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Application of Multi-Criteria Analysis to Urban Land-Use Planning

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Risk, Modeling and Policy

Contents

Abstract

It is generally agreed that developed countries should reduce their energy consumption, which directly and indirectly causes climate change and other global issues. Therefore, it is necessary to improve urban land-use planning in order to decrease energy consumption while maintaining a desirable lifestyle, although optimization of urban land-use is difficult because it includes many conflicting objectives. Multi-criteria model analysis can be used to help analyse such complex problems. In such an analysis, decision variables are the shares of floor area allocated to a certain type of building and at a certain type of district. 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. After the case study using the test data set of Tokyo, I obtained the following results. This analysis can help to plan the adequate urban land-use that solves various trade-offs between conflicting objectives.

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1. Introduction

1.1 Background

The increase of energy consumption is one of the key problems in global issues. It causes climate change, air pollution, radioactive waste, the shortage of resources and other global issues. The increase is predicted to appear in urban area especially in developing countries, as well as population growth. The difficulties of international agreements for reduction of CO_2 emission mostly come from the insufficiency of reduction measures except for the improvement of productive efficiencies. It is said that the renovation of social systems is required. It is important to illustrate the desirable and agreeable urban land use planning as the measure to reduce energy consumption in urban areas.

a) Contribution of urban areas to total energy consumption

One of the population projections [i] says that the world population will be 9.9 billion in the year 2050. Most of the people will live in urban areas of developing countries. People living in urban areas generally demand more energy, because they have a higher living standard than others living in rural areas. Therefore, considering the structure of and the lifestyle in urban areas is important in order to solve various environmental issues.

In 1990, the CO_2 emissions from the residential and commercial sector including the emissions for constructions sum up to 36% of total CO_2 emission in Japan [ii]. After adding the emission from the transportation section [iii] of 23% to that percentage, about 60% of total CO_2 are related to urban activities. Furthermore, this percentage does not include the indirect energy consumption that comes from purchasing furniture and items for daily activities.

Of course, people in developing countries should be supplied what they demand, because it requires more energy to meet the demands of developed countries. Developed countries should be good models to reduce the energy consumption in urban areas.

b) Agreement for reduction of energy consumption

It seems unfair that some developed countries in the negotiation for prevention of climate change claim that they have difficulties reducing energy and that the responsibilities and the burden for reducing energy consumption should be taken by developing countries. However, people of developed countries should make agreements in their own countries to reduce the energy consumption. In fact, situations have changed recently. It becomes acceptable for the public of developed countries to have responsibility and burden in order to maintain the global environment [iv].

c) Possibilities of reducing energy consumption in urban area

Most methods for reducing energy consumption aim at improving the efficiencies of systems: power plants, automobiles, electronic appliances and so on. This analysis attempts to improve urban land use planning in order to reduce energy consumption while maintaining the desirable level of our lifestyles. Densities of volumes of floor serve as representative indices of urban activities and therefore they are controlled in order to achieve the desirable levels of plural objective functions.

d) Method of Analysis

Modeling of urban land use is difficult because the real land use includes a large number of variables and the complex relationships among them. A single criteria optimization method is not applicable because its application typically results in the recommendation of extreme (either on a lower or on an upper bound) land use as a solution. Therefore, I have chosen Multi-Criteria Analysis as a tool for this analysis because it has good features to consider conflicting objectives.

1.2 Objectives

The purpose of this paper is to illustrate a desirable urban land-use planning using Multi-Criteria Analysis (MCA). In this analysis, the criteria of the desirable urban land-use are: minimizing Energy Consumption, maximizing Open Space and minimizing Urban Area. The last criterion implies maximization of Agricultural and Natural Area. Multi-Criteria Analysis is a good tool to find the agreeable solutions with respect to these conflicting objectives.

2 Urban Land Use Planning Model

This chapter shows the formulation of urban land use planning models. Multi-Criteria Analysis can deal with many conflicting objectives simultaneously. Currently available software requires the model of urban land use planning to be a linear programming model.

2.1 Assumptions

The following basic assumptions have been adopted for the urban land use model specification. First, the total volume of floor area is given. In this context, floor area means an amount of space used for residences, shops, offices, and so on. It is not necessary to determine the precise volume of floor area because most outcome variables are shown as the values per floor. The population scale treated by this analysis ranges from 10 thousand to 1 million.

Second, differences of urban land use are described as the height of the building and the area of districts prepared for the building. They mean the rate of the floor area to the building area, and to the district area, respectively. However, the decision variables are the shares of floor areas allocated to certain building types in certain district types. So the functions become linear, even if the relationship between the height (or the district areas) and outcome variable is non-linear. It should be noticed that the non-linear relationship is dealt with in form of parameters for each variable.

Last, the locations of each land use are not taken into consideration because the functions would become non-linear and such functions are not handled by MCMA. Neither the differences of the land use, such as residence and business, are taken into consideration for the same reason. These functions will be dealt with later.

2.2 Decision Variables

The decision variables of the model are the share of the floor area to be allocated to the building type *i* at the district type *j*. Let these be denoted by x_{ij}, where *i* is the index of a building type and *j* is the index of a district type. Since the total volume of floor areas is given, the following constraint should hold:

$$\sum_{j\in J}\sum_{i\in I} x_{ij} = 1 \qquad (1)$$

where *I* is the number of types of buildings and *J* is the number of types of district.

2.3 Model Description

This section shows the list of variables considered for reducing the urban environmental load, especially energy consumption, while maintaining the comfortable lifestyles. The first part describes the functions of the urban environment model, the second part describes the variables related to the densities of urban land-use which will be included in the core model.

The following variable is about energy consumption:

$$Energy = \sum_{j\in J}\sum_{i\in I} e_{ij} x_{ij} \qquad (2)$$

where e_{ij} is an energy coefficient. The energy consumption is defined by energy related to building and energy for transportation as follows:

$$e_{ij} = c_h + t_u$$

where c_h is an energy coefficient related to buildings of a given building type (per unit floor) and t_u is an energy coefficient for transportation of a given district type (per unit floor).

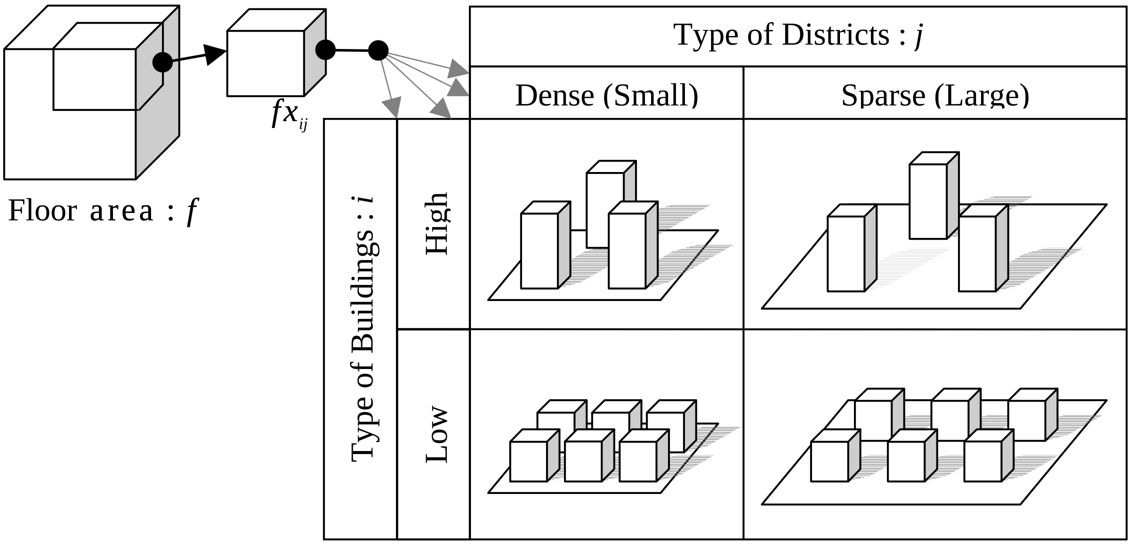

Figure 1: Concept of the type of buildings and the type of districts

The building types are different in the height shown with the number of the floor h_i as illustrated in Figure 1. The height of the building equals the ratio of the floor area to the building area. Its reciprocal is the ratio of the building area to the floor area.

The district types are different in the extent of areas shown as the Floor Area Ratio. The Floor Area Ratio is one of the frequently used terms in urban planning, which is the ratio of the floor area to the district area. The parameter u_j is the reciprocal of the Floor Area Ratio. This decision variable x_{ij} is determined in the height of buildings and the area of the district but the number of individual buildings.

The equation(2) is derived from the following relation:

$$Energy = \sum_{j \in J} \sum_{i \in I} e_{ij} fx_{ij} / f$$

where f is the total floor area that is given and fx_{ij} is the floor area allocated to building type i at district type j. The value of this variable shows the energy consumption per floor area. It should be noted that the value of these variables is shown as the value per floor area.

The following equation is about open spaces in urban areas:

$$OpenSpace = \sum_{j \in J} \sum_{i \in I} (u_j - 1/h_i) x_{ij} \tag{3}$$

Multiplied by the volume of floor, $1/h_i$ and u_j become the building area and the district area respectively. This function roughly shows the rest of the building area as open spaces. As discussed later, this estimation of open spaces includes various types of open spaces.

The following equation is about urban areas:

$$UrbanArea = \sum_{j \in J} \sum_{i \in I} u_j x_{ij} \tag{4}$$

It means at the same time maximizing agricultural and natural areas.

It should be noticed that u_i and h_j are parameters given as a data file. So these equations are the linear functions of x_{ij}.

The following shows a detailed description of each variable.

a) Energy for Construction

The energy related to buildings consists of the energy for construction of buildings and energy of households. These should be considered separately, if precise data were available.

Energy for constructing buildings is usually estimated as industrial sector in the statistics of energy consumption. Though the CO_2 emission is not considered in this analysis, the construction of buildings highly contributes to the CO_2 emissions because it uses a large amount of cement concrete which produces CO_2 gas. The CO_2 emission from construction sums up to about 12% of the total CO_2 emission in Japan in 1990.

Energy for construction is different in corresponding to the height of the building, which determines the structure, equipment and the rent-able ratio of the building.

b) Energy Consumption of Households

There are discussions whether energy consumption of households relates to the density of the land use and the height of the building. The height of the building relates to the number of household members, the area of a household, and common spaces for elevator and so on. Furthermore, it relates to the income and the lifestyles. However, the relation of the height of the buildings and the lifestyles to the energy consumption is not clear.

In this analysis, the available data as energy consumption related to buildings are used for the examination in the next chapter.

c) Energy for Transportation

People living in urban areas travel in order to go shopping, working and doing other activities in their daily-life. These trips are basically inevitable to meet their desirable lifestyle. Three methods will be mentioned to reduce the energy consumption for traffic: changing the transport mode, improving the efficiency of the mode and shortening the length of trips, except for reducing the frequency of trips from the methods because it may degrade their lifestyles. This analysis assumes that the frequency of trips, the selection and the efficiency of the mode are given. Only the length of trips can be changed to correspond with the density that is related to the area of the district.

d) Open Spaces

Parks, gardens, stadiums and other open areas are the most popular places for people to spend their leisure time. In open spaces, they can touch nature: water, soil, plants, animals and get fresh air and sunlight. This plays an important role in maintaining their desirable lifestyles. The increase of open spaces has a typical trade-off relationship with reducing energy for trips as follows: if an urban planner provides large open spaces, the density of land use become lower and this increases the length of the trips.

The parking space and roads are a kind of open space. They are necessary if people use automobiles in daily life. For simplification, they are considered open spaces in this analysis, although preferences of people for parks and parking spaces are different.

e) Rent-able Ratio

Rent-able Ratio is the ratio of the floor area for rent to the whole floor area of the building. The floor area for rent is composed of the residential area after deduction of the area for common space, i.e., stairs, elevators and halls.

This factor seems not directly related to energy. However, if the building becomes higher, rent-able ratio becomes lower. It means that if the estimation of energy consumption for each household is small, additional energy consumption for common spaces cannot be neglected.

The common spaces can be considered as the passage. In this analysis, the building areas for these will be dealt with as open spaces and only the floor area for rent will be dealt with as the floor area.

f) Urban Areas

Maximizing urban areas means at the same time minimizing the agricultural and natural areas. The places suitable for the cultivation or habitation become fewer in most countries. The development of new urban areas destroys nature or the farming areas. So the extent of the urban areas becomes one of the criteria. The difference between open spaces and agricultural areas is shown in Figure 2.

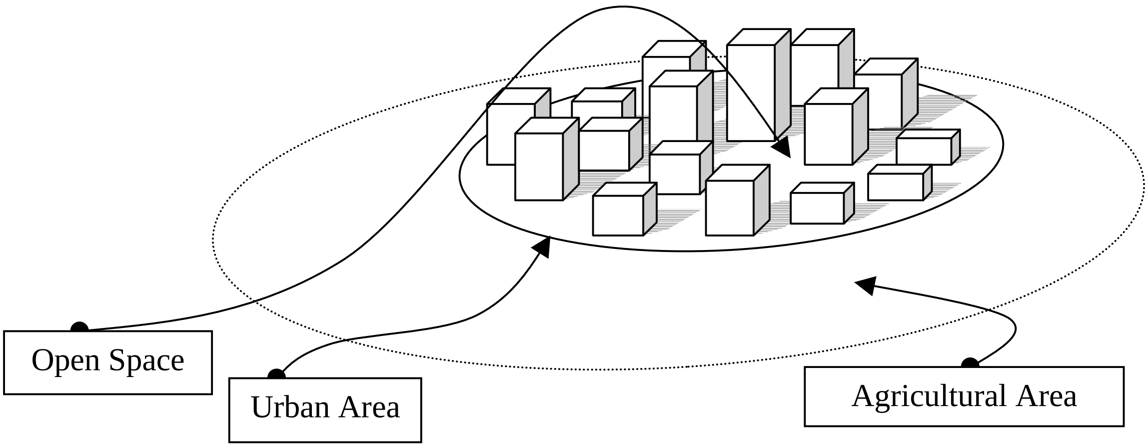

Figure 2: Open Spaces, Urban Areas and Agricultural/Natural Areas

g) Air Pollution

This is supposed to be included as a criterion in the future model. If the floor concentrates on high density, the air pollutant from automobiles and the heat supply will be generated in high density, which is causing air pollution especially in many developing countries. The resulting concentration of the pollutant will be calculated in such an analysis because it is difficult to consider the diffusion of pollutants.

2.4 Criteria used for the model analysis

The following three outcome variables of the model are chosen as criteria.

- Minimizing energy consumption (defined by (2))
- Maximizing open spaces in urban areas (defined by (3))
- Minimizing urban areas outside urban areas (defined by (4))

3 Application of Multi-Criteria Model Analysis

3.1 Role of Multi-Criteria Model Analysis

Multi-criteria model analysis is a good method to deal with urban problems because of the conflictive feature of urban planning problems that is very often neglected in single criterion based methods for urban policy analysis.

As the application of Multi-Criteria Analysis to urban land use planning, Nijkamp analysed urban planning with the soft multi-criteria method so as to treat qualitative data [v]. On the other hand, this analysis makes an effort to treat quantitative data in order to show the outcome variables in cardinal values. It helps the decision-maker to find satisfactory levels of these criteria.

As noted before, Multi-Criteria Analysis is not a method for finding an optimal solution for a given problem. It is rather a methodology that supports a decision-maker in analysing a problem and in finding and comparing various satisfactory solutions that have different properties. The single criterion optimization method is not suitable for these conflicting urban-environment criteria. A limitation of currently used software for Multi-Criteria Analysis is that it can treat only linear programming models. However, a new version of software that can handle non-linear models will be available in the near future.

3.2 Selection and Definition of Criteria

In the first phase of analysing a decision problem, a decision-maker chooses several criteria from the core model and chooses whether maximizing or minimizing each criterion. The core model itself includes only physical and logical relations and it does not include preferences of decision-makers.

3.3 Aspiration/Reservation Level

As a next step, the decision-maker selects for each criterion an aspiration level (value of a criterion that he wants to achieve) and a reservation level (value of criterion that he wants to avoid). After that, the Multi-Criteria Model Analysis program computes a Pareto-Optimal solution that corresponds to the set of the aspiration/reservation levels. The decision-maker considers the result and selects interactively again a new set of the aspiration/reservation levels. These interactive iterations continue until the decision-maker finds a satisfactory solution. At the same time, the value of decision variables corresponding to the solution will be illustrated. As mentioned before, Multi-Criteria Model Analysis is not a method for mathematicians, but a tool for decision-makers, who analyse the decision problem by specification of their preferences in a most natural way, namely by setting for each criterion aspiration and reservation values.

4 Case study

The purpose of this case study is to illustrate the methodology using a simple example. This example assumes that:

- Land use type is mainly residence.
- Population scale is about 100,000.
- Unit data of energy consumption is that of Tokyo.

4.1 Data set

This section describes the test data set.

a) Format

Software for Multi-Criteria Model Analysis (MCMA) requires specification of the core model (described in Section 2) in the LP-DIT format [vi]. Therefore, a specialized problem generator has been developed, which provides the model in the LP-DIT format, a utility that converts MPS files into LP-DIT files is available.

b) List of data

The data needed for specification of the model has to be provided in a text data file. The structure of an input data file is simple. The list of test input data is as follows:

(Comment) ulup.dat 970821

9 # I: Number of building type

7 # J: Number of district type

2 3 4 5 6 7 8 9 10

h_i: Height of building type i ($0 \le i < I$)

0.99 1.04 1.09 1.15 1.2 1.25 1.3 1.35 1.4

c_h: Energy coefficient for construction corresponding to h_i (Mcal/m^2/year)

0.6 0.8 1 1.2 1.4 1.6 1.8

u_j: Reciprocal of Floor Area Ratio of district type j ($0 \leq j < J$)

0.23 0.35 0.46 0.56 0.65 0.73 0.81

t_u: Energy coefficient for transportation corresponding to u_j (Mcal/m^2/year)

End of file

New criteria will be added to this data file.

c) Calculated parameters

In this test analysis, these data are calculated on some assumptions because data aggregated in the same category as the height of buildings and the Floor Area Ratio are not available. The method to determine these coefficients will be sophisticated. However, this analysis determines coefficients by the following method.

The height of buildings and the area of the district are determined as a feasible range in urban planning of Japan. The energy for construction is assumed linear to the height of buildings and calculated ranging from lower 99 to higher 130(Mcal/m^2/year). The energy for traffic is assumed linear to the area of district and calculated ranging from more dense 23 to sparser 73(Mcal/m^2/year). These data are calculated from the data of questionnaires and estimations [vii]. For the computer calculation these energy coefficient values are divided with 100.

4.2 Model analysis

MCMA software read a specification of an instance of the core model in LP-DIT format file, which is produced by the problem generator that uses a data set documented in section 4.1.b.

The guide to use MCMA is described in detail in the paper about ISAAP (Interactive Specification and Analysis of Aspiration-based Preferences) [viii]. According to the guide, after selecting criteria and their type (maximization/minimization), first the Nadir and Utopia points, and second the compromise solution will be obtained as shown in Figure 3. The compromise solution is illustrated as point 0.

The decision-maker does the iterations noted in Section 3.3 as follows:

- Set Aspiration/Reservation levels to each criterion
- Solver calculate Pareto Efficient solution
- Considering these solutions, set again Aspiration/Reservation levels

One example of iterations is shown in Figure 3 and Table 1. As illustrated above, the 0th iteration is for the calculation of Nadir and Utopia points and their compromise solutions. From the 1st to the 3rd the iterations show the setting of aspiration/reservation levels and their Pareto-Efficient solutions. The right side table shows the share of each floor area for these levels and solutions. For example, in the 3rd iteration, the decision-maker sets the reservation level of energy as 1.6, aspiration level as 1.3 and so on. MCMA calculate the solution of energy as 1.48. In this case, the share of floor area x_{20} (which is a decision variable and shows that the height of buildings is 4.0 and the ratio of district area to floor area is 0.6) is 12.7%. Other decision variables shown here converge into minute value. The averages of the height and the reciprocal of Floor Area Ratio are summed up with the weight of the share. Of course, the average of reciprocal of the Floor Area Ratio is equal to Urban Area because their definitions are the same.

If the decision-maker chooses tight reservation levels for Energy and OpenSpace as the 1st iteration, UrbanArea becomes larger and buildings stand lower. Next, if he/she looses aspiration/reservation levels for Open Space, Urban Area becomes larger and Energy improves. And last, if he/she chooses severe reservation levels for Energy and Urban Area, the urban land-use of small Energy with proper OpenSpace and UrbanArea are illustrated as the 3rd iteration. As described above, this iterations process of MCMA adjusting aspiration/reservation levels for each criterion with considering previous solutions is useful for searching the agreeable Pareto-Efficient solutions for multi-criteria.

4.3 Discussion of results

The solutions exist between these Aspiration/reservation levels. It means that these levels are in the feasible area and the solutions can be calculated. In case the achievement functions (it is the value shown on the left side of the graph in Figure 3) for each criterion are 0, it means that these levels are so tight and the decision-maker

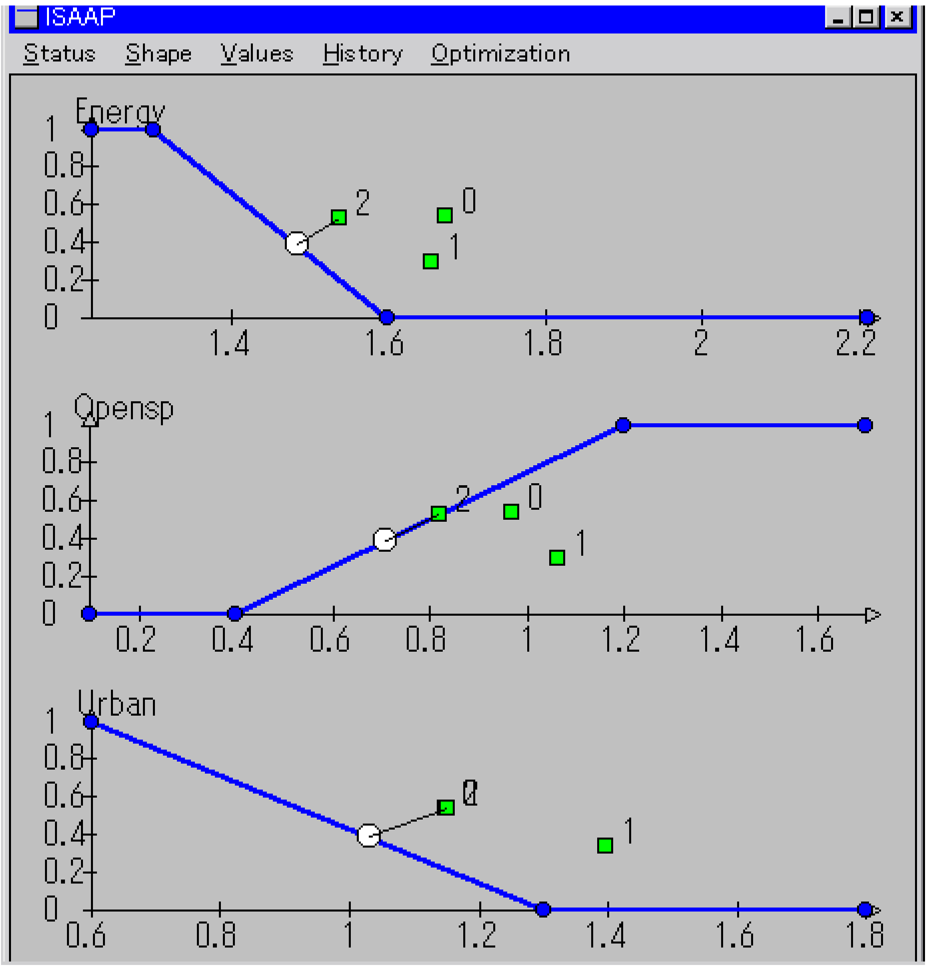

Figure 3: Iterations of Asp/Res. level setting on ISAAP

Table 1: Example of MCMA process

0	Nad.	Uto.	Com.
Energy	2.21	1.22	1.67
OpenSpace	0.1	1.7	0.97
UrbanArea	1.8	0.6	1.15

D.V.	Height	1/FAR	Share
x_{30}	5.0	0.6	33.1%
x_{36}	5.0	1.8	11.5%
x_{40}	6.0	0.6	21.1%
x_{46}	6.0	1.8	34.2%
Ave.	5.6	1.1	100.0%

1	Res.	Asp.	Sol.
Energy	1.8	1.3	1.65
OpenSpace	0.8	1.7	1.06
UrbanArea	1.8	0.6	1.40

D.V.	Height	1/FAR	Share
x_{10}	3.0	0.6	33.7%
x_{16}	3.0	1.8	66.3%
Ave.	3.0	1.4	100.0%

2	Res.	Asp.	Sol.
Energy	1.8	1.3	1.54
OpenSpace	0.4	1.2	0.82
UrbanArea	1.8	0.6	1.15

D.V.	Height	1/FAR	Share
x_{10}	3.0	0.6	53.9%
x_{16}	3.0	1.8	46.1%
Ave.	3.0	1.2	100.0%

3	Res.	Asp.	Sol.
Energy	1.6	1.3	1.48
OpenSpace	0.4	1.2	0.71
UrbanArea	1.3	0.6	1.03

D.V.	Height	1/FAR	Share
x_{10}	3.0	0.6	51.4%
x_{16}	3.0	1.8	35.7%
x_{20}	4.0	0.6	12.7%
x_{26}	4.0	1.8	0.2%
Ave.	3.1	1.0	100.0%

should choose the looser aspiration/reservation levels. On the contrary, in case every achievement function is 1, it means that the decision-maker can choose tighter aspiration/reservation levels.

Seeing the existing decision variables, types of buildings sometimes differ in adjacent two heights. On the other hand, the type of district differs in two extreme values of density among the input data. With respect to the types of buildings, the set of different types presents the mediate value between these two types. However, with respect to the types of buildings, this does not apply. If the core model includes the district data of more dense or sparse, the decision variables of more dense or sparse district will share the most percentages. It results from the assumption of models, which do not consider the accessibility to open spaces. As a consequence, in order to reduce the energy for traffic, buildings are prompted to concentrate on the high density, even if the concentration causes the low density in another district, while maintaining desirable extension of Open Space. It causes purification among building areas and open spaces. There are a few ways to consider accessibility to open spaces. The first is to set lower boundary conditions on the area of the district, which maintains open spaces in the densest district. Second is to constrain the extension of urban areas, which insures the accessibility to open spaces in the urban area. It leads to the necessity to limit the scale of the urban area and the total floor area in future models.

5 Conclusion

This paper primarily aims at applying MCMA to urban land use planning and illustrating the energy saving land use style while maintaining desirable lifestyle. Using MCMA, Pareto-Efficient solutions for various conflicting criteria, such as saving energy and maintaining desirable lifestyles, can be found. Furthermore, the desirable land use as the decision variables to achieve the agreeable Pareto-Efficient solutions can be found. It should be stressed that this interactive analysis determines the desirable levels of outputs previously in the field of urban land use planning, while most methods estimate various values deductively using given floor areas and given densities. It has been confirmed that this analysis helps to plan the energy-saving urban land-use properly.

With respect to the illustration of the energy saving land use style, decreasing open spaces in urban areas is one of the most effective policies for reducing the energy consumption, although parks and gardens are required in urban areas because they play roles to keep the urban-lifestyle comfortable. On the other hand, especially walkers generally dislike parking-lots and highways. The energy-saving effects of changing the traffic mode from automobiles to public transportation are large in respect to the land use as well as the transport effectiveness. Furthermore, the effective land use in high density is preferable for introducing public transportation to the urban area, which has not yet been considered in this analysis.

It can be said for other models as well that the interactive iterations have a role to inform decision-makers of their real reservation and aspiration levels. In addition, the Pareto-Efficient solutions are shown in quantitative values. It will be interesting to apply this method to the decision-making involving public preferences, though this method is originally designed for one decision-maker.

One future problem of the analysis is to prepare the precise data set about energy consumption because the current data set is not precise enough. Another problem is to separate open spaces relative to floor areas such as parks, gardens and parking-lots from other inevitable spaces such as minimum road, elevator shafts and so on. It gives a clearer vision to improving the urban land use planning.

As an extension of this model, more variables (for example, scale of the city, land use type, location of the land use) and more realistic forms of functions (non-linear functions) are planned to be dealt with.

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