. The distance is measured between the geometrical centers of each zone and traced over the actual road network.

Table (5-2). Distance between each geometrical centers of zone in km.

Zone no.	**226**	**227**	**228**	**231**	**232**	**233**	**234**	**241**	**242**	**243**	**244**	**245**	**246**	**247**	**248**
226	1.9	3.9	6.2	4.9	2.7	5.5	6.9	5.7	5.1	6.9	7.7	7.8	6.5	6.6	7.9
227	3.9	1.9	3.8	5.8	3.8	2.3	3.6	7.8	6.5	5.3	4.8	6.1	7.5	7.3	6.9
228	6.2	3.8	1.9	8.4	6.4	3.9	2.7	7.9	6.4	6	5.2	6.5	7.8	6.9	7.2
231	4.9	5.8	8.4	1.9	4.4	6	7.3	3.7	4.9	5.7	6.9	7.5	5	6.5	7.6
232	2.7	3.8	6.4	4.4	1.9	5	3.8	3.5	4.3	6.1	6.5	4.5	5.5	6.7	6.7
233	5.5	2.3	3.9	6	3	1.9	2.8	5.3	4.1	4.1	3.8	5.2	5.9	5.7	6
234	6.9	3.6	2.7	7.3	6.5	2.8	1.9	6.7	5.1	4.3	4	5	6.5	5.7	5.8
241	5.7	7.8	7.9	3.7	3.8	5.3	6.7	1.9	2.8	4.5	6	6.2	3.1	4.2	5.4
242	5.5	6.5	6.4	4.9	3.5	4.1	5.1	2.8	1.9	2.3	4	4	3	3.7	4.7
243	6.9	5.3	6	5.7	4.3	4.1	4.3	4.5	2.3	1.9	3.2	3.1	3.8	3.6	3.9
244	7.7	4.8	5.2	6.9	6.1	3.8	4	6	4	3.2	1.9	2.8	5.8	5.7	5.2
245	7.8	6.1	6.5	7.5	6.5	5.2	5	6.2	4	3.1	2.8	1.9	4.5	3.6	5.3
246	6.5	7.5	7.8	5	4.5	5.9	6.5	3.1	3	3.8	5.8	4.5	1.9	2.5	3.8
247	6.6	7.3	6.9	6.5	5.5	5.7	5.7	4.2	3.7	3.6	5.7	3.6	2.5	1.9	2.8
248	7.9	6.9	7.2	7.6	6.7	6	5.8	5.4	4.7	3.9	5.2	5.3	3.8	2.8	1.9

Goal 5: To minimize capital cost.

One common objective used in many facility location studies is to minimize the cost associated with locating new facilities. In this case study, there are two associated costs; the construction cost and the land cost. A cost index C_i has been calculated for each zone (i) such as:

C_i = Construction cost for new facility + Land cost

According to DHA the construction cost for a new facility = 12 million Dirhams ($3.3 million). The land cost depends on the availability of land in each zone. If no land is readily available the cost of land acquisition is estimated based on a land value for each zone. Zones where current healthcare centers exist have cost index equal to zero. For zones where no centers exist but there is land available, only the construction cost will be considered. Otherwise both costs will be considered as presented in the Table (5-3). The objective can then be formulated as follows:

$$\sum_{j=1}^{m} Y_j C_j + d_{\cos t}^{-} - d_{\cos t}^{+} = 0$$

Table (5-3). Land and construction cost data. (Source: DMPD, DHA)

Zone no.	land cost	construction cost	Cost index
226	0	0	0
227	6,000,000	12,000,000	18,000,000
228	0	12,000,000	12,000,000
231	0	12,000,000	12,000,000
232	0	0	0
233	0	0	0
234	0	12,000,000	12,000,000
241	0	12,000,000	12,000,000
242	0	12,000,000	12,000,000
243	0	12,000,000	12,000,000
244	0	12,000,000	12,000,000
245	0	12,000,000	12,000,000
246	4,500,000	12,000,000	16,500,000
247	0	12,000,000	12,000,000
248	0	12,000,000	12,000,000

D- Constraints:

1- System constraints:

System constraints may be necessary to force the Y_j to be 1 if ($X_{ij} \neq 0$). In other words, if the model decides that no center is recommended in zone j then no patients will be assigned to this zone. Patients will be assigned to a center only if a center is there. The following equations are a modified version of similar constraints found in th literatures (Badri et al 1998 and Lee et al., 1981) where M is an arbitrarily very large number.

$$\sum_{i=1}^{n} X_{ij} - Y_j M \leq 0$$

$X_{ij} \geq 0$ And integer.

For each j = 1,2,3,….m

2- Policy-related constraints:

In case the decision-maker wants to impose a facility in a certain location or prohibit a facility in certain zones these constraints can be easily formulated by constraining the Y value for these zone as follows:

$Y_3 + Y_5 = 0$ This will prohibit facilities in both zone 3 and 5.

$Y_4 + Y_6 = 2$ This will impose facilities in both zone 4 and 6.

E- Objective Function:

The objective function will attempt to minimize the deviation resulting from not attaining the goals specified in goal equations. The priority of each goal is specified by the decision maker. Hence, given the above goal equations, constraints and considering the priorities assigned to the achievement goals, the objective function can be formulated as follows:

Minimize $Z = P_1 \sum (d_{cap}^- + d_{cap}^+) + P_2 \sum (d_{dem}^- + d_{dem}^+) +$

$P_3 (d_{num}^- + d_{num}^+) + P_4 (d_{dist}^- + d_{dist}^+) +$

$P_5 (d_{cost}^- + d_{cost}^+)$

Where P_1, P_2, P_3, P_4, P_5 are the priorities of Goal 1,2,3,4,5 as specified by the decision maker.

Step 6 Interaction process with the decision maker to generate solutions.

Generating alternatives from the model requires acquiring the decision maker preferences. Traditional Goal Programming method requires the decision-maker to specify fairly detailed a *priori* information about his/her aspiration levels, preemptive priorities, or the importance of goals as weights. One can expect that in a complex facility location problem, the decision maker will find it difficult to provide such precise *priori* information. (Malczewski, 2000, Tamiz M., 1995).

This research follows an interactive approach where the decision maker actively contributes to the process of generating alternatives. The process involves the decision maker, the analyst/ planner, and a computer model (fgure 5-5). The analyst/planner, using the model, proposes a starting solution to the decision maker. The latter gives his preference information with respect to this solution to the analyst. The preferences are expressed in terms of trade-off with respect to target values or changing priorities levels of objectives (preemptive priorities). The analyst transfers this information to a new solution, again using the model. This new solution is presented to the decision maker who expresses his preferences, and so on, until a final solution is reached which is judged satisfactory.

Normally, the role of the analyst during the interactive process is more passive. Nevertheless, the analyst still has to be involved to instruct and reinstruct the decision maker about the properties of the interactive procedure at hand, to help analyze the model results and if necessary to prepare possible model revision.

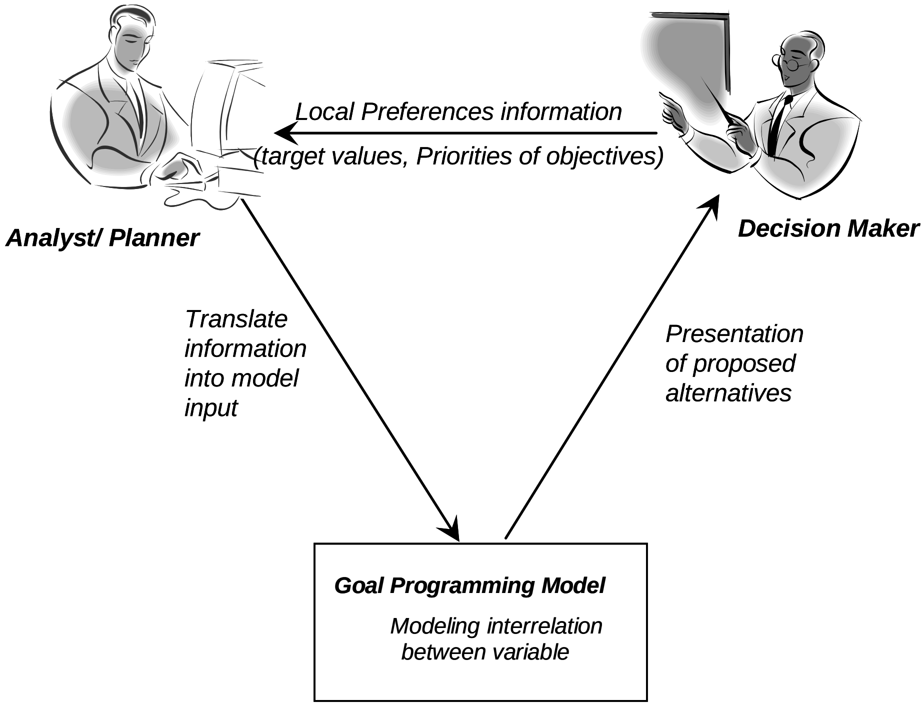


Figure (5-5). Diagram of the interactive process.

The process can be summarizing in the following steps:

Step 1: The analyst proposes an initial solution and presents it to decision maker.

Step 2: If the solution is acceptable by decision maker, then stop.

Step 3 If not acceptable, the decision maker should change the target levels or/and the priority level of any (or all) objective.

Step 4: The analyst translates this preference into model input and runs the optimization model to get a new alternative.

Step 5: If the alternative is acceptable, then stop, otherwise repeat step 3.

By the mean of interactive decision procedures, decision maker becomes more closely involved in the process of solving his decision problem thus obtains more insight into the trade-offs among different goals variables. It is a learning process as the decision maker's perception of the decision situation changes during the process which, in turn may change the decision maker's preferences.

For the case study at hand, the interactive process took place in a dedicated session organized by the lead author under the supervision of Dubai Municipality; Planning Department DMPD. The session was attended by representatives of the two main groups of stakeholders (and also decision-makers in this case) concerned with the allocation of healthcare centers in Dubai: Dubai Municipality Planning Dept DMPD and Dubai Health Authorities DHA with the lead author playing the role of the analyst. It should be noted that the decisions have been taken during the session by consensus between stakeholders. Dubai municipality officials accepted the researchers request to organize the session for two reasons:

(1) It was consistent with the municipal policy to explore various avenues concerning involving stakeholders into the land-use planning process to achieve sustainable development;
(2) To investigate the validity and practicality of the proposed modelling-based framework for wider implementation and further applications.

The interactive process involved several iterations (steps). In each step an alternative scenario for locating healthcare centers was generated together with a related population assignment strategy. The output of each step was presented to decision-makers/ stakeholders both graphically and in a tabular format. The decision maker's feedback with respect to each scenario was collected and processed into a new scenario to be presented in the following step. Six scenarios have been developed until a final compromised solution was accepted by the decision makers. During the process the decision-makers have sharpened their preferences as they got more knowledgeable about the necessary trade-offs between objectives. The interaction process is illustrated in Figure (5-6) and the output is summarized in Table (5-4). The interactive process is discussed in detail below.

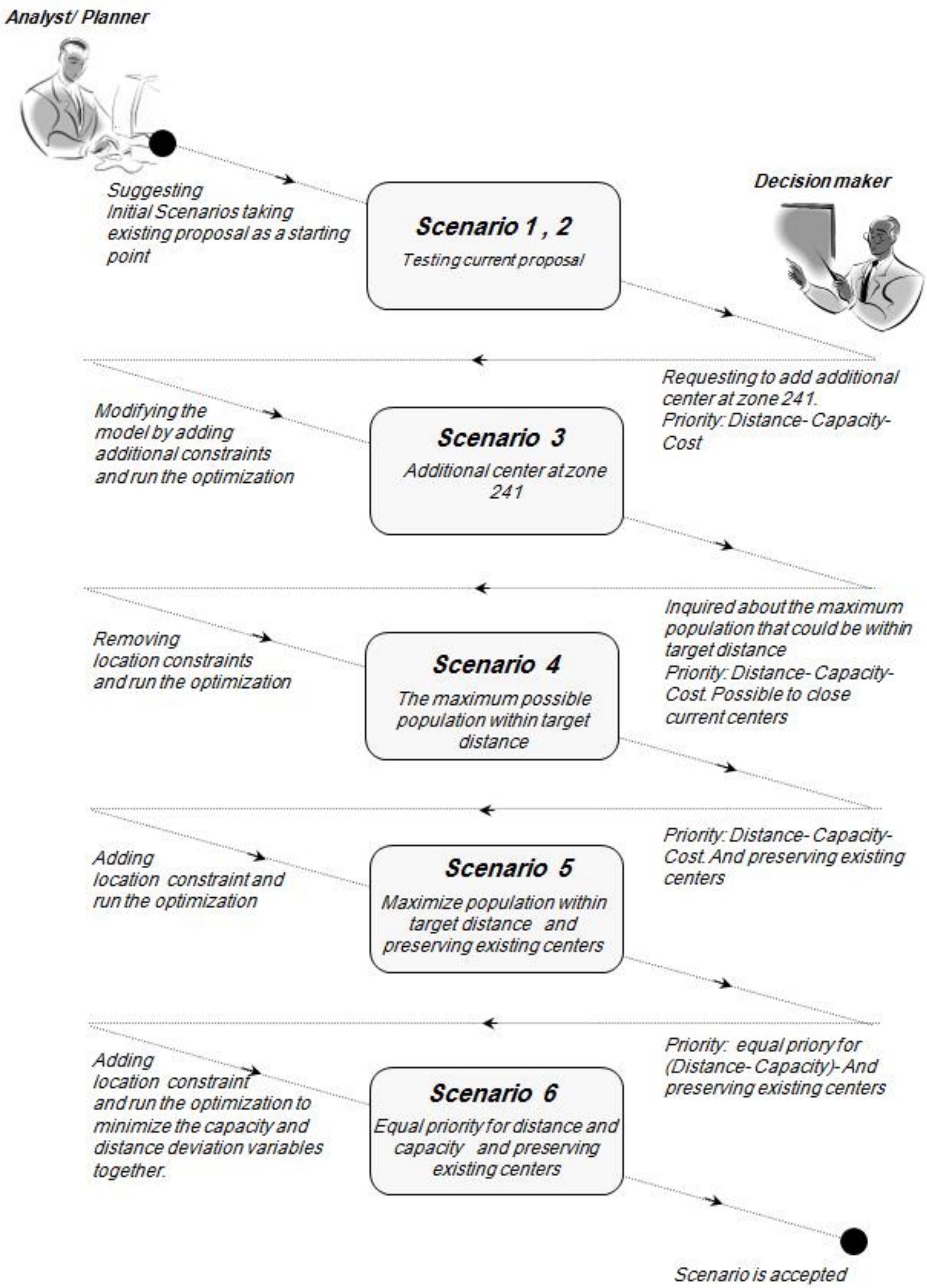


Figure (5-6). Details of the interactive process to generate alternative scenarios of healthcare locations.

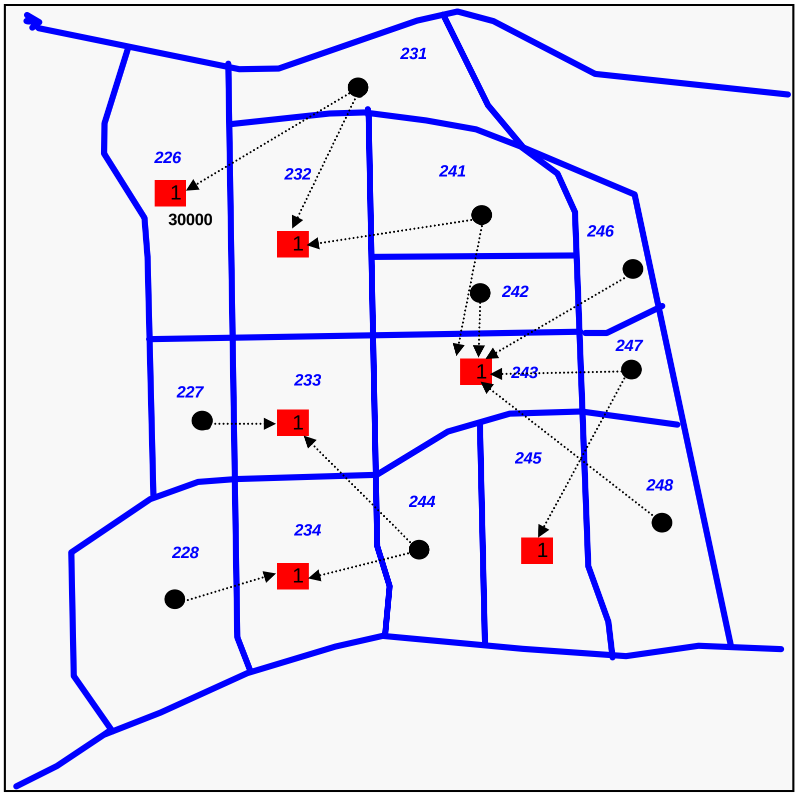
Table (5-4). Output summery of each generated scenarios.

Scenario no.	Priority levels	No. of Centers	Accessibility % of population within target distance	Capacity (person)		Cost (Mill. Dhs)
				Max d_{cap}^{+}	Max d_{cap}^{-}	
Scenario 1	$P_2 - P_1 - P_4 - P_5$	6	63.2%	0	5130	36
Scenario 2	$P_2 - P_4 - P_1 - P_5$	6	70.1%	27700	14200	36
Scenario 3	$P_2 - P_4 - P_1 - P_5$	7	80.1%	0	14200	48
Scenario 4	$P_2 - P_3 - P_4 - P_1 - P_5$	6	93.3%	9840	14900	60
Scenario5	$P_2 - P_3 - P_4 - P_1 - P_5$	6	80.2%	14800	18000	36
Scenario 6	$P_2 - P_3 - (P_4, P_1) - P_5$	6	75.5%	2000	3000	36

Initial step : Generating Scenarios 1, 2 (Analyzing the current proposal)

At the outset of the interactive process, Dubai Health Authority representatives asserted that, according to DHA policy, health service should be provided to all the population. Therefore Goal 2 should always be given the first priority. As a starting point, the distribution of healthcare centers proposed by the Dubai Municipality Planning Dept. was analyzed. As the locations of the centers had been fixed, the population assignment was generated under two priority scenarios; Scenario 1: (Service capacity – Distance-cost) and Scenario 2: (Distance – Service capacity – cost).

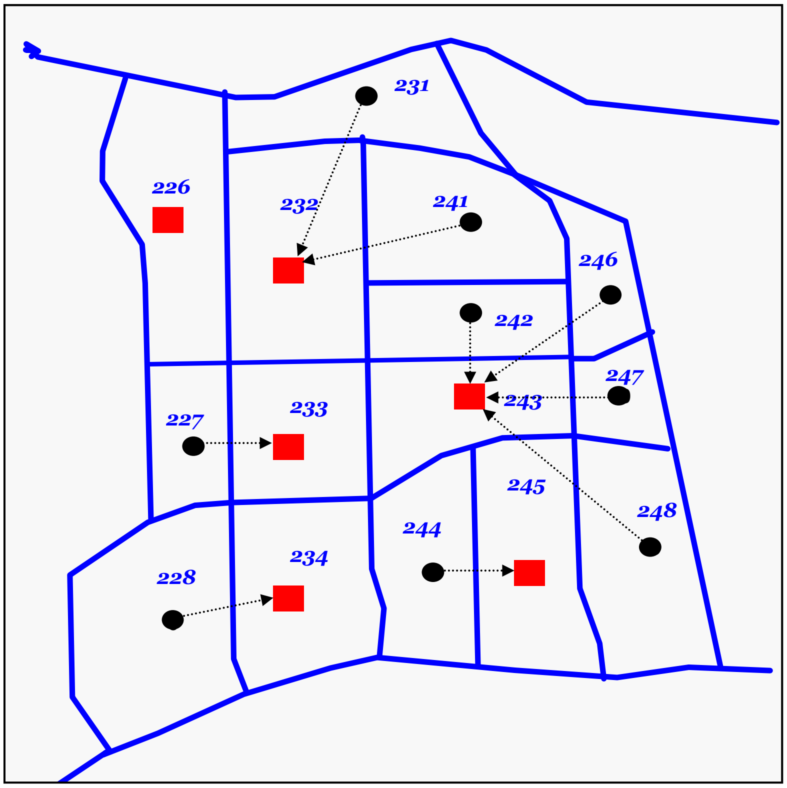
This was simply done by fixing the number of centers at F= 6 and adding the following constraint to the model: $Y_1 + Y_5 + Y_6 + Y_7 + Y_{10} + Y_{12} = 6$. Then the model was run twice with different priority scenarios to generate two alternatives (Figures 5-7 and 5-8). The output revealed that, under the current proposal, a maximum of 70.1% of population will be within the target distance from a healthcare center. The two goals "achieving a service capacity of 30000" and "maximize the population within the target distance of 3 km" are in conflict. To fully achieve the first goal, only 63.2 of the population will be within the target distance. Optimizing the second goal results in an unbalanced population assignment between centers. The center at zone (232) will serve almost double the acceptable capacity whereas the center at zone (226) will serve only half the target capacity. After discussing the result, the decision-makers suggested testing scenario 2 after adding an additional center at zone (241) to alleviate the load on the center at zone (232).



Proposed Centers		**Population assignment**											
Location	***Capacity***	***Zone no.***	Pop.	***Zone no.***	Pop.	***Zone no.***	Pop.	***Zone no.***	Pop.	***Zone no.***	Pop.	***Zone no.***	Pop.
226	30000	***226***	15800	***231***	14200								
232	30000	***231***	900	***232***	13660	***241***	15440						
233	30000	***227***	3800	***232***	5940	***233***	16100	***244***	4160				
234	24870	***228***	11530	***234***	11400	***244***	1940						
243	30000	***241***	7560	***242***	4500	***243***	5740	***246***	2200	***247***	2000	***248***	8000
245	30000	***245***	28000	***247***	2000								

Percentage of population withine (3 km)	**63.2**	%
Total Cost	**36**	Million Dhs
Total unserved Population	**0**	

Figure (5-7). Graphical and tabular presentation of scenario 1- (priority: Service capacity – Distance- cost)



Proposed Centers		Population assignment										
Location	Capacity	Zone no.	Pop.	Zone no.	Pop.	Zone no.	Pop.	Zone no.	Pop.	Zone no.	Pop.	
226	15800	***226***	15800									
232	57700	***231***	15100	***232***	19600	***241***	23000					
233	19900	***227***	3800	***233***	16100							
234	22930	***228***	11530	***234***	11400							
243	24440	***242***	4500	***243***	5740	***246***	2200	***247***	4000	***248***	8000	
245	34100	***244***	6100	***245***	28000							
		Percentage of population within target distance (3 Kkm)								**70.09** %		
		Total Cost								**36** Million Dhs		
		Total unserved Population								**0**		

Figure (5-8). Graphical and tabular presentation of scenario 2 (priority: Distance-Service capacity –cost).

Iteration 1: Generating Scenario 3 (Adding a center at zone 241)

The decision-maker's feedback has been translated by adding the following constraint to the model : $Y1 + Y5 + Y6 + Y7 + Y10 + Y12 + Y8 = 7$ and adjusting parameter $F = 7$. The output (Figure 5-9) revealed that the percentage of population within the target distance has increased to 80.1% and the load on all centers never exceeded the target capacity. However, the cost of development has increased to 48 million. Perceiving the conflict between "service capacity" and "distance", the decision-makers requested to investigate the distribution that will maximize the population within target distance with only 6 centers.

Iteration 2: Scenario 4 (Maximizing the population within target distance)

The decision-makers feedback on scenaio3 has been processed by fixing the parameter F = 6 and running the optimization with travel distance as the first priority. The result (Figure 5-10) revealed that, having 6 centers in operation, the maximum percentage of population within the target distance cannot exceed 93.3%. However, to achieve this, the model suggested cancelling two existing centers (at zones 226,233), therefore, increasing the cost of development to 60 million. It addition, population assignment will be unbalanced. Three centers will be overloaded, while two will work with almost half capacity.

Iteration 3: Generating Scenario 5 (Maximize the served population within the target distance while preserving the existing centers)

After discussing the results of scenario 4, the decision makers requested to explore a new scenario which maximize the percentage of population within target distance without allowing the model to cancel any of the existing centers (at zones 226, 232, 233). This has been done simply by fixing the parameter $F = 6$, adding a following constraint to the model: $Y_1 + Y_5 + Y_6 = 3$, and running the optimization with distance as the first priority. The result (Figure 5-11) suggested three centers at zones 241, 245, 248. The population within the target distance increased to 80.2% but with unbalanced assignments among centers. Seeking a trade-off between the two conflicting objectives (distance and service capacity), the decision-maker requested to run the model giving equal priority to both. They also allowed the service capacity target to be relaxed with a range between 3000 resident/center plus or minus the target level

Iteration 4: Generating Scenario 6 (Equal priority to Service capacity and distance and preserving the preserving the existing centers).

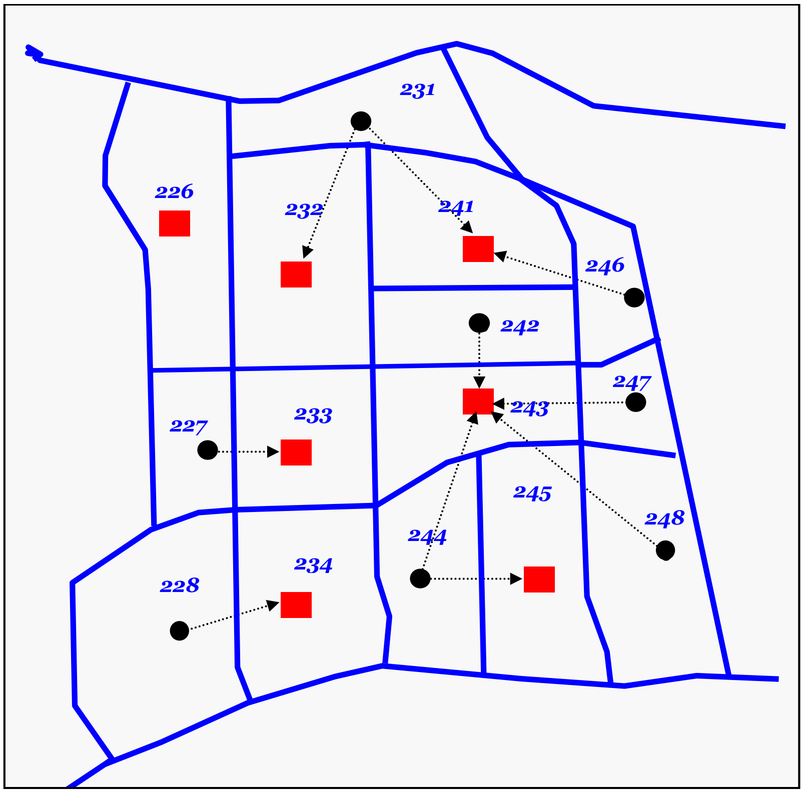
The decision-makers' feedback on scenario 5 has been processed by adding a constraint to bound the service capacity between 27000 and 33000 person as follows:

$$33000 \geq \sum_{i=1}^{n} X_{ij} \geq 27000 \quad \text{For each } j = 1,2,3,\ldots.m$$

However, instead of optimizing each goal one at a time, both goals have been optimized together. To unify the measurement unit, the deviation variables in the objective function have been normalized using the percentage normalization method (Frederick, 1989, Tmiz, 1995, El-Iraqi 2006). This is done by dividing the deviation variables by the right hand side in the corresponding goal equation. Therefore, the objective function for the first priority level will be as follows:

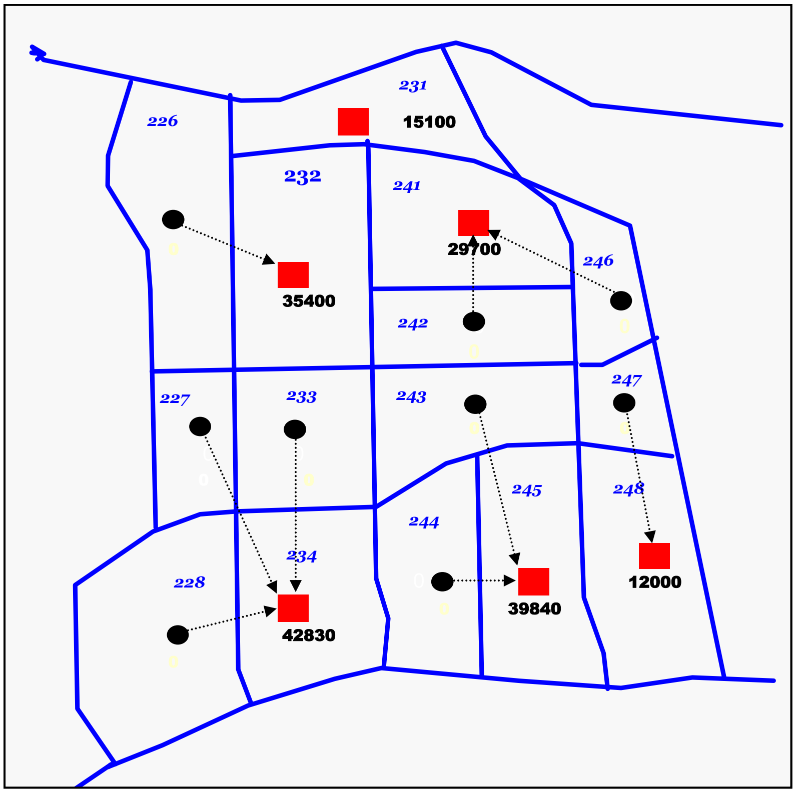
$$\text{Min } Z = (d_{cap}^{-} + d_{cap}^{+}) / 30000 + d_{dist}^{-} / 0.8$$

The result (Figure 5-12) of the optimization suggested three new centers at zones (234 -241-245). The result also revealed a better balance between the two conflicting objectives (distance and service capacity). The achieved percentage of population within the target distance = 75.5% and, at the same time, all the centers are serving a number of residents within a range acceptable to the decision-maker. Therefore this scenario has been accepted by the decision-makers and considered as a final conclusion for the inactive process. Scenario 6 also outperforms the current proposal as will be discussed later. Accordingly Dubai Municipality Planning Department commenced the necessary actions to reserve a site for a healthcare center in zone 241 (Figure 5-13). In the next section, the robustness of the selected scenario with respect to uncertain parameters or changes in target values is discussed.



Proposed Centers		Population assignment										
Location	***Capacity***	***Zone no.***	Pop.	***Zone no.***	Pop.	***Zone no.***	Pop.	***Zone no.***	Pop.	***Zone no.***	Pop.	
226	15800	***226***	15800									
232	29900	***231***	10300	***232***	19600							
233	19900	***227***	3800	***233***	16100							
234	22930	***228***	11530	***234***	11400							
241	30000	***231***	4800	***241***	23000	***246***	2200					
243	26340	***242***	4500	***243***	5740	***244***	4100	***247***	4000	***248***	8000	
245	30000	***244***	2000	***245***	28000							
		Percentage of population within target distance (3 Kkm)									**80.09**	%
		Total Cost									**48**	Million Dhs
		Total unserved Population									**0**	

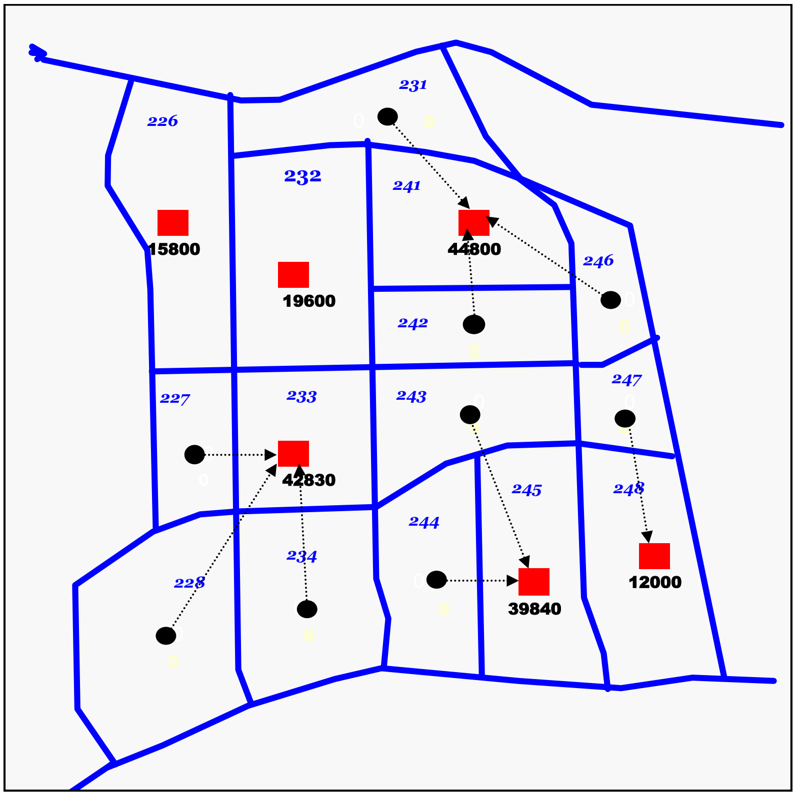
Figure (5-9). Graphical and tabular presentation of scenario 3 (adding a center at zone 241).



Proposed Centers		**Population assignment**											
Location	*Capacity*	*Zone no.*	Pop.	*Zone no.*	Pop.	*Zone no.*	Pop.	*Zone no.*	Pop.	*Zone no.*	Pop.	*Zone no.*	Pop.
231	15100	***231***	15100	***231***	14200								
232	35400	***226***	15800	***232***	19600	***241***	15440						
234	42830	***227***	3800	***228***	11530	***233***	16100	***244***	11400				
241	29700	***241***	23000	***242***	4500								
245	39840	***243***	5740	***244***	6100	***245***	28000						
248	12000	***247***	4000	***248***	8000								

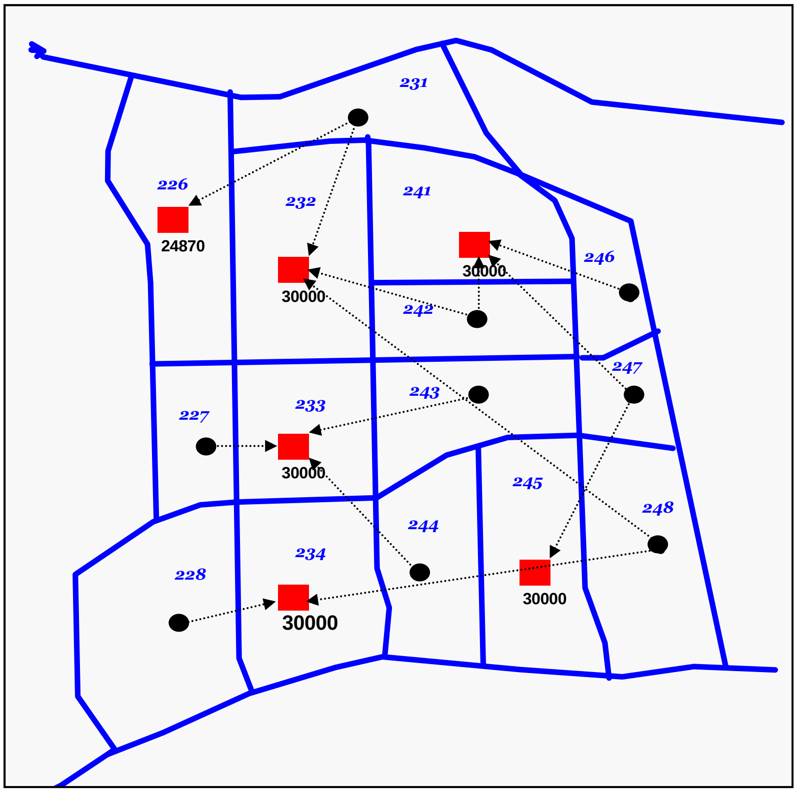
Percentage of population withine (3 km)	**93.3**	%
Total Cost	**60**	Million Dhs
Total unserved Population	**0**	

Figure (5-10). Graphical and tabular presentation of scenario 4 (Equal priority to Service capacity and distance and preserving the preserving the existing centers).



Proposed Centers		Population assignment											
Location	*Capacity*	*Zone no.*	Pop.	*Zone no.*	Pop.	*Zone no.*	Pop.	*Zone no.*	Pop.	*Zone no.*	Pop.	*Zone no.*	Pop.
226	15800	***226***	15800										
232	19600	***232***	19600										
233	32570	***227***	3800	***228***	11530	***233***	16100	***234***	1140				
241	44800	***231***	15100	***241***	23000	***242***	4500	***246***	2200				
245	39840	***243***	5740	***244***	6100	***245***	28000						
248	12000	***247***	4000	***248***	8000								
		Percentage of population withine (3 km)									**80.2** %		
		Total Cost									**36** Million Dhs		
		Total unserved Population									**0**		

Figure (5-11). Graphical and tabular presentation of scenario 5 (Maximize the population within target distance while preserving the existing centers).



Proposed Centers		Population assignment											
Location	***Capacity***	***Zone no.***	Pop.	***Zone no.***	Pop.	***Zone no.***	Pop.	***Zone no.***	Pop.	***Zone no.***	Pop.	***Zone no.***	Pop.
226	27000	***226***	15800	***231***	11200								
232	27000	***231***	3900	***232***	19600	***248***	3500						
233	29440	***227***	3800	***233***	16100	***243***	3440	***244***	6100				
234	27430	***228***	11530	***234***	11400	***248***	4500						
241	32000	***241***	23000	***242***	4500	***246***	2200	***247***	2300				
245	32000	***243***	2300	***245***	28000	***247***	1700						
		Percentage of population withine (3 km)								**75.5** %			
		Total Cost								**36** Million Dhs			
		Total unserved Population								**0**			

Figure (5-12). Graphical and tabular presentation of scenario 6 (Equal priority to Service capacity and distance and preserving the preserving the existing centers).

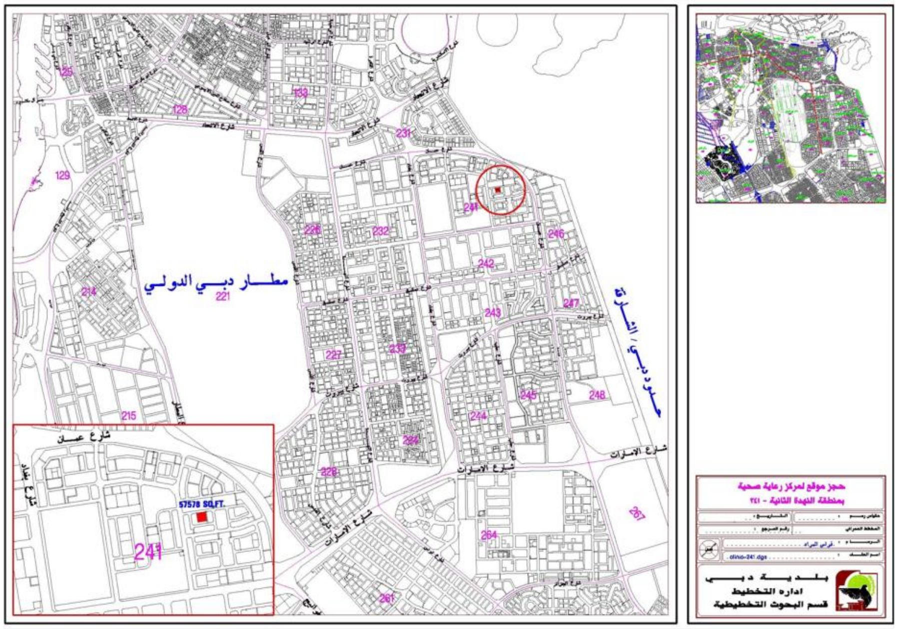


Figure (5-13). The site that has been reserved by Dubai Municipality for Healthcare center in zone 241 as a response to the case study result. (Source: DMPD)

<u>Step 7: Sensitivity Analysis.</u>

Sensitivity analysis (SA) is an important task in the decision-making framework: it looks at how robust (or weak) the final decision is, in the case that even a slight change in the input parameters or previously expressed preferences is made. Sensitivity analysis is used to deal with uncertainties in the input parameters and will provide an understanding of how the model responds when inputs are changed. (Mattei 2008, Mashrur 2002). Most optimization software packages have the facility of performing sensitivity analysis on any input parameters without the need for further computational efforts (Frontline Systems Inc. 2009) . For the case study at hand, three sensitivity analyses have been conducted on the preferred scenario (Scenario 6) to check its robustness to uncertain parameters as follows:

Sensitivity to potential increase in population of Zone 232:

Zone 232 is expected to witness intensification of population due to its proximity to a new light rail system which is currently under construction. Sensitivity analysis has been done to investigate the accessibility implication (% of population within the target distance) under different intensification levels. Figure (5-14) shows how accessibility changes with an increment increase of 10% in population. The result reveals that increasing population in zone 232 will result in enhancing the overall accessibility to health care centers. This result is somehow expected as there are three proposed centers nearby, operating on a lower capacity bound, and can accommodate the expected increase in demand.

Sensitivity to change the lower limit of capacity.

The second sensitivity analysis aimed at investigating how a change in the lower capacity limit may affect the accessibility. Figure (5-15) shows how accessibility changes with an incremental change of 1000 in the lower capacity limit. The result reveals that accessibility increases with increasing the lower capacity until 25000, then starts to decrease. Accessibility decreases sharply with increasing lower capacity limit to more than 27000 persons. This is an important result as the decision-maker may consider relaxing the limit to 25000 to increase accessibility.

Sensitivity to change the upper limit of capacity.

The third analysis was similar to the second but concerned the upper capacity limit. Figure (5-16) shows the relationship between accessibility and the upper capacity. The graph shows that accessibility increases sharply as the upper bound increases until a limit of 32000 persons. However, further increases from 32000 to 38000 persons has no impact on accessibility. Again, this result is important. It alerts decision makers that increasing the limit to more that 32000 persons may add extra load on centers without any significant impact on accessibility.

In short, the output of this step illustrates that the selected scenario (Scenario 6) is robust. It is insensitive to an increase in population. In addition, decision maker can relax both the upper and lower limits of capacity without a significant impact on accessibility. However, the decision-maker should not to make the upper limit less than 32000 persons or the lower limit more than 27000 persons.

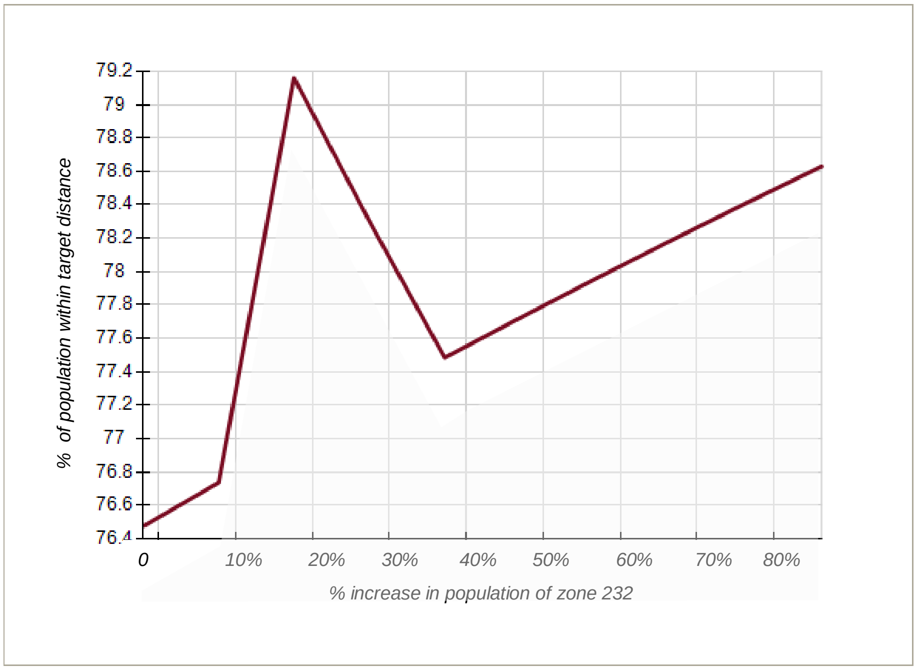


Figure (5-14). Sensitivity analysis result : The impact of increasing population in Zone 232 on the percentage of population within the target distance.

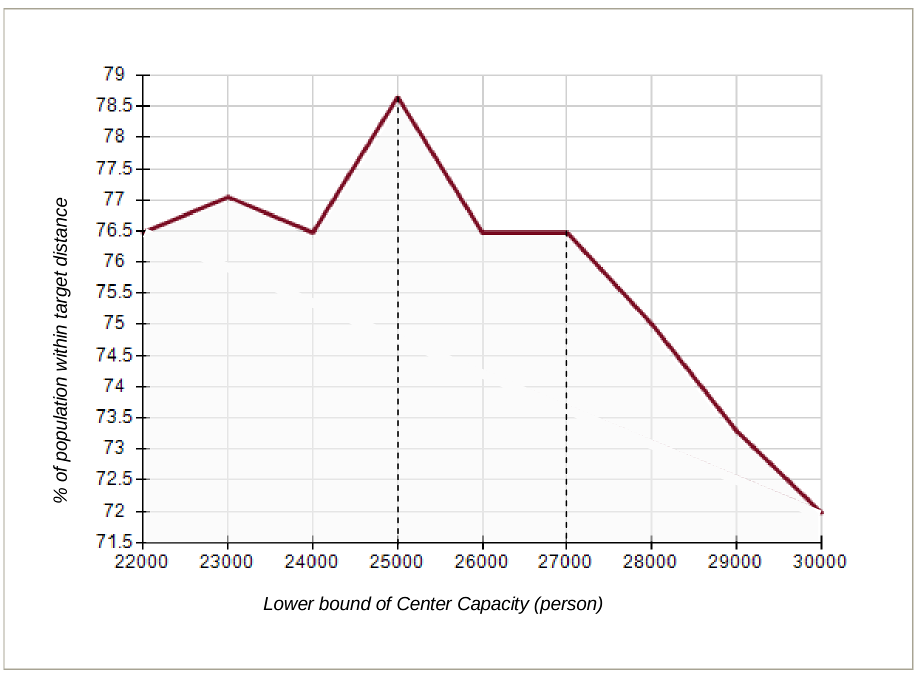
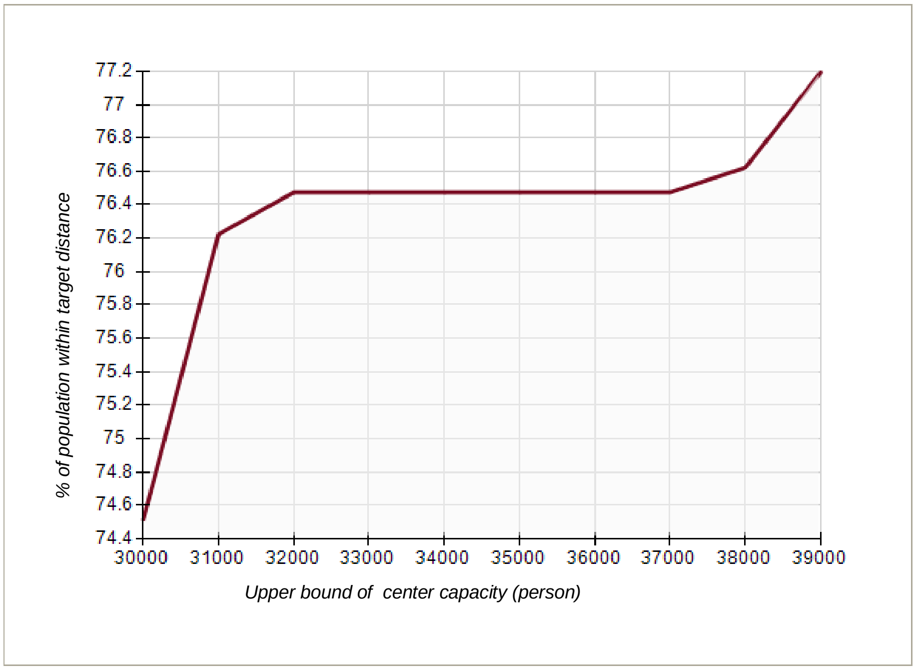


Figure (5-15) Sensitivity analysis result : the impact of changing the lower limit of capacity on the percentage of population within the target distance.



Figure(5-16) Sensitivity analysis result : the impact of changing the upper limit of capacity on the percentage of population within target distance.

5-4 Analyzing The Case Study Results:

This section aims at testing the research hypothesis regarding the added value of the proposed multiobjective decision-making framework. Therefore, a comparative analysis between the current proposal obtained by the conventional GIS-overly suitability process and that obtained by the proposed interactive multiobjective optimization process is conducted. Two aspects of comparison are considered: Comprehensiveness of results, and efficiency of the output as follows:

A. Comprehensiveness of the output:

This comparison tests the richness of the information derived from each process and whether the required output mentioned in the problem statement has been achieved.

As indicated in Table 5, the proposed approach based on multiobjective optimization with Goal Programming is more informative as it has achieved all required outputs, including accessibility information.

Table (5-5) Comparison between information derived from the processes

No	**Evaluation criteria**	**Conventional Approach (GIS overlay)**			**Multiobjective Approach**		
		Achieved	Partially achieved	Not achieved	Achieved	Partially achieved	Not achieved
1	Defining number of centers to be constructed	X			X		
2	Defining the location of centers by zone	X			X		
3	Defining the assignment pattern of population to each proposed center			X	X		
5	Quantifying accessibility (% of population within target distance)			X	X		

.

B. Efficiency of the Outcome (the quality of proposed distribution).

This comparison tests the extent to which both approaches have fulfilled the goals raised by stakeholders. In other words, it aims at testing the quality of the initial proposal and the proposal obtained through the multiobjective optimization approach.

As both proposals yield the same number of centers (6 centers) and same cost (36 million Dirham) the remaining criteria to be examined are:

(1) Accessibility: % of population with target distance from centers (3 km.)
(2) Efficiency of service: measured by the maximum upper and lower deviation values (d_{cap}^{+} , d_{cap}^{-}) from the optimal service capacity (30000 person/ center). The higher the deviation the lower the efficiency of service.

To compare the two proposals for healthcare centers distribution on equal terms, the capacity constraints of the current proposal (done by Dubai Municipality) has been relaxed to be between (27000-33000). Then the two proposals have been tested under the three scenarios of priorities as shown in Table (5-6).

Table (5-6). Comparison between the current and the proposed healthcare centers distributions.

	Scenario description.	**Conventional Approach** Dubai Municiplaity proposal			**Multiobjective Approach** Scenario 6 (selected during the interactive process)		
		Accessibility: % of population within target distance	Efficiency: Upper and lower deviation values		Accessibility: % of population within target distance	Efficiency:. Upper and lower deviation values	
			Max d_{cap}^{+}	**Max** d_{cap}^{-}		**Max** d_{cap}^{+}	**Max** d_{cap}^{-}
Scenario 1	Equal priority for accessibility and efficiency	63.6%	3000	3000	75.5%	2000	3000
Scenario 2	Higher priority for accessibility	70.1%	27700	14200	80%	21840	14200
Scenario 3	Higher priority for efficiency	63.2%	0	5130	73%	0	5130

The result reveals that the proposed framework outperforms the conventional approach :

- The distribution of healthcare centers as proposed by the multiobjective optimization approach provides better accessibility under all three scenarios.
- It also provides higher efficiency under the first and second scenarios and equal efficiency under the third scenario.

5-5 Discussions

In the light of the application presented in chapter, the effectiveness of the proposed multiobjective framework as a decision making tool for sustainable urban development can be concluded. The framework responds positively to the requirements raised in Chapter 1 as follows:

1- Simultaneous integration of sustainability objectives:

The proposed framework translates environmental, economic, and social objectives into explicit objective functions. This mathematical formulation allows the objectives to be addressed simultaneously and on equal bases.

2- Balancing conflicting sustainability objectives:

The framework promoted an interactive process through which stakeholders managed to trade-off between conflicting objectives (accessibility and efficiency) until a satisfactory solution is reached.

3- Stakeholder participation:

The proposed framework proved to be highly participatory at all the decision making stages. The interactive session proved to be a learning process through which stakeholders got more insights about various aspects of the problem and articulated their preferences. Throughout the process, many scenarios have been generating as a respond to "What if?" question raised by stakeholders. The framework worked as a platform for negotiation and discussion between stakeholders until reaching a consensus on a final solution.

4- Addressing Uncertainty:

Uncertainty has been addressed by conducting sensitivity analysis to check the robustness of the final solution.

5- Integrating indicators and benchmarks:

Problem-specific indicators have been developed through the process. The framework also integrated the benchmark obtained from a strategic planning level (the target distance to public facility).

Therefore, it can be concluded that the proposed multiobjective framework was an effective tool for supporting decision making in the context of sustainable urban development pertaining to the case study at hand.

5-6 Summary and Conclusions

- In this chapter, the proposed multiobjective framework is applied to support decision making for community facility planning.

- The literature review revealed that proper allocation of community facilities is very critical for achieving urban sustainability as it has direct impacts on economic, social and environmental aspects of urban sustainability and a powerful tool to guide growth.

- Conventional modeling approaches for allocating community facilities have been surveyed including *GIS-based overlay suitability*, G*IS-based multicriteria modeling*, and *location allocation modeling*. Advantages and limitations of each approach have been discussed.

- This case study responds to recommendations by recent literatures (e.g. Rahman S., and Smith D., 2000) to integrate the goal programming model within the planning process taking into account stakeholders preferences.).

- The proposed multiobjective framework has been applied in a real world decision making situation pertaining to achieving a sustainable location of healthcare centers in Dubai, United Arab Emirates. An interactive Goal Programming model has been formulated based on environmental, social, and economic concerns raised by stakeholders including efficiency of service, accessibility, development cost. The optimal locations are reached through an interactive process with stakeholders in a real institutional sitting. The quality of the output proved to outperform that achieved by a conventional GIS/overlay model. The output has been initially approved by the planning authority and considered for implementation. The main conclusion of this chapter is proving the research hypothesis regarding the effectiveness of the proposed multiobjective framework as an interactive decision making tool for sustainable urban development pertaining to the case study at hand.

CHAPTER 6

AN INTERACTIVE MULTIOBJECTIVE APPROACH FOR TRANSIT-ORIENTED DEVELOPMENT (TOD) PLANNING

This chapter aims at testing the proposed framework in a decision-making situation where the decision-maker is not available to interact with the planner at the design stage, which is quite often in planning practice. The framework is applied to a real-world case study pertaining to achieving a sustainable transit-oriented development (TOD) around metro stations in Dubai, United Arab Emirates. The purpose is to achieve the optimal intensification of land use and land use mix taking into consideration conflicting objectives of various stakeholders. A multi-objective optimization model is formulated and used to generate 20 non-dominated alternative solutions. An interactive tool has been developed by which the decision-maker can identify the alternative that reflects his preference. The tool also provides a platform for negotiation, communication during stakeholder meetings and conflict resolution..

6-1 Literature Review on Transit-oriented Development Concept

6-1-1 Definition

Transit-oriented development (TOD) is a popular planning approach toward achieving urban sustainability. Throughout literature review, TOD is referred to by a variety of names, including *transit-focused development*, *transit-based development*, *transit-supportive developmen*t, or *transit villages*. According to Dock and Swenson (2005) Transit-oriented development (TOD) is the functional integration of land use and transit via the creation of compact, walkable, mixed-use communities within walking distance (1/4 mile) of a transit stop or station. It focuses compact growth around transit stops, thereby capitalizing on transit investments by bringing potential riders closer to transit facilities and increasing ridership. These principles have been recognized by many literatures as an integral component of any endeavor to achieve a sustainable urban form. (Dock et al, 2005, Jen J., and Hsiao 2006, and Newman 1996).

6-1-2 History of the TOD concept

TOD is simply the 1990's branding of an old concept (Carlton, 2007). According to Newman (1996) people throughout urban history showed one characteristic that has shaped the morphology of our cities: they do not like to travel more than half an hour to major urban destination. This had caused three types of cities to develop as transportation technology has evolved towards greater speed and freedom **(Figure 6-1).** *The walking city* existed up till 1850 where all destinations can be reached on foot in half an hour and thus the city was rarely more than 5 km across with high density, mixed use and narrow streets. *The transit city* appeared later in the 19th century as the trains allowed faster travel therefore created sub-centers at the railway stations that are small "cities" with walking scale and medium density characteristics. The city spread over 20-30 km with rail lines met the city center. Then *The automobile city* spread after the second world war. Automobiles made it possible to develop in any direction, first filling between the train lines and then creating dispersed and isolated suburbs going out as far as 50 km. Town planning began separating functions by zoning which also increased travel distance and the city began to decentralize and disperse with much lower density. After 50 years of automobile-based growth such cities have spread to the limits of comfort car commuting. Automobile-based problems such as air pollution, traffic jam, urban sprawl, high accident rate, loss of public safety etc., have made the social, environmental and economic cost of development to be extremely high calling for new urban planning thoughts to take over.

As a reaction to the automobile based problem, Peter Calthorpe codified the concept of Transit-Oriented Development (TOD) in his publication "Sustainable Communities: A new Design Synthesis for Cities, Suburbs, and Towns" (1986). TOD became a fixture of modern planning when Calthorpe published "The New American Metropolis" in 1993. TOD has been defined generally as "a mixed-use community that encourages people to live near transit services and to decrease their dependence on driving." Calthorpe saw it as a neo-traditional guide to sustainable community design. Beyond its definition of built form, it was also a community design theory that promised to address a myriad of social issues. According to Carlton (2007), TOD has gained popularity as a strategy to address a number of urban problems and has become a fundamental element reshaping metropolitan Landscape for many cities by developing transit corridors (Figure 6-2).

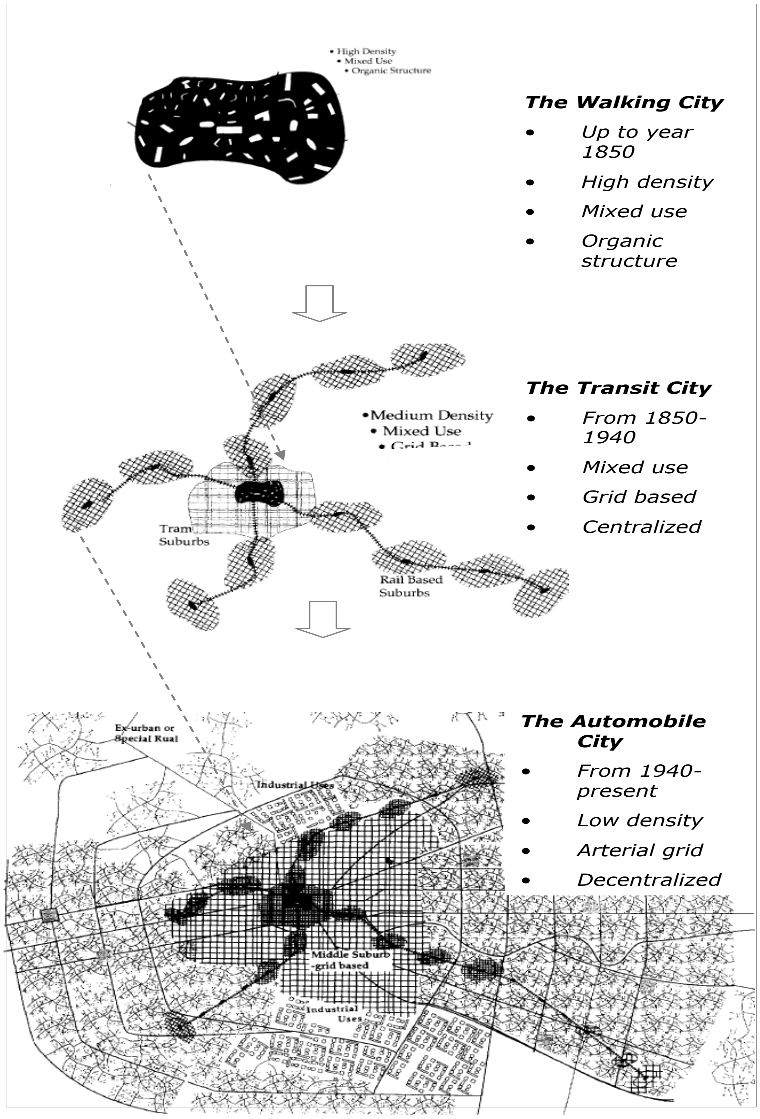


Figure (6-1) City shape and size influenced by transport technology
(Source: Newman and Kenworthy 1996).

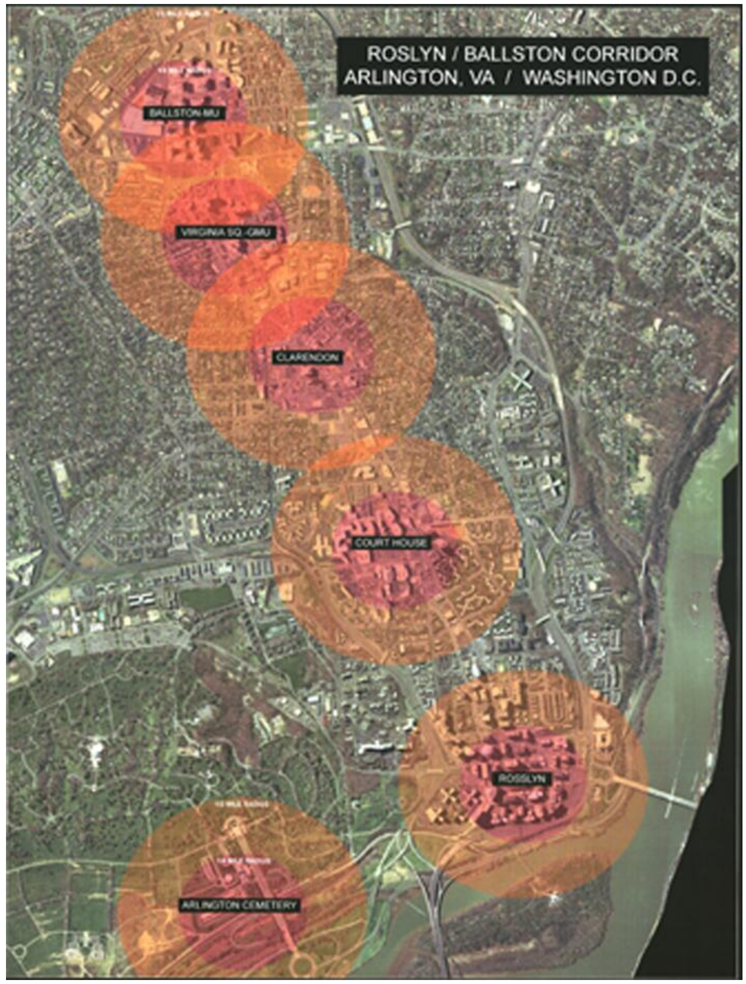


Figure (6-2)
Applying TOD on a metropolitan scale to reshape Rosslyn-Ballston transit corridor in Arlington, Virginia. High density, mixed use development is concentrated within ¼–½ mile from stations (shown in red), with limited density outside those areas. (source:Wikipedia.com)

6-1-3 TOD as a crucial element for urban sustainability:

TOD successfully addresses the three aspects of urban sustainability as follows:

Economic Benefits	***Increase transit ridership***	TOD improves the efficiency and effectiveness of transit service investments by increasing the use of transit near stations by up to 20 to 40 percent. (Parker et al 2002)
	TOD reduces infrastructure cost	Depending on local circumstances, TOD can help reduce overall infrastructure costs for expanding water, sewage and roads to local governments by up to 25% through more compact and infill development. (Parker 2002)
	Play a role in economic development.	TOD is increasingly used as a tool to help revitalize aging downtowns and declining urban neighborhoods. Increasing accessibility open up more investment and development opportunities to decapitated areas. (Dalryample 2002)
	Contribute to more affordable housing.	TOD adds to the supply of affordable lower-cost and accessible housing by reducing household transportation expenditures. Housing costs for land and structures can be significantly reduced through more compact growth patterns. (Dalryample 2002)
Environmental benefits	***TOD reduces air pollution and energy consumption rate***	By reducing auto dependence, TOD can lower rates of air pollution and energy consumption. Also, TODs can reduce rates of greenhouse gas emissions by 2.5 to 3.7 tons per year for each household. (Parker et al 2002)
	Conserve resource lands and open space	Because TOD consumes less land than low-density, auto-oriented growth, it effectively reduce urban sprawl and protect environmentally sensitive land. (Padeiro 2014, Dalryample et al 2002, and Newman 1996)
Social benefits	***Increase livability and pedestrian friendliness.***	TOD involves encouraging pedestrianzing old walking cores and building new walking –scale urban villages as people discover the joy of good pedestrian areas. (Newman 1996)
	Increase public safety.	By creating active places that are busy through the day and evening and providing “eyes on the street”, TOD helps increase safety for pedestrians, transit-users, and many others. (Parter 2002)

6-1-4 Crucial elements for TOD success:

Three major criteria are crucial for successful TOD. ***The "three Ds"***, as defined by Cervero (1996), are ***d**ensity, **d**iversity, and **d**esign*. These refer to the densities needed to sustain transit investment: diversity in the mixture of enriching land-use compositions, which creates a vibrant environment and decreases auto dependence; and design that enhances the quality of public environment, especially in the area of pedestrian access. These elements apply to the area within walking distance (1/4 mile) from a transit (rail or metro) station:

Density:

High residential and employment densities are key elements to increase transit ridership (Figure 6-3). Dense and compact TOD places a critical mass of people in a single location, providing the ridership numbers necessary to make transit feasible and efficient. High density offers three benefits to improve transit service: 1) routes to a relatively large number of points can be offered; 2) the cost per ride of operating transit is reduced when ridership increases; and 3) increased density allows transit service to be provided more frequently. According to Chen (2010), in Portland , Oregon, central city TOD has a transit share 4 times as high as that of outlaying TOD. When planning for TOD, densities will be gradually tapering down with distance from transit station. For example, according the TOD Guidelines for Portland Tri-Met requires residential densities (Dwelling units/acre) to be 30 within 1/8 mile from the station, 24 within 1/8 to 1/4 mile, and 12 within 1/4 to 1/2 mile (Chen 2010).

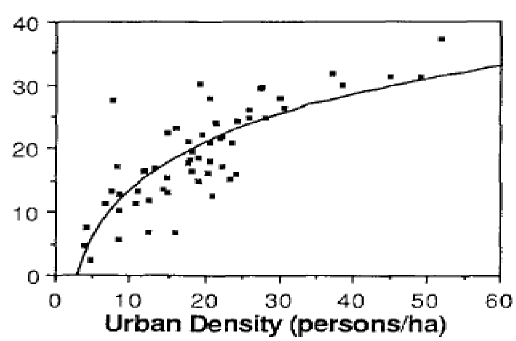


Figure (6-3). Urban density versus the proportion of workers using transit to work in Melbourne, (Source: Newman and Kenworthy 1996).

Diversity:

Mixed land uses contribute to the livability of the TOD district due to the presence of transit users and activities along the day which also add more safety, security and economic vitality. In addition, mixed land uses encourage more walking trips and internally capture vehicle trips (Evan et al 2007). Dalrymple (2004) recommended some general guidelines for land use within TOD area:

- At least half of the land within the TOD zone should be designated for housing;
- Affordable housing units should form 20% of the units within the TOD area;
- Automobile-oriented uses, including retail stores measuring over 50,000 square feet and warehouses and other low-employment-density facilities, are prohibited.

Design:

Parker (2002) provides some guidelines for successful urban design for TOD zone:

- Providing continuous and direct physical linkages between major activity centers; sitting of buildings and complementary uses to minimize distances to transit stops;
- Providing street walls of ground-floor retail and varied building heights, textures, and facades that enhance the walking experience;
- Integrating major commercial centers with the transit facility;
- Using grid-like street patterns that allow many origins and destinations to be connected by foot; avoiding cul-de-sacs or other arrangements that create circuitous walks;
- Minimizing off-street parking supplies; where land costs are high, placing parking under buildings or in peripheral structures;
- Providing such pedestrian amenities as attractive landscaping, continuous and paved sidewalks, street furniture, urban art, screening of parking, building overhangs and weather protection, and safe street crossings;
- Convenient sitting of transit shelters, benches, and route information.
- Creating public open spaces and pedestrian plazas that are convenient to transit.

6-1-5 Implementing TOD in Practice.

Applying TOD has been associated with the implementation of almost all light rail systems in North America and Europe. Overwhelming online resources for best practice can be found in (VTPI, 2008). In general TOD projects focus on the area within 400 m radius (5 minutes walking) around transit station. *A station area plan* is usually prepared for each station. The plan can foster one of the following strategies:

1- New development, often called *Transit Village,* designed based on TOD principles. The centerpiece of the village is the transit stations itself and the civic or public spaces that surround it and act as a gathering space. The station is surrounded be height density mixed used development and high quality pedestrian environment connecting passengers to the station. Transit village is the coming trend in community planning (Jacobson and Forsyth, 2008) . One of the best example is Fruitvale Transit Village at BART Station in Oakland (Figures 6-4, 6-5).

2- Retrofitting existing communities to promote transit ridership. This is often done by changing the zoning ordinance around transit stations toward higher density and transit supportive mixed land use (Figure 6-6). The zoning should be tailored to respect the unique setting of individual stations.

6-1-6 TOD as a Multi-objective Decision-making Problem.

In general, TOD studies are undertaken by planning authorities and involve the preparation of Station Area Plans covering a district within a 400 meter radius (5 minutes walking) around each transit station. A major task is to revise existing zoning ordinances to achieve more intensified and mixed land use. However, achieving a sustainable density and land use mix is a challenging task as it entails quite complex decision making. This process involves conflicting economic, social, and environmental objectives that arise from multiple stakeholders including governmental agencies, private businesses and community members. For example, increasing land use density may be advocated by real estate developers and transit agencies for potential economic benefits (e.g. higher development returns and transit ridership), while opposed by local residents as the quality of the living environment within the TOD area may decline with the increasing load on existing public facilities (Maplewood 2007). Another equity concern may arise with increasing density as property owners outside the TOD area are denied the right, granted to others inside the TOD area, to intensify the development on their lands and gain additional economic benefits. Apparently there is no single solution that can satisfy all objectives at the same time, as increasing one benefit typically decreases other benefits (Herath and Perto 2006). In such a context, a TOD planner needs an efficient procedure to generate a wide spectrum of feasible alternative solutions rather than a limited set of alternatives (Stewart et al. 2004), to explore the trade-offs between conflicting objectives, and to facilitate the negotiation and communication between stakeholders to achieve consensus on a compromise solution.

Although TOD planning strategies have been comprehensively studied, research on detailed TOD planning methods for assisting TOD planners remains insufficient. Li et al (2010), and Lin and Gau (2006) developed multi-objective optimization models for TOD planning in China and Taiwan. However, only a limited number of non-dominated alternatives were generated. Integrating the model within the planning process has not been addressed. In addition, the TOD planner has not been provided with a tool or a mechanism to facilitate stakeholder negotiation. The remaining of this chapter contributes to the field of TOD planning by introducing a procedure, underpinned by multi-objective optimization (MOO) and multi attribute decision making (MADM), to achieve a sustainable density and land use mix. While MOO is used to generate a wide range of Pareto-optimal alternatives to be presented to stakeholders, MADM is used to develop an interactive tool by which stakeholders can explore the solution space and investigate the trade-offs between objectives. It is also a platform for negotiation, communication, and conflict resolution during stakeholder meetings. The methodology has been applied to a real world case study pertaining to sustainable TOD planning around metro stations in Dubai, United Arab Emirates.

Figure (6-4).
The completed Fruitvale Transit Village in Oakland includes a mix of affordable housing, community services and retail space. It is connected to Fruitvale's commercial center via a popular pedestrian-only plaza. (Source: Chapple, Hickey, and Rao, 2007)

Figure (6-5).
Proposal of Al Nahda transit village in Dubai. Mixed use high density development directly connected to Dubai Metro station. (source: Dubai Municipality)

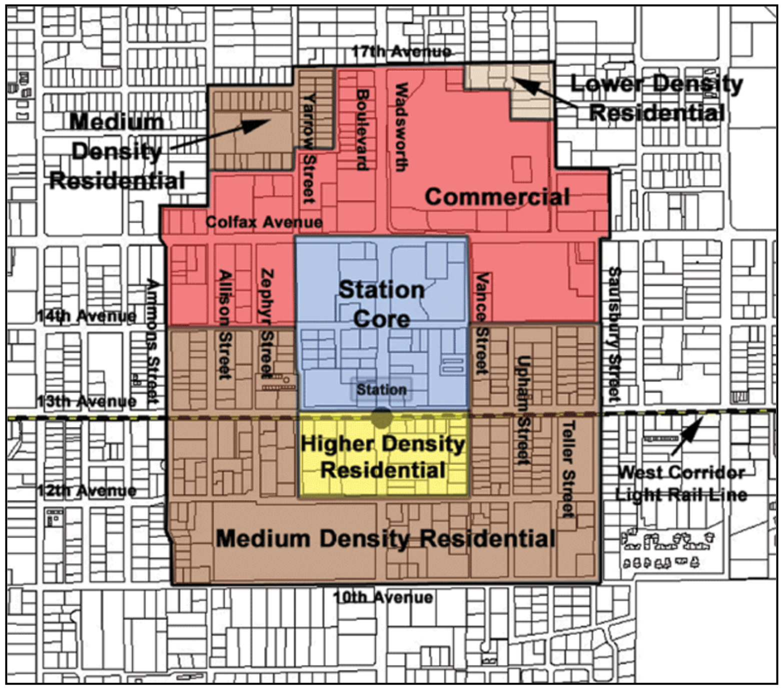


Figure (6-6). Special zoning ordinance to retrofit community around transit station in Denver (Source: http://www.thecprc.org/takings2.htm) [Accessed 12 Nov. 2012]

6-2 Application Of the Proposed Decision-making Framework.

6-2-1 The case study spatial context:

Through studies carried out since 1997, the Dubai Municipality has identified the need for a light rail system to relieve growing motor traffic associated with the rapidly growing population (expected to reach 2.8 million by 2020) and to support continuing urban development. In May 2005 the Dubai government started constructing a light rail network with a total cost approaching 730 million US $. The network consists of two main lines covering the heavily populated parts of the Dubai Urban Area. The red line is a 50 Km segment, connecting Dubai Business District CBD in the north with the new development to the south. The Green line is a 20 Km loop, connecting the business and activity centers around the CBD area (Figure 6-7). Dubai Metro has a total of 47 stations, including 9 underground. A specialized planning study titled *“PS007 Station Context*

Planning Study" (Systra 2004) has been conducted by Dubai Municipality, aiming at applying Transit-Oriented Development TOD principles to the area within walking distance (400m radius) around each station. Two main objectives have been defined for this land-use planning exercise:

(3) To intensify population and employment in order to increase metro ridership;
(4) To enhance pedestrian accessibility and connectivity between the community and the station.

To achieve the first objective the study has reviewed the current Dubai zoning code in order to investigate the possibility of increasing the allowable development densities for residential and commercial land uses. Development density is expressed in the zoning code in terms of Floor Area Ratio (FAR). FAR is the ratio of the total floor area of buildings on a certain plot to the area of this plot. For example, an FAR of 2.0 would indicate that the total floor area of a building should not exceed twice the gross area of the plot on which it is constructed. The study has applied a conventional planning approach including problem definition, data collection, identification of objectives and constraints with the help of various stakeholders and finally proposed three intensification scenarios for each station area. Each scenario represents a potential level of intensification (high, medium, and low intensification) and the associated economic and environmental consequences. The decision-maker, the governmental officials in Dubai Municipality Planning Department DMPD, will select between these three alternative scenarios. The major drawback of this approach is that it lacks the ability to test whether the presented alternatives are non-dominated. The very limited number of alternatives is also a significant limitation towards achieving a sustainable decision, as highlighted in Chapter 1.

Considering the serious and long term implications of changing land use density, the decision-making process should be well informed, transparent, and based on an awareness of all possible alternative actions. The following section presents the implementation of the proposed framework to Al-Nahda Station area, located on the Green Line of the Dubai Metro. The current zoning ordinance allows for mixed land uses around the station (residential, commercial, offices, and public facilities), as presented in Figure (6-8). The station area has been given a priority for TOD planning due to the availability of vacant lands and old housing plots that can be redeveloped based on the intensification proposals (Systra 2004).

In the following section, the proposed multiobjective decision-making framework is examined in the context where the decision-maker is not able to (or not willing to) provide preferences and value judgment prior to generating alternatives. The framework is applied in a real world case study pertaining to achieving a sustainable intensification of land use around metro stations in Dubai, United Arab Emirates. In this case, as presented in the shaded part of Figure (6-9), MOO is used to generate a wide range of Pareto-optimal alternatives to be presented to the decision-maker, while MADM is used to develop an interactive tool by which the decision-maker can explore the solution space and investigate the trade-offs between objectives. It is also a platform for negotiation, communication, and conflict resolution during stakeholder meetings. The result has been compared against that achieved by a conventional approach to prove the research hypothesis regarding the added value of the proposed decision-making framework. The framework proved to be capable of integrating the environmental, social, and economic considerations of various stakeholders, performing trade-off between conflicting objectives, providing decision-maker with comprehensive knowledge of possible solutions and integrating the decision-maker into the design stage. The framework can be easily automated into a practical Decision Support System DSS.

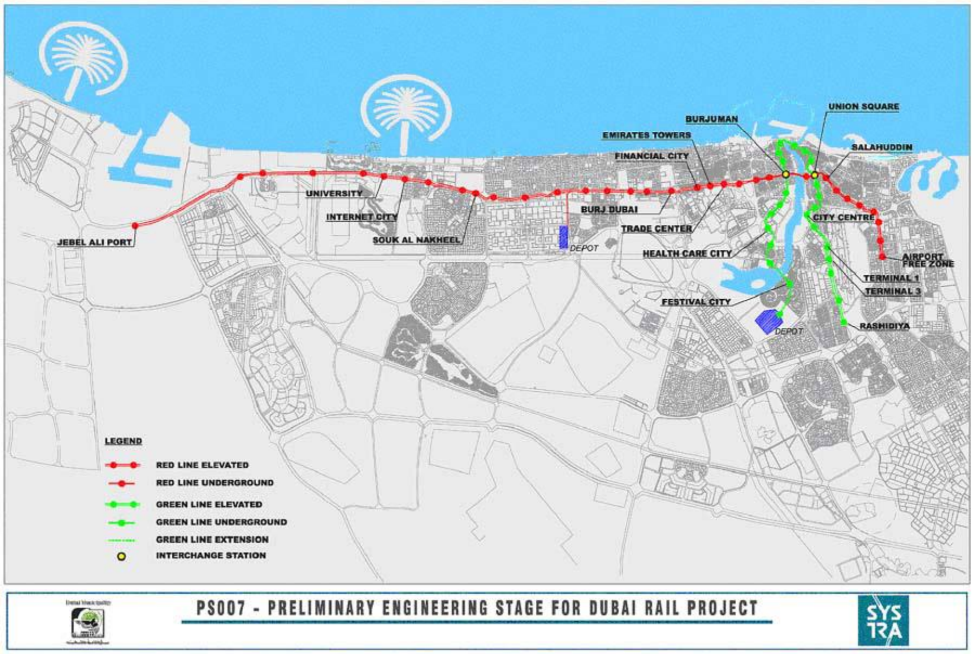


Figure (6-7). Dubai Metro Network. (source: Systra, 2004)

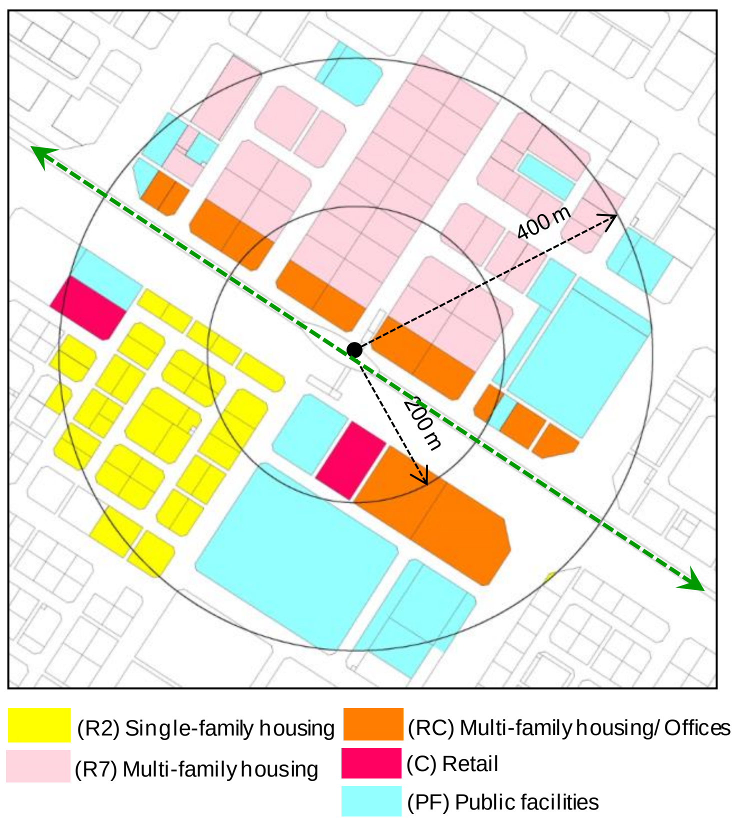


Figure (6-8). Current zoning map for the study area.
(source: Dubai Municipality, Planning Department)

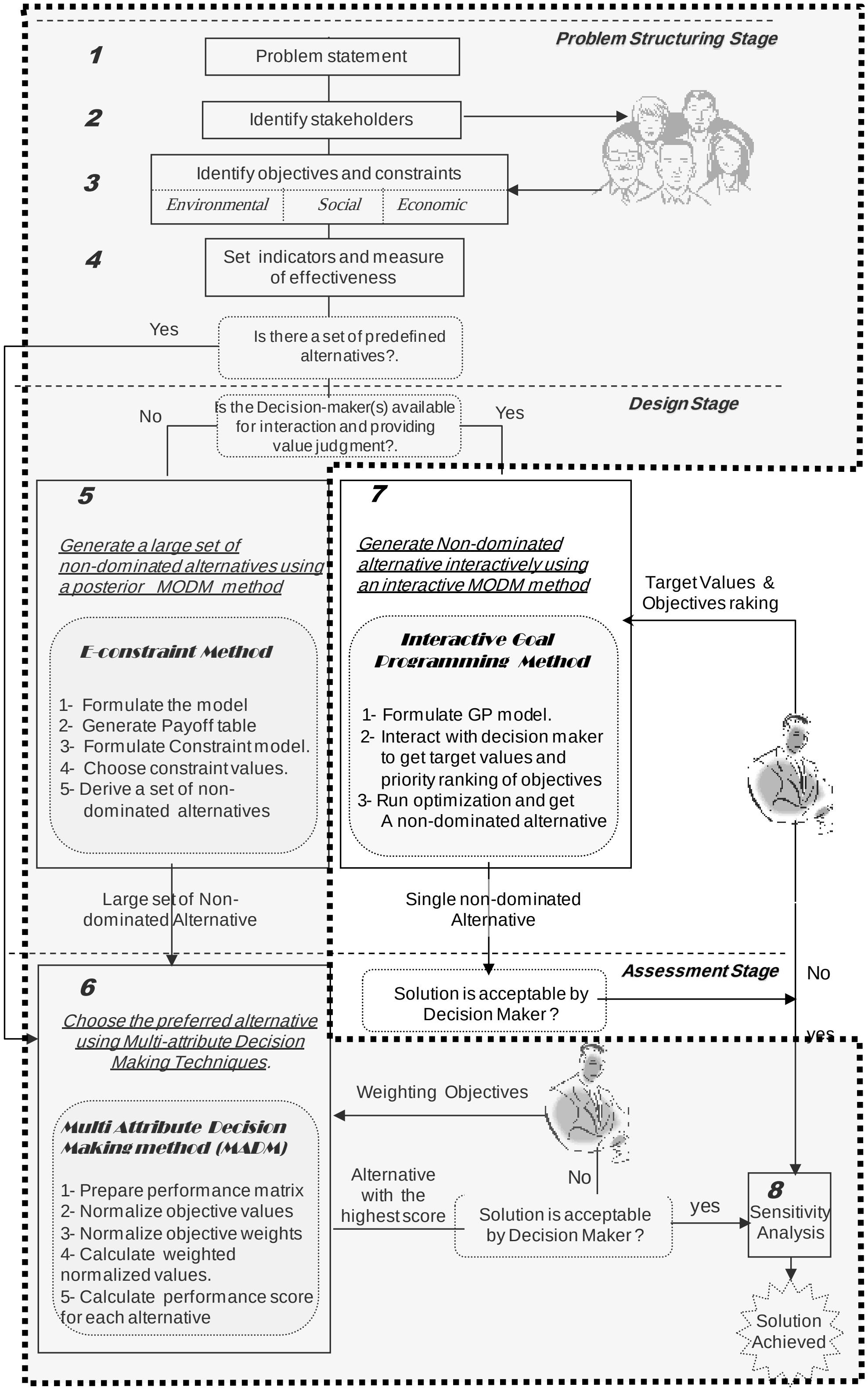


Figure (6-9). The proposed framework.

6-2-2 Details of decision-making process

<u>Step 1: Problem Statement</u>

To plan for transit-oriented development (TOD) of the area within walking distance (400 meters radius) from Dubai Metro stations, it is required to retrofit the existing planning regulations towards more intensified and mixed land uses. However, in order to progress towards sustainable TOD, the decision-maker at the TOD planning stage must comprehensively consider the trade-offs among three groups of objectives: economy, environment and equity. Therefore the purpose of the decision making process is to identify the following:

(5) The optimal increase in density of each land use (Residential and Commercial) in terms of increasing the allowable Floor Area Ratio (FAR).

(6) The optimal mix of land use (Residential and Commercial) in terms of percentage of floor space for each land use.

<u>Step 2: Identify Stakeholders</u>

Three stakeholders are directly concerned with the TOD planning:

(7) Roads and Transportation Authority (RTA): The RTA is responsible for constructing and operating the Dubai Metro;

(8) Dubai Municipality (DM): The DM is responsible for setting and implementing land use plans and planning regulations, controlling air pollution and providing basic infrastructure (drainage system, sewage system, and garbage collection);

(9) Residents of the TOD area: These are the people living and working within a 400 meter radius from metro stations;

(10) Property owners inside and outside the TOD area.

<u>Step 3: Identify objectives and constraints</u>

The following objectives have been identified by stakeholders. The same objectives have been considered by PS007 (2004) study for developing the current proposal. The objectives can be classified into three main categories: economic, environmental and equity as indicated in Table (6-1).

Table (6-1) Objectives and constraints imposed by various stakeholders.

Economic Objectives	
Objective 1	**Increase metro ridership**: This is the main concern of RTA as a Metro operator. DM also seeks to encourage metro ridership to reduce automobiles air pollution.
Objective 2	**Increase tariffs (tax revenues) generated from zoning changes**: This is a DM concern. DM collects marginal tariff from property owners who are seeking to increase the intensity of their development. The more the intensification, the more tariff generated.
Social Objectives	
Objective 3	**Maintaining equity and fair distribution of wealth:** This is a concern of property owners outside TOD as they are denied the rights, granted to others in the TOD area, to develop more floor space. The more the intensification inside the TOD area, the more the feeling of inequity.
Environmental Objectives	
Objective 4	**To enhance the quality of the living environment around the station:** This is a main concern for the residents of the TOD area, as increasing population density puts pressure on public facilities including parks, schools, etc, and therefore reduces the attractiveness of the area as a living environment.
Objective 5	**Creating identity and sense of arrival:** This is mainly a DM concern. DM is responsible for urban design, and aims to provide the TOD area with a unique identity and a strong sense of community.
Constraints:	
Constraint 1	**FAR bounds:** DM planning regulations set an upper bound of allowable density for each land use. The upper bound is usually curbed by the capacity of infrastructure networks in the area (water, electricity, etc.).
Constraint 2	**Capacity of public facilities in the district:** DM planning standards set upper and lower thresholds for the number of individuals served by each type of public facility. It is required not to exceed the upper limit.
Constraint 3	**The lower ridership limit**: RTA requires that a certain minimum level of ridership should be secured at each station to cover the operating costs for the Metro.
Constraint 4	**Lower limit of residential and office spaces in RC category:** DM planning regulations restrict changing the existing land use of any plots. It is allowed to change the land use mix by adding more floor spaces of either residential or office use without changing the use of the existing spaces.

Step 4: Setting indicators and Measures Of Effectiveness MOEs

MOEs provide scales to measure the performance of each alternative on all of the objectives specified in step 2. In this case study, the following MOEs have been defined as indicated in Table (6-2).

Table (6-2). Measures of effectiveness

Goal no.	**Measures of effectiveness (MOEs)**	**Unit**
Objective 1	Total number of metro trips generated from the TOD area per day.	Trips/day
Objective 2	Total tariffs generated from the TOD area.	Dirham
Objective 3	Rate of population served by each square meter of public facility land area.	Person/m2
Objective 4	The difference between the total FAR in the station area and the total FAR of nearby areas.	ratio
Objective 5	The ratio between floor space at the immediate vicinity of the station (200 m radius) and total floor space of the entire station area. It is assumed that a higher ratio will encourage creating higher landmark buildings close to stations and, therefore, contribute to achieving a distinct visual identity and a sense of arrival.	ratio

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Step 5: Formulating the model and generating large set of non-dominated alternatives.:

A- Notations and Symbols

The proposed model uses the symbols represented in the following table.

Variable, Constant, or index	**Description**
i	Index for alternative zoning category.
L_i	Land area for zoning category *i* (in square meters)
L_p	Land area for public facilities available in the station area (400 m radius from station)
$L_{p\text{-}district}$	Land area for public facilities available in the district

	(800 m radius from station)
L	Land area for the TOD area (= 502700 m2)
T_i	Trip generation rate for each zoning category (trip per m2 per day)
M_i	Metro modal split for each zoning category (%)
X_{ie}	Existing FAR for each zoning category.
$X_{i\text{-}upper}$	Upper bound of FAR for each zoning category.
V_i	Land value for each zoning category (Dirham per m2 of floor area).
P_i	Population rate per square meter of residential category (person/m2)
$P_{district}$	Existing district-level population (person)
$FAR_{district}$	The overall FAR for the district. (the ratio of total floor spaces of residential and commercial activities to total district area)
e	The lowest limit of intensification around each station required to sustain Metro operation (% of total existing floor space at station area)
Y_{ire}	The existing percentage of residential floor space to the total floor space of Residential/Commercial (RC) category. (%)
Y_{ice}	The existing percentage of offices and commercial floor space to the total floor space of Residential/Commercial category (%)

B- Decision Variables:

Two types of decision variables have been defined: variables that describe the proposed FAR values for each zoning category and variables that describe the percentage of both residential and commercial floor spaces in the RC category.

FAR related variables	**Description**
X_i	FAR for each zoning category i *($i = 1, 2, \ldots, 7$) where:*
$i= 1$	Residential zoning category type R2 (single-family detached villas)
$i= 2$	Residential zoning category type R7 (multi-storey

	apartment building) located inside the vicinity area (within 200 radius from the station)
i= 3	Residential zoning category type R7 (multi-storey apartment building) located outside the vicinity area..
i= 4	Residential/commercial zoning category type RC category (mixed residential and office building) located inside the vicinity area.
i= 5	Residential/commercial zoning category type RC category (mixed residential and office building) located outside the vicinity area.
i= 6	Commercial and retail zoning category type C located inside the vicinity area
i= 7	Commercial and retail zoning category type C located outside the vicinity area

Percentage related variables

Y_{ir}	Percentage of residential floor space to the overall floor space in RC category. (i = 4, 5)
Y_{ic}	Percentage of offices and commercial floor spaces to the overall floor space in RC category (i = 4, 5)

C- Formulation of objectives

Objective 1: Maximize Transit Ridership

Ridership is directly correlated with the magnitude and type of land uses around the station. The number of expected Metro passengers can be estimated based on total floor space, trip generation rate and modal split rate for each land use type. Therefore this objective can be formulated as such:

$$\text{Maximize} \quad \sum_{i=1}^{7} X_i L_i T_i M_i \qquad \text{[trips per day]}$$

Objective 2: Maximizing the generated tariff

According to Dubai Municipality regulations, in the case of increasing the FAR of any plot, the plot owner will be charged a minimal tariff recognizing the increase of land value. The tariff (in UAE Dirham) is calculated based on the following formula:

[The increase in floor space (m2)] [0.3] [land value] / [existing total floor space]

The same formula can be used in this model as follows:

Maximize $\sum (X_i L_i - X_{ie} L_i) 0.3\ V_i \Big/ X_{ie} L_i$ [Dirham]

Objective 3: Maintaining the quality of living environment:

As mentioned earlier, the living environment around the station has been quantified in terms of the quantity of public facilities on the neighborhood level (mainly open spaces and parks). Intensifying population will decrease the share of public facility area per person. Accordingly, this objective can be formulated as follows:

Maximize $\sum_{i=1}^{7} L_p \Big/ X_i L_i P_i$

The same equation can be presented in the following linear form:

Minimize $\sum_{i=1}^{7} X_i L_i P_i \Big/ L_p$ [person/m2 of public facility]

Objective 4: Maintaining Social equity:

Due to land use intensification, the owners of the properties inside the station area have the right to build more floor space which stimulates land value, while other owners do not have such a privilege. It seems unfair to create excessive differences between the station area and others in nearby areas. In other words, social equity increases with decreasing the absolute difference between development density in the station area and the overall development density of the district where it locates. This can be formulated as follows:

Minimize $\left| \left(\sum_{i=1}^{7} X_i L_i \Big/ L \right) - \left(FAR_{District} \right) \right|$ [ratio]

Objective 5: Creating Identity and science of arrival:

As explained earlier, the PS007 study (Systra 2004) considered that the vicinity zone (within a 200m radius from the station) is worthy of special consideration. It is assumed that a higher development density, compared to the outer zone, will encourage the creation of higher landmark buildings and add variety to the skyline closer to the station. These features contributes to creating distinct visual identity, orientation, and a sense of arrival to the station area (Puren 2007, and Tep1996). Prioritizing the vicinity area for intensification can be simply formulated as follows:

Maximize $\left(\sum_{i=2,4,6} X_i L_i \right) \Big/ \left(\sum_{i=1}^{7} X_i L_i \right)$ [m²]

<u>D- Formulating constraints:</u>

Constraint 1: FAR bounds

The proposed FAR for each zoning category should be within certain upper and lower bounds. The lower bound is the existing FAR for each category. In other words, it is not allowed to reduce the existing floor space of each category. The upper bound for each category is defined by the Dubai Municipality zoning documents. This constraint could be formulated as follows:

$X_{ie} \le X_I \le X_{i-upper}$ [ratio]

Constraint 2: Capacity of public facilities in the district:

The district-level population, after applying the proposed land use intensification, should not exceed the capacity of the district level-public facilities (schools, health centers, etc). Dubai Municipality planning standards has defined the unit share of community facilities on the district level to be between 0.3 – 0.5 m2 per person. The lower limit has been selected to allow for the maximum intensification. This constraint can be formulated as follows:

$$[(\sum_{i=1}^{7} X_i L_i P_i - \sum_{i=1}^{7} X_i L_i P_i) + P_{district}]\,(0.3) \leq L_{p-district} \quad [m^2]$$

Constraint 3: The lower ridership limit

A certain level of ridership is required to maintain the economic viability of the metro infrastructure. "PS007 Station Context Planning Study" (Systra 2004) has studied the holding capacity of all the communities surrounding the Metro lines and provided a recommendation for the minimum intensification level required at each station that maintains feasible ridership limits for Metro projects. Below this limit, it will not be justified to build a station at this location. This important parameter can be integrated into the model as follows:

$$\sum_{i=1}^{7} X_i L_i \geq e \sum_{i=1}^{7} X_{ie} L_i \quad [m^2]$$

Constraint 4: Lower limit of Residential and office spaces in RC category.

Proposed floor space for both residential and office activities in the RC category should not be less than existing levels. In other words, the model is allowed to only add various amounts of floor space for each activity without reducing what already exists. This constraint can be formulated as follows:

$$Y_{ir} X_i L_i \geq Y_{ire} X_{ie} L_i \quad \text{for i= 4, 5} \quad [m^2]$$

$$Y_{ic} X_i L_i \geq Y_{ice} X_{ie} L_i \quad \text{for i= 4, 5} \quad [m^2]$$

Constraint 5: Technical constraints:

These constraints define the limits of Y variables.

$$0 \leq Y_{ir} \leq 1 \quad \text{for each i= 4,5}$$

$$0 \leq Y_{ic} \leq 1 \text{ for each i= 4,5}$$

$$Y_{ir} + Y_{ic} = 1$$

Table (6-3) includes all input parameters pertaining to the case study at hand, the area around Al-Nahda Station in Dubai. The land-use related parameters (X_i, X_{ie}, $FAR_{district}$) were obtained by investigating the Dubai Municipality (2001) zoning ordinance report. Trip generation rates for each land-use were available from the Dubai Municipality (1999) trip generation and parking manual. P_i *and* $P_{district}$ *values* were *determined* based on data available from the Dubai Municipality (2010) Public Facility Standards Report. Other area-specific data (L_i, $L_{p\text{-}district}$, L_p, Y_{ire}, Y_{ice}) have been determined by consulting the Dubai Municipality GIS Department. The values of M_i and e are defined based on data available in Systra *(2004)*.

Table (6-3). Input parameters for the study area.

Zoning Category	Inside the priority zone (200 m radius from station)	***L**i* (m2)	*M*i (%)	*Ti* (trip/ day/ m2)	*Vi* (Dhs/ m2 of floor space)	*Xi*-upper	*Xie*	*Pi*
R2 residential **villas**		40750	20	1.01	1800	2	1	0.024
R7 residential apt.	yes	45000	30	0.62	2800	9	5	0.035
R7 residential apt	no	68770	30	0.06	2800	7	5	0.035
RC residential apt	yes	15500	30	0.62	2800	7	5	0.035
Office			30	1.5	2100	9	5	-
RC residential apt	no	18285	30	0.62	2800	7	5	0.035
Office			20	1.5	1210	9	5	-
C retail	yes	5000	30	4.5	3300	3	1.5	-
C retail	no	4550	30	4.5	3300	1.5	1	-

FAR district	1.27		*Yire*	70%
Lp-district	354620 m2		*Yice*	30%
Lp	101720 m2		*e*	1.1
Pdistrict	110400 person			

E- Generating a Set of Non-dominates Alternatives Using ε -constrained method.

E-1 Constructing a Payoff Table:

The first task is to construct a payoff table by optimizing the five objectives separately to the constraints to get the maximum and minimum values as indicated in Table (6-4). The first row, for example, shows the objective values when the first objective is optimized (single objective optimization). The optimization is repeated five times to optimize each of the five objectives separately. The last two rows show the maximum and minimum obtained values for each objective.

Table (6-4). The pay-off table.

	Maximize Ridership (Thousand trips per day)	Maximize Tariffs (Million Dirham)	Minimize load on public facilities (person/m2)	Minimize inequality (ratio)	Maximize Identity (ratio)
Max Ridership	272.0	234.2	10.8	0.93	0.48
Max tariff	257.6	260.3	10.8	0.93	0.46
Load on public facilities.	192.6	15.7	7.9	0.35	0.31
Inequality	192.6	15.7	7.9	0.34	0.31
Identity of space	259.0	254.6	10.8	0.93	0.49
Maximum Value	272.0	260.3	10.8	0.93	0.49
Minimum Value	192.6	15.7	7.9	0.34	0.31

E-2 Formulating a Constraint Model

The second task is to transform the multi-objective problem into a single objective problem using the ε-Constraint Method. In this case the maximized ridership objective is chosen as a primary objective and all other objectives are transformed as constraints. In other words, the multi-objective optimization is transformed to the following single-objective form:

Maximize (Ridership)

Subject to: (Generated Tariff) ≤ L1

(Quality of life) ≤ L2

(Equity) ≤ L3

(Identity) $\leq$ L4

Plus all other constraints in the original multi-objective problem.

The values of L1, L2, L3, L4 are chosen for the range of minimum and maximum objective values obtained in the payoff table. Twenty combinations of L values have been selected with equal intervals between the minimum and maximum values as shown in Table (6-5).

Table (6-5). The collected L values for 20 possible combinations.

Combination no.	Generated Tariffs (Million Dirham)	Loads on Public facilities (person/m2)	Inequality (ration)	Identity (ratio)
1	15.7	7.9	0.34	0.311
2	25.5	8.1	0.37	0.320
3	35.4	8.2	0.40	0.329
4	45.2	8.4	0.43	0.338
5	54.7	8.6	0.46	0.347
6	63.7	8.7	0.49	0.356
7	72.7	8.9	0.52	0.366
8	81.7	9.0	0.56	0.375
9	91.0	9.2	0.59	0.384
10	102.9	9.3	0.62	0.393
11	116.0	9.5	0.65	0.402
12	129.2	9.6	0.68	0.408
13	142.3	9.8	0.71	0.408
14	185.4	10.0	0.74	0.408
15	260.3	10.9	0.93	0.459
16	181.7	10.3	0.80	0.411
17	194.8	10.4	0.83	0.413
18	207.9	10.6	0.87	0.415
19	221.0	10.7	0.90	0.417
20	234.2	10.9	0.93	0.478

E-3 Deriving Non-dominated Solutions from the Model

The final task is to solve the constrained single-objective model by maximizing the ridership subject to all constraints for every combination of L values presented in Table 4. The optimization software (Risk Solver Platform Vs.95) was run 20 times, with each run including a different combination. The result is a set of 20 non-dominated solutions (alternatives), representing different levels of satisfaction. Tables (6-6) and (6-7) show the results from the 20 runs including the corresponding performance values for each objective and the decision variables. Table (6-6) constitutes the "Performance Matrix" required to start the selection stage.

Table (6-6). The Performance Matrix (objective values of 20 generated non-dominated alternatives).

Alternative Non-dominated Solutions	Metro Ridership (thousand Trip/Day)	Generated Tariffs (Million Dirham)	Load on public facilities (person/m2)	Inequality (ratio)	Identity (ratio)
Alternative 1	192.6	15.7	7.9	0.34	0.311
Alternative 2	199.6	25.5	8.1	0.37	0.320
Alternative 3	206.7	35.4	8.2	0.40	0.329
Alternative 4	213.7	45.2	8.4	0.43	0.338
Alternative 5	219.7	54.7	8.6	0.46	0.347
Alternative 6	224.4	63.7	8.7	0.49	0.356
Alternative 7	229.0	72.7	8.9	0.52	0.366
Alternative 8	233.8	81.7	9.0	0.56	0.375
Alternative 9	238.5	91.0	9.2	0.59	0.384
Alternative 10	242.9	102.9	9.3	0.62	0.393
Alternative 11	245.8	116.0	9.5	0.65	0.402
Alternative 12	248.7	129.2	9.6	0.68	0.408
Alternative 13	251.6	142.3	9.8	0.71	0.408
Alternative 14	254.5	185.4	10.0	0.74	0.408
Alternative 15	257.6	260.3	10.9	0.93	0.459
Alternative 16	260.4	181.7	10.3	0.80	0.411
Alternative 17	263.3	194.8	10.4	0.83	0.413
Alternative 18	266.2	207.9	10.6	0.87	0.415
Alternative 19	269.1	221.0	10.7	0.90	0.417
Alternative 20	272.0	234.2	10.9	0.93	0.478

Table (6-7). The decision variable values for the non-dominated alternatives.

Alternative non-dominated solutions	*X2*	*X3*	*X4*	*Y4r*	*Y4c*	*X5*	*Y5r*	*Y5c*	*X1*	*X6*	*X7*
Alternative 1	5.00	5.00	5.21	67.17	28.79	5.52	63.36	36.64	1.00	3.00	1.50
Alternative 2	5.00	5.00	5.83	60.01	39.99	5.67	61.69	38.31	1.00	3.00	1.50
Alternative 3	5.00	5.00	6.23	56.18	43.82	6.19	56.54	43.46	1.00	3.00	1.50
Alternative 4	5.00	5.00	6.63	52.80	47.20	6.71	52.18	47.82	1.00	3.00	1.50
Alternative 5	5.00	5.00	7.03	49.81	50.19	7.00	50.00	50.00	1.10	3.00	1.50
Alternative 6	5.00	5.00	7.42	47.14	52.86	7.00	50.00	50.00	1.33	3.00	1.50
Alternative 7	5.00	5.00	7.82	44.74	55.26	7.00	50.00	50.00	1.56	3.00	1.50
Alternative 8	5.00	5.00	8.22	42.57	57.43	7.00	50.00	50.00	1.80	3.00	1.50
Alternative 9	5.00	5.02	8.62	40.61	59.39	7.00	50.00	50.00	2.00	3.00	1.50
Alternative 10	5.02	5.15	9.00	38.89	61.11	7.00	50.00	50.00	2.00	3.00	1.50
Alternative 11	5.42	5.11	9.00	38.89	61.11	7.00	50.00	50.00	2.00	3.00	1.50
Alternative 12	5.68	5.17	9.00	38.89	61.11	7.00	50.00	50.00	2.00	3.00	1.50
Alternative 13	5.68	5.39	9.00	38.89	61.11	7.00	50.00	50.00	2.00	3.00	1.50
Alternative 14	5.68	5.62	9.00	38.89	61.11	7.00	50.00	50.00	2.00	3.00	1.50

Alternative 15	5.79	6.01	9.00	38.89	61.11	7.00	50.00	50.00	2.00	3.00	1.50
Alternative 16	5.87	6.18	9.00	38.89	61.11	7.00	50.00	50.00	2.00	3.00	1.50
Alternative 17	5.95	6.36	9.00	38.89	61.11	7.00	50.00	50.00	2.00	3.00	1.50
Alternative 18	6.03	6.53	9.00	38.89	61.11	7.00	50.00	50.00	2.00	3.00	1.50
Alternative 19	8.71	5.00	9.00	38.89	61.11	7.00	50.00	50.00	2.00	3.00	1.50
Alternative 20	7.88	6.14	9.00	49.70	50.30	7.00	78.57	21.43	1.00	3.00	1.50

E-4 Normalizing the objective values and generating value path graphs

In order to help the decision-maker to perceive the relative level of achievement for each objective, the objective values has to be measured on an equal scale. In other words, the values have to be normalized. One of the well known methods to do this is by transforming the objective values into 0 to 1 scale using the following linear functions (Prato, 2006, Fondazione Mattei, 2008):

For the objective with positive attribute values; in other words, if it is desirable to maximize the values (such as ridership, generated tariff, and identity values):

$$Z^* = Zp - Zp(min) /[Zp(max) – Zp(min)]$$

For objective values with positive attributes; if it is desirable to be minimize the values (such as inequality, and public facility load values):

$$Z^* = Z(max) - Zp/[Zp(max) – Zp(min)]$$

Where Zp = the value of objective (p) .

Zp(min), Z(max) are the minimum and maximum values

Z* = the normalized value

It should be noted that the last function converts the negative attribute values it positive attribute values. In other words, a higher the normalized value is more desirable whether the objective is minimized or maximized. The following table represents the normalized values for the non-dominated alternatives.

Table (6-8). The normalized objective values for the non-dominated alternatives.

Alternative Non-dominated Solutions	Metro Ridership	Generated Tariffs	Load on public facilities	Inequality	Identity
Alternative 1	0.00	0.00	1.00	1.00	0.00
Alternative 2	0.09	0.04	0.95	0.95	0.06
Alternative 3	0.18	0.08	0.89	0.89	0.11
Alternative 4	0.27	0.12	0.84	0.84	0.16
Alternative 5	0.34	0.16	0.79	0.79	0.22
Alternative 6	0.40	0.20	0.74	0.74	0.27
Alternative 7	0.46	0.23	0.68	0.68	0.33
Alternative 8	0.52	0.27	0.63	0.63	0.38
Alternative 9	0.58	0.31	0.58	0.58	0.43
Alternative 10	0.63	0.36	0.53	0.53	0.49
Alternative 11	0.67	0.41	0.47	0.47	0.54
Alternative 12	0.71	0.46	0.42	0.42	0.58
Alternative 13	0.74	0.52	0.37	0.37	0.58
Alternative 14	0.78	0.69	0.32	0.32	0.58
Alternative 15	0.82	1.00	0.00	0.00	0.88
Alternative 16	0.85	0.68	0.21	0.21	0.57
Alternative 17	0.89	0.73	0.16	0.16	0.59
Alternative 18	0.93	0.79	0.11	0.11	0.60
Alternative 19	0.96	0.84	0.05	0.05	0.63
Alternative 20	1.00	0.89	0.00	0.00	0.99

The normalized values are then used to plot a value path graph (figure 6) for each of the 20 non-dominated alternatives. Each alternative is represented by one individual line. It should be noted here that the value path of each non-dominated alternative crosses all other paths at least once since non-dominated solutions are incomparable. In other words, when comparing any pair of alternatives, each one performs better than the other for at least one objective (Cohon, 1978). This value path graph is an important tool by which the decision-maker can visualize all the alternatives and be informed about the relative performance of each alternative with respect to each objective. Xiao et al (2007) recommended that value path diagrams be an integral part of any spatial decision support system.

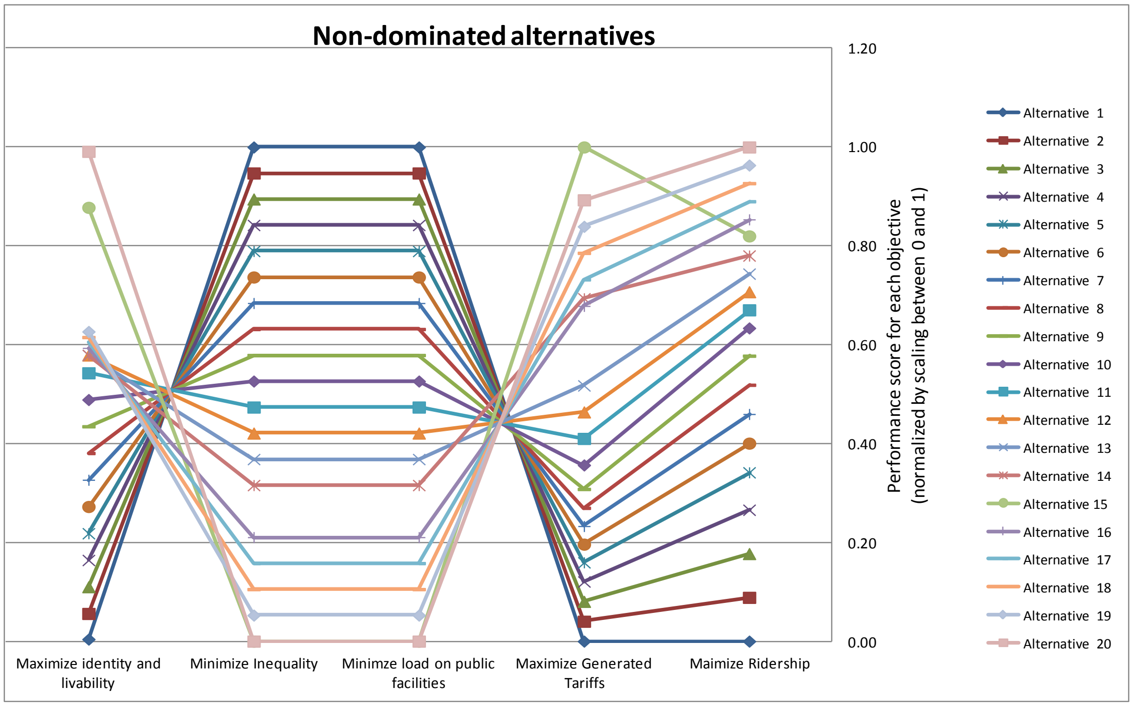


Figure (6-10). The value path graph for the 20 non-dominated alternatives.

6- Trade-off and choosing the preferred alternatives using interactive instrument.

The number of non-dominated alternatives in the Pareto set may be overwhelming to the decision-maker. Therefore, this research introduces an interactive and user-friendly instrument to assist the decision-maker in exploring the non-dominated alternatives and selecting the alternative that suits their preferences. The development of such a tool comes as a response to a recommendation from research in the field of multiobjective spatial decision making (Xiao et al 2007). With this instrument, termed the ***Decision-Making Slider,*** the decision-maker can identify the alternative that reflects his preference by defining the relative importance (weight) of each objective.

The ***Decision-Making Slider***, which is developed in Excel, facilitates modeling the relative importance of objectives using the *swing method* as well as calculating the final ranking of alternatives using the *Simple Additive Weighting SAW* method. As presented in Figure 7 the decision-maker can adjust the sliders to assign a raw weight from 0 to 100 to each objective. The weight is then normalized on a scale from 0-1 with a total weight of 1 for all objectives. This normalized weight reflects the relative importance of each objective. The normalized weights are then multiplied by the normalized objective values and summed up to achieve an aggregated performance score of each alternative. This aggregated performance score reflects how "good" the alternative is, considering the relative importance of objectives defined by the decision-maker. The Decision-Making Slider will automatically rank the alternatives based on the performance scores. The alternative with the highest score will be highlighted as the preferred alternative. Therefore, for each combination of weights the Decision-Making Slider will point to the optimal solution from among the Pareto set. This occurs in real time. The Decision-Making Slider is a useful, interactive and user friendly tool for decision-making for the following reasons:

(11) It gives the decision-maker the opportunity to explore the trade-off between various objectives by testing the result of various weighting scenarios simply by adjusting the raw weights using the side bars. ;

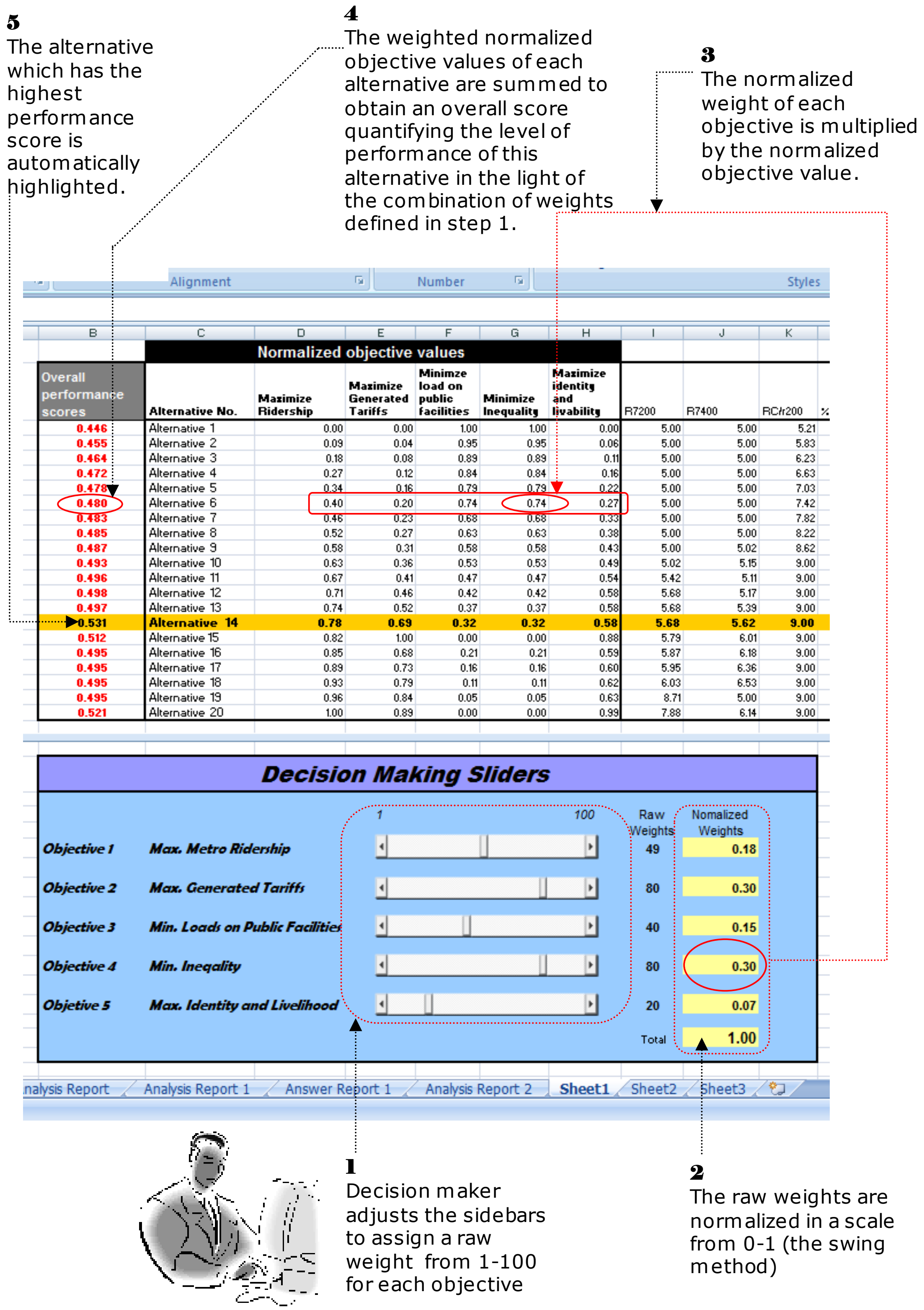
(12) The decision-maker gains a comprehensive knowledge of the problem at hand by identifying the alternatives that suit every stakeholder simply by adjusting the sliders to reflect the preferences of a particular stakeholder. Therefore, the decision-maker can investigate the optimal solution from the perspective of each stakeholder before coming up with a final decision;

(13) The Decision-Making Slider also promotes stakeholder participation in the selection process and provides a platform for communication, negotiation and conflict resolution. Every stakeholder is invited to explore the alternative that best suits his preferences. Stakeholders can then work together to reach a compromise solution. It is a common approach, in case of multi-stakeholder problems, to have major stakeholders agree on the weights assigned to objectives through open discussion (Feng, keller, and Zheng 2008). This can be achieved, for example, by integrating different weighting sets- by means of an arithmetic average- to obtain only one set of weights which expresses synthetically the points of view of all the involved stakeholders. The Decision-Making Slider can then be used to point to the compromise alternative;

(14) The Decision-Making Slider can be developed further into a full Spatial Decision Support System (SDSS), by extending its visualization capability. This can be done by transferring the data for each alternative (the values of the decision variables) to a suitable 3D visualization software (e.g. SketchUP V. 4). It would be then possible to develop a 3D impression for each alternative scenario as shown in Figures (6-12) and (6-13). The decision-maker can visualize the impact of his decision on the urban fabric and therefore can make a more informed decision.

7- Sensitivity Analysis

With the Decision-Making Sliders the decision-maker can check the sensitivity of any selected alternative to changes in weighting schemes by adjusting the raw weights on objectives. The decision-maker visually observe changes in the overall values of each alternative as he moves sliders for the raw swing weights on the objectives. If the rank of the selected alternative is less sensitive to change in weights this implies that the alternative could satisfy a wider group of stakeholders. The Decision-making slider provides a useful contribution to sensitivity analysis in decisions under certainty as there is relatively little discussion in literature on sensitivity analysis of weights (Feng, Keller, and Zheng (2008) .



B	C	D	E	F	G	H	I	J	K
	Normalized objective values								
Overall performance scores	Alternative No.	Maximize Ridership	Maximize Generated Tariffs	Minimze load on public facilities	Minimize Inequality	Maximize identity and livability	R7200	R7400	RC/r200
0.446	Alternative 1	0.00	0.00	1.00	1.00	0.00	5.00	5.00	5.21
0.455	Alternative 2	0.09	0.04	0.95	0.95	0.06	5.00	5.00	5.83
0.464	Alternative 3	0.18	0.08	0.89	0.89	0.11	5.00	5.00	6.23
0.472	Alternative 4	0.27	0.12	0.84	0.84	0.16	5.00	5.00	6.63
0.478	Alternative 5	0.34	0.16	0.79	0.79	0.22	5.00	5.00	7.03
0.480	Alternative 6	0.40	0.20	0.74	0.74	0.27	5.00	5.00	7.42
0.483	Alternative 7	0.46	0.23	0.68	0.68	0.33	5.00	5.00	7.82
0.485	Alternative 8	0.52	0.27	0.63	0.63	0.38	5.00	5.00	8.22
0.487	Alternative 9	0.58	0.31	0.58	0.58	0.43	5.00	5.02	8.62
0.493	Alternative 10	0.63	0.36	0.53	0.53	0.49	5.02	5.15	9.00
0.496	Alternative 11	0.67	0.41	0.47	0.47	0.54	5.42	5.11	9.00
0.498	Alternative 12	0.71	0.46	0.42	0.42	0.58	5.68	5.17	9.00
0.497	Alternative 13	0.74	0.52	0.37	0.37	0.58	5.68	5.39	9.00
0.531	**Alternative 14**	**0.78**	**0.69**	**0.32**	**0.32**	**0.58**	**5.68**	**5.62**	**9.00**
0.512	Alternative 15	0.82	1.00	0.00	0.00	0.88	5.79	6.01	9.00
0.495	Alternative 16	0.85	0.68	0.21	0.21	0.59	5.87	6.18	9.00
0.495	Alternative 17	0.89	0.73	0.16	0.16	0.60	5.95	6.36	9.00
0.495	Alternative 18	0.93	0.79	0.11	0.11	0.62	6.03	6.53	9.00
0.495	Alternative 19	0.96	0.84	0.05	0.05	0.63	8.71	5.00	9.00
0.521	Alternative 20	1.00	0.89	0.00	0.00	0.99	7.88	6.14	9.00

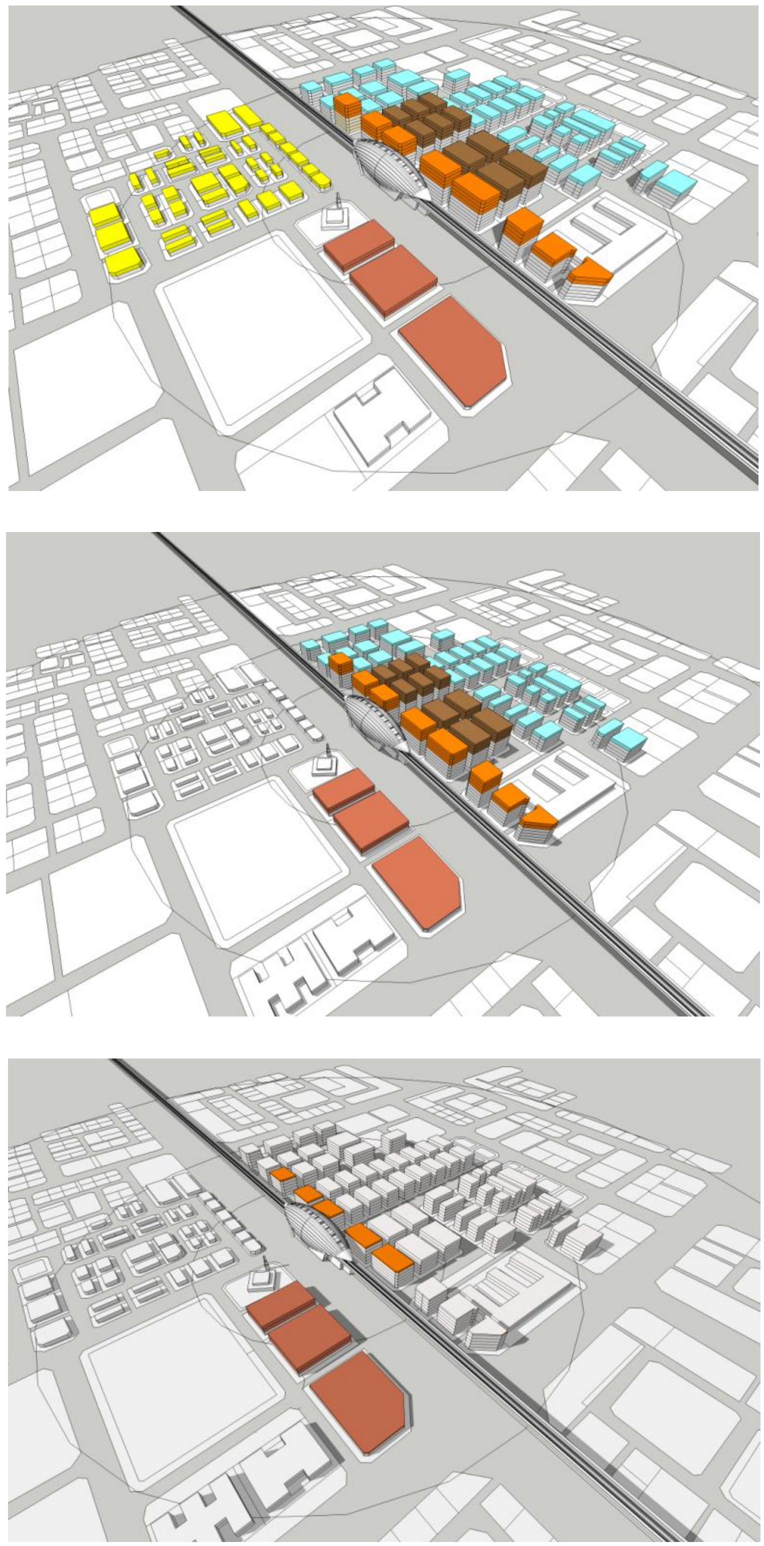
Figure (6-11). The Decision-Making Slider.

Existing condition

Minimum load on public facilities

Maximum Identity and livelihood

Fig (6-12) 3D visualization of some intensification alternative scenarios generated by transferring the model output to a graphic software (Sketch UP V.4) as a step toward building a full Spatial Decision Support System SDSS.



Maximum Ridership

Maximum Generated Tariff

Minimum inequality

Fig (6-13) 3D visualization of some intensification alternative scenarios generated by transferring the model output to a graphic software (Sketch UP V.4) as a step toward building a full Spatial Decision Support System SDSS.

6-3 Analyzing Case Study Results:

This section aims at testing the research hypothesis regarding the added value of the proposed multiobjective decision-making framework. Therefore, comparative analysis between the current proposal obtained by the non- modeling approach presented in Systra (2004) and that obtained by the proposed multiobjective framework is conducted. Two aspects of comparison are considered: *Comprehensiveness of results, efficiency of the output* and the *effectiveness of the decision-making process* as follows:

Comprehensiveness of the output:

This comparison tests the richness of the information derived from each process and whether the required output mentioned in the problem statement has been achieved. This comparison reveals the following:

- PS007 study considered increasing ridership as a main objective therefore presented three scenarios: *Minimum intensification scenario* limited by the lower acceptable holding capacity to justify a station at this particular location. And a_*maximum intensification scenario* based on the maximum acceptable increase that can be supported by the existing public facilities. The third scenario represented a *middle range of intensification*. The output was presented in terms or a cumulative FAR for all the land uses assuming equal level of increase among deferent land use.
- The multiobjective optimization model provides far richer information including 20 intensification scenarios, defining the intensification level of each land use type and quantifying the level of performance of each alternative pertaining to each objective.

Therefore the modeling approach is more informative and provide the decision-maker with more insight on the problem. However, it requires more time and expertise.

The Effectiveness of the decision-making process

In the light of the application presented in this chapter, the effectiveness of the proposed multiobjective framework as a decision-making tool for sustainable urban development can be concluded. The framework responds positively to the requirements raised in Chapter 1 as follow

1- Simultaneous integration of sustainability objectives:

The proposed framework translates environmental, economic, and social objectives into explicit objective functions. This mathematical formulation allows the objectives to be addressed simultaneously and on equal bases. This explicit integration of objectives was lacking in the scenario (non-modeling) approach.

2- Balancing conflicting sustainability objectives:

The Decision Making Slider allows the decision-maker to explore the trade-off between sustainability objectives based on his view regarding the relative importance on each objective. The scenario (non-modeling) approach limits the trade-off as only few alternatives are generated.

3- Stakeholder participation:

The proposed framework proved to be ***highly participatory*** for the following reasons:

- It allows for stakeholders objectives to be explored, quantified into clear measures of effectiveness and to be formulated as an objective function.
- A wide range of high quality (non-dominated) alternatives has been generated within which each stakeholder most probably find the alternative that suits his preference.
- The decision-making slider provides a platform for communication, negotiation and conflict resolution among stakeholders. Every stakeholder is can explore the alternative that best suits his preferences and then they can work together to reach a compromise.

4-Addressing Uncertainty:

Uncertainty of alternatives to changes in decision-maker preference is easily facilitated by the Decision-making Slider.

5- Integrating indicators and benchmarks:

Problem-specific indicators have been developed at the problem structuring stage by translating the objectives into clear measures of effectiveness (step 4). These indicators have been used to quantify the performance of each alternatives (performance indicators.

Therefore, it can be concluded that the proposed multiobjective framework satisfies the requirements specified in chapter 1. It can therefore be considered as an effective tool for supporting decision-making in the context of sustainable urban development pertaining to the case study at hand.

6-4 Summary and Conclusion

- This chapter aims at testing the proposed framework in a decision-making situation where the decision-maker is not available to interact with the planner at the design stage, which is quite often in planning practice. The case study aims at achieving a sustainable transit-oriented development (TOD) around a metro station in Dubai, UAE. The purpose is to achieve the optimal intensification of land use and the optimal land use mix taking into consideration the conflicting objectives raised by stakeholders.

- Literature review reveals the significance of this case study for two reasons: the importance of TOD for achieving urban sustainability and the lack of research addressing the integration of optimization in planning process for TOD.

- The application begins with the problem structuring stage where the problem statement is defined, stakeholders are identified and related social, environmental, and economic concerns were investigated. Five objectives need to be balanced: Increasing transit ridership, increasing municipality revenue, maintaining the quality of life around stations, maintaining equity, and promoting the sense of arrival. Measures of effectiveness (performance indicators) have been developed for each objectives to be used for evaluating alternatives.

- As the decision-maker is not available to reveal his preference at the design stage it is the planner responsibility to develop a wide range of high quality alternatives to be presented to decision-maker at a later stage. Therefore a *multi objective optimization model* has been formulated and used to generate 20 non-dominated alternatives. to be presented to decision-maker.

- To assist decision-maker in the selecting an optimal alternative that reflect his preferences a Multi-attribute Decision-making MADM process has been applied including developing the performance matrix and normalizing performance values. At this stage The decision-maker should interact with the model to reveal his preferences (relative importance of each objective). To facilitate the interaction process this research introduces an interactive instrument (developed in Excel) by which the decision-maker assigns weight to each objective and identify the alternative that reflects his preference. Using this tool (called The Decision-making Slider) the decision-maker can investigate the trade-off between various objectives. This tool is also a platform for communication and negotiation between stakeholders. It can also be developed to a full Spatial Decision Support System SDSS. The development of the Decision-making Slider is an important contribution of this research responding to recommendations of resent publications in the field (Xiao et al 2007).

- By testing the output against that obtained by a conventional approach the framework proved to be very informative.

- The main conclusion of this chapter is proving the research hypothesis regarding the effectiveness of the proposed multiobjective framework as an interactive decision-making tool for sustainable urban development pertaining to the case study at hand.

CHAPTER 7

DISCUSSION AND RECOMMENDATIONS

This chapter synthesizes the main conclusions and recommendation of the research. It also highlights potential future research in the area of decision-making and decision support systems for urban sustainability.

7-1 Proving The Research Hypothesis:

The main result of this study is proving the research hypothesis as rephrased in Chapter 4:

The proposed decision support framework which incorporates the capacity of both Multi-attribute Decision-making (MADM) and Multi-objective Decision-making (MODM) techniques into the planning process can satisfy the prerequisites for successful decision-making in the context of sustainable urban development.

This hypothesis has been tested through the application of the decision-making framework to two real world urban planning problems facing a public sector planning agency (In the Dubai Municipality). The results, in both cases, were superior to those achieved by conventional planning approaches.

7-2 Main Research findings:

- The main objectives of the study have been achieved through developing a decision support framework that integrates the capabilities of two powerful analytical tools; Multi-objective Decision-making MODM as a tool for generating a wide range of alternatives and Multi-attribute Decision-making as a tool to evaluate and rank the alternatives based on the decision maker's preferences. These tools have been organized in a structured and participatory process starting from identification of objectives and sustainability indicators with the help of stakeholders, generating non-dominated alternatives and finally allowing the decision maker to trade-off between alternatives to reach a satisfactory solution.

- The framework promotes the specific role of every participant in the process including the *planner* who conducts the analysis (the modeling) without imposing any preferences or judgment, *the decision maker* who provides value judgment regarding the relative importance of objectives and is therefore responsible for the final decision, and *stakeholders* who provide their environmental, social, and economic concerns. In some cases the stakeholders are also the decision-maker.

- The applied studies confirmed that the proposed framework supports decision-making in the context of planning for urban sustainability by responding to the following general requirements proposed by researchers and practitioners in this field:
  1. Integrating stakeholders objectives and values into the analysis;
  2. Incorporating sustainability indicators and benchmarks into analysis;
  3. Simultaneous integration of a large number of multi-disciplinary objectives with incommensurable measures into the design and evaluation process;
  4. Generating a wide range of high quality alternatives;
  5. Facilitating the stakeholder's and/or decision maker's interaction and involvement into the design stage by responding to "What if?" question;
  6. Providing the means to decision makers to trade-off between competing alternatives until reaching a satisfactory solution;
  7. Ensuring robustness of the preferred alternative through conducting sensitivity analysis;
  8. Facilitating negotiation and communication between stakeholders;
  9. The process is transparent, explicit, provides audit-trail and is open to scrutiny by all interested parties;

- The applied studies presented in this research prove that the proposed framework is a flexible tool that can be adopted to solve a variety of problems pertaining to urban sustainability.
- The proposed framework proved to be practical in dealing with different decision-making situations as follows:
  - It has been applied to generate and evaluate alternatives in the presence of decision-makers (and stakeholders) through interactive sessions. This is particularly important in public policy planning context;
  - It has also been applied in the case where the decision maker is not available for interaction, which is quite prevalent. In such a case, the planner generates a wide range of high quality alternatives to ensure addressing all possible solutions to be presented to the decision maker at a later stage.

- Multi-objective Decision-making MODM, proved to be a powerful tool for generating high quality alternatives in an urban context. This methodology helps the decision maker to focus on non-dominated alternatives by screening out the less qualified alternatives (dominated alternatives). In addition, instead of generating a limited number of alternatives, as in conventional planning approaches, the mathematical optimization models can generate a wide spectrum of non-dominated alternatives for consideration.

7-3 Limitations of the proposed framework:

- Multi-objective decision-making (MODM) is oriented toward solving continuous types of problems which have an infinite number of possible alternatives. Alternatives for discrete problems need to be defined outside the framework.
- Mathematical modeling is oriented toward solving quantitative types of problems. Problems with qualitative dimensions such as esthetics and cultural values cannot be solved unless there is a way to reasonably quantify the objectives.

- Mathematical modeling best suits tactical and operational types of problems. Strategic problems which require visionary solutions are best addressed by other solution techniques.
- There are some technical limitations in the selected methods. For example, with Interactive Goal Programming there is no guarantee that the achieved solution is non-dominated. The analysis stops when a satisfactory solution is achieved.
- The framework is oriented to deal with uncertainty only in input values which can be addressed by sensitivity analysis. In other words, the framework deals with deterministic problems where there is only one output for a given input. In case of probabilistic or stochastic problems, where there are many possible outputs for a given input, other techniques such as fuzzy set analysis could be applied but is considered outside the scope of this study.

7-4 Research Contributions:

This research contributes to many fields as follows:

1- It contributes to the field of planning for urban sustainability by providing a practical, flexible, and tested decision support framework which can be applied to solve a variety of planning problems with multiple and conflicting objectives and multiple stakeholders with opposing views. According to Hearth and Prato, (2006) there is a dearth of tested methodologies in this field;

2- It contributes to the field of public facility planning. The case study presented in this research responds to recommendations in the literature (Rahman S., and Smith D., 2000) to improve public facility planning through integrating a goal programming model within the planning process to take into account stakeholders preferences;

3- It contributes to the field of multi criteria decision-making by responding to recent literature in this field (Xiao et al , 2007 and Lotove 2004) which called for developing an interactive and user-friendly tool to facilitate trade-off between objectives based on the decision maker's preferences. The Decision-making Slider developed within the applied part of this research responds to this recommendation;

4- This study stresses the importance of mathematical modeling as an essential skill for practicing planners. It also provides a practical example of how modeling can be implemented within an Excel environment without the use of any programming language.

7-5 Recommendations for Further Research:

The study opens the door for further research to enhance the capacity and practicality of the proposed framework. The streams of future research could include the following:

1- The integration of GIS within the modeling process to generate a full Spatial Decision Support System SDSS;
2- Replacing the classical e-constraint method with a more advanced evolutionary method such as the Genetic Algorithm in order to generate larger numbers of alternatives in less time;
3- To enable parameter uncertainties, the framework may be extended, to incorporate fuzzy or grey programming, in the future;
4- To automate the modeling process with user interface and additional visualization of the outputs;
5- To further test the framework in solving additional planning problems in various contexts.

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