Housing Arrangements in Pursuit of Maximum GFA Under CO₂ Emission Constraint

Peng Tang^{*1}, Junzo Munemoto² and Daisuke Matsushita¹

¹ Research Associate, Graduate School of Engineering, Kyoto University, Japan

² Professor, Graduate School of Engineering, Kyoto University, Japan

Abstract

This paper attempts to develop a management instrument for housing arrangements under given constraints regarding household annual CO₂ emissions (HACO₂). HACO₂ was defined as the sum of the life cycle CO₂ emission from house construction and operation (LCCO₂) and the CO₂ emission from commuting (CTCO₂). Under such an instrument rule, genetic algorithm (GA) was used to find a housing arrangement scheme in pursuit of the maximum average gross floor area (GFA) in an urban area. Simulation tests were performed and compared on three traffic modes: public-mode, self-mode, and mixed-mode. The results indicated that, 1) the closer the house was to the workplace (the nucleus of the city), the larger the GFA would be; 2) different traffic modes might lead to different patterns of housing arrangement; and 3) the self-mode had high-energy demand resulting in the lowest evaluation value, and was the least efficient in obtaining better living conditions under the constraints.

Keywords: housing arrangement; scheme; HACO₂; traffic mode; gross floor area (GFA)

1. Introduction

1.1 Background

Global warming can be largely attributed to increased carbon dioxide (CO₂) emission induced by human activities (Karl and Trenberth, 2003). A common understanding in controlling CO₂ emission is to achieve its stabilization to an acceptable level (Kyoto Protocol, 1992). Although the frameworks of international emission trading schemes have been initiated, the development of practical instruments to guide human activities without concern for wealth and poverty, are urgently needed. From the perspective of architectural and urban planning, we prefer to investigate the social activities of households and their environmental impact.

Environmental impact resulting from the life cycle of households is induced by house building, operation, demolition, traffic, and so on. CO₂ emission per year (kg-C/yr) is a commonly used measure. We define the household's annual CO₂ emission (HACO₂) as the sum of all the above impacts. The annual CO₂ emission from house construction, operation and demolition throughout the house's life cycle was defined as LCCO₂. The CO₂ emission from commuting (CTCO₂) was defined as the emissions from traffic occurring on a daily basis. HACO₂ can be expressed as:

$$HACO_2 = LCCO_2 + CTCO_2 \quad (1)$$

Formula (1) suggested that the constraint on HACO₂ would lead to a tradeoff between LCCO₂ and CTCO₂. LCCO₂ is determined by house type, such as construction method, materials, dimensions, duration, etc (Munemoto *et al.*, 2002). CTCO₂ is relevant to commuting distance and traffic mode. HACO₂ is therefore the outcome of the households' activities including location, choice of traffic mode and house type. A commuter who prefers a large house (leading to high LCCO₂) has to live closer to their workplace, or choose the traffic mode with low energy demands (corresponding to the low CTCO₂) if the house type he/she lives in is the same. If the living condition is represented by gross floor area (GFA) of the house, the rule of the management instrument can be expressed as: the gain of increased GFA is the payoff from CTCO₂ saving.

Based on such a rule, we attempted to establish a methodology for exploring the potential of planned housing with better living conditions. With detailed data, operational capabilities of computers, and a flexible adaptation system, the methodology is expected to become a consultative means in urban planning. Evolutional computation is recognised as a powerful algorithm in solving the problems involved in searching for appropriate housing arrangements from among the millions of possible patterns.

1.2 Purpose

The primary purpose of this study is to seek an effective housing arrangement in pursuit of the maximization of average GFA for residents who commute to the same place, based on a management instrument with constraint placed on HACO₂. Furthermore, simulation tests were performed and

*Contact Author: Peng TANG, Research Associate, Graduate School of Engineering, Kyoto University.

Kyotodaigaku-Katsura, Nishikyo-ku, Kyoto 615-8540, Japan

Tel: +81-75-383-2917 Fax: +81-75-383-2916

e-mail: tangpeng@archi.kyoto-u.ac.jp

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compared for three different traffic modes, which established effective patterns of housing arrangement for each mode.

The study addresses the following questions:

- 1) How can the problem of housing arrangement be mapped to genetic algorithm (GA) optimization.
- 2) What kind of housing arrangement configuration will yield the given constraint on $HACO_2$?
- 3) What is the difference between the housing arrangement configurations in different traffic modes?

1.3 Related Studies

Numerous efforts have been made during the past decade to reduce environmental emissions and energy demand. In architectural planning, most of the related studies focused on the approach to calculating $LCCO_2$, life cycle cost (LCC), and/or the final waste (FW) of individual buildings or models (Ishizaka 1985; Urushizaki *et al.* 2002, 2003, etc). Some studies investigated effective ways to reduce environmental loads. Yada *et al.* (1999) and Munemoto *et al.* (2002) applied GA to the solution of the multi-objective problem of reducing $LCCO_2$, LCC and FW simultaneously.

In the field of urban planning, spatial configuration of the city and its relationship with the urban environment has been the subject of empirical, theoretical and political studies (Anderson *et al.*, 1996). Relevant studies have addressed the issue of optimal land use by minimizing energy consumption for journeys using 3D urban models (Suzuki 1993; Matsuhashi 1996). There are few studies, however, on the broader question of reducing environmental load by implementing urban renewal projects in real cities (Takemoto *et al.*, 1999). Recently, Kondo *et al.* (2003) proposed a trading system using the household as a unit so as to control CO_2 emission at an acceptable level. The CO_2 emission they defined included the use of energy in daily life without considering the mass and energy consumption of house construction and the residents' commuting.

Fig.1. General Idea of This Paper

This study incorporates both $LCCO_2$ and $CTCO_2$ into the concept of $HACO_2$, based on achievements in the fields of architectural and urban planning (Fig.1.). As the average GFA is an overall measure of living condition, it is a global optimization problem to find

the optimal values from the numerous configurations of housing arrangement. GA is adopted as a means to solving this problem (Kitano 1993).

2. Materials and Models

2.1 Urban Model and $CTCO_2$

Archetypal urban forms include the concentric, the radial, and the multinucleated city, as shown in Fig.2.(a). The concentric and radial cities can be regarded as special cases of the latter form. The nucleus of a city is usually a location with the maximum employment density and maximum number of journey endings (Anderson *et al.*, 1996).

A square urban area with an edge of 40 km was defined, as shown in Fig.2.(b). The area was divided into grids of equal-length. One grid is composed of the workplace, while others around it are composed of land occupied by commerce, residences, the public-sector, and so on. In each grid, the acceptable total GFA is St .

$$St_i = a \cdot b \cdot l^2 \quad (2)$$

where,

St_i : total GFA in the grid i (m^2);

l : length of the grid ($l=2000m$);

a : ratio of residential land to total area of the grid i ;

b : floor area ratio of each house lot.

Each household is supposed to have only one house.

The acceptable number of households in the grid i (N_i) is:

$$N_i = (int) St_i / S_i \quad (3)$$

where,

N_i : the acceptable number of households in the grid i ;

St_i : total GFA in the grid i (m^2);

S_i : GFA of each house in the grid i (m^2). This will be further addressed in section 2.3.

The commuter in this paper refers to people who commute to the same workplace: the nucleus. The public transportation network was assumed to be composed of railway and regular bus routes (Fig.2.(b)). The railways intersect at right angles through the nucleus, and there must be at least one bus station in each grid.

The commuter can live anywhere in the city. Three traffic modes were addressed in this study. The first, involving travelling to a bus or railway station by bike or on foot and then taking the public vehicle, is "public-mode". The commuting distance in this case is the sum of the distance by each vehicle. Assuming that people always select the shortest route, the commuting distance would then be $D_{pb} = D_1 + D_2$. The second mode involves commuting by motorcar, which is defined as "self-mode". The commuting distance in this case was assumed to be from the center of the grid where the commuter lives to the center of the nucleus.

Fig.2. Urban Space Model

Therefore, $D_{sf} = \sqrt{D_1^2 + D_2^2}$ (Fig.2.(b)). In the third mode, the commuter was assumed to sometimes commute by public-mode and sometimes by self-mode. Commuting days by either Public-mode or self-mode is half year. This mode is the "mixed-mode".

This assumption was based on the commuting habits of only one commuter in a household. CTCO₂ could be expressed as:

$$Tt_i = \sum E_j \times D_j \quad (4)$$

where,

Tt_i : CTCO₂ (kg-C/yr) value of the grid i

D_j : commuting distance by vehicle j (km)

E_j : CO₂ emission unit of vehicle j (kg-C/km.yr.p) (Note¹.)

2.2 House Model and LCCO₂

The detached house is of concern in this study. A detailed description of the estimated amount of LCCO₂ generated by a detached house can be found in Munemoto *et al.* (2002). A wooden Standard House was used as the typical model in this research, and its details can be found in Fig.3. and Table 1, in which the dimensions and the materials used were fixed. Only the GFA was changeable as a measure of the living conditions. According to the Statistics Report of the Japanese Government Housing Loan Corporation (2004), the average GFA of newly built detached houses in 2001 was 138.2m². Approximately 96.9% of the houses' GFA ranges from 80m² to 200m². This range was therefore adopted for this study. A change in GFA will lead to a change in the LCCO₂.

Fig.3. Dimension of Standard House Model

Table 1. Details of the House Model

Part	Component	Material	Thickness (m)
Framework	Frame work	Conventional	—
	Frame	Wooden	0.03
Wall	External finish	Mortar	0.005
	External substratum	Plywood board	0.005
	Insulator	Rock wool	0.115
	Inner substratum	Lumber	0.01
	Inner finish	Plaster board	0.01
Window	Type of window	Double glass	area ratio of window to floor
	Sash	Aluminum	0.158
Floor	Frame	Wooden	—
	Finish	Plywood board	0.005
	Substratum	Lumber	0.01
	Insulator	Rock wool	0.115
Ceiling	Frame	Lumber	—
	Substratum	Plaster board	0.025
	Insulator	Lumber	0.21
Roof	Frame	Wooden	—
	Finish	Cement board	0.005
	Substratum	Lumber	0.005
	Insulator	Rock wool	0.21

2.3 HACO₂

Of concern is how much HACO₂ should be determined as a desirable or acceptable level. Until now, no such commonly accepted standard exists. According to formula (1), HACO₂ is determined by LCCO₂ plus CTCO₂. Since LCCO₂ per square meter of a wooden Standard House Model was 3.3(kg-C/m²_yr) (Munemoto *et al.*, 2002), LCCO₂ of the whole house is 3.3(kg-C/m²_yr)×125.9(m²)=413.4(kg-C/yr). For the commuter who lives in the farthest grid from the nucleus in the urban space model, and commutes by the public-mode, we had 114.1(kg-C/yr). HACO₂ was then 527.5 (kg-C/yr) and this was used as the constraint level.

Once the traffic mode is decided, the CTCO₂ of a household in a certain grid i can be estimated. From formula (1), LCCO₂ can then be obtained (LCCO₂=HACO₂-CTCO₂). As stated in section 2.2, for the same type of housing model, LCCO₂ was only relevant to GFA. The GFA of each house in a certain grid (S_i) can then be obtained. In this way, S_i is related to housing location and traffic mode.

2.4 GA Based Evaluation Method

GA can facilitate the search for the maximum value of average GFA, and find the optimal housing arrangement. Since the traffic network was symmetrical with respect to the center nucleus, 156 grids in the upper right side of Fig.2. were selected and used in the GA evaluation model. After evaluating 1/4 part of the layout, we completed it by redrawing it symmetrically (Fig.4.).

Fig.4. Flow of GA Evaluation

2.4.1 Encoding

The chromosomes were composed of 158 genes. They are expressed by 0 or 1 for the genes from *gene [0]* to *gene [155]*, and a combination of two real numbers for *gene [156]* and *gene [157]* (Fig.5.).

0 or 1 for each gene denoted whether households live in the grid or not. The combination of 0 and 1 for genes from *gene [0]* to *gene [155]* were used to map the diverse pattern of housing arrangements. *Gene [156]* and *gene [157]* denoted two land-use parameters, a and b, in formula (2), respectively. *Gene [156]* is the ratio of the residential land to the total land in each grid. It ranged from 20% to 100%, separated into 8 levels. *Gene [157]* is the floor area ratio for each house lot. It ranged from 40% to 200%, being separated into 16 levels. *Gene [157]*=200% means that the area of the house lot is the same as the area of the ground floor.

Fig.5. Chromosome Structure

2.4.2 Evaluation Function

The average GFA represented the level of living condition. In this study, it acted as the overall measure in GA evaluation. The average GFA of all the households is calculated from the following evolutionary function:

$$\bar{S} = \frac{\sum_{i=0}^{155} S_i \times n_i \times gene[i]}{n_t} \rightarrow \max \quad (5)$$

where,

$\bar{S}$: average GFA (m²)

S_i : acceptable GFA of each house in the grid i (m²)

n_i : a random integer from 1 to N_i

n_t : actual number of the total households

gene [i]: 0 or 1

In each evaluation experiment, GA first calculates the acceptable number of households that live in one grid (N_i). Then, $n_i \times gene[i]$ households are located randomly in grid i . n_i is an integer ranging from 1 to N_i . If *gene [i]*=0, it means that there are no people in the grid i , if *gene [i]*=1, the number of households living in the grid i is n_i . The evaluation system then summed up the total number of households (n_t):

$$n_t = \sum_{i=0}^{155} n_i \times gene[i] \quad (6)$$

where,

n_i : a random integer from 1 to N_i

n_t : actual number of total households

Gene [i]: 0 or 1

There are two constraints in the evaluation. The first is that the total number of households (N_t) in this urban area was constant in this study. The question is how to make n_t approach the decided N_t . Generally, the GA system applied the penalty strategy to solve such problem: if $n_t \neq N_t$, the chromosome was then thrown away, and the system turned to search for another. Using this strategy the system may lose some superior characters of the string, which may cause premature convergence during evaluation, and no result at all. In this study, we adopted the restoration strategy to gain more efficiency (Fig.6.). Before being evaluated, n_t was checked to see if it was larger than N_t . If so, the evaluation continued. If not, the system would randomly pick up a grid and check if it was "unoccupied" (check if *gene [i]*=0). If so, the system changed it into "occupied" (change *gene [i]*=0 to *gene [i]*=1). The above approach was repeated until n_t was slightly larger than N_t .

The second constraint is the limited number of households in one grid. According to formula (1), given a constraint on HACO₂, the closer the house location was to the workplace (the nucleus), the larger the GFA would be. Obviously, if all the households are gathered in the nucleus, the CTCO₂ will be zero and the average GFA will be the largest number. However, as we know, too centralized a population will probably cause other environmental problems such as the heat island phenomenon, etc. In order to control the diffusion and condensation of the urban area, the number of households living in one grid (4km²) may not be larger than 4,000 (< 1000 households/km²).

Fig.6. Flow of Restoration Strategy

2.5 Simulation

The definition and implementation of the operators of GA were based on GENESIS Version 5.0 (Note ²). The appropriate values for the main parameters of GA were as follows: Total trails=1000,000 (as a terminate condition); Population size=200; Crossover rate=0.6; Mutation rate=0.002; Generation gap=1.

The simulation was run several times. First, it ran for the case of the pub-mode only. The purpose of this step was to clarify the evolutionary process as well as to seek answers to the question "What kind of housing arrangement configuration will yield the given constraint on HACO₂?" Second, simulation was run in three different patterns of traffic modes in order to answer the question "What is the difference between the housing arrangement configurations in different traffic modes?"

3. Results and Discussion

3.1 Simulation on Public-mode

The evaluation process is shown in Fig.7. The experiments by GA were taken for more than 1×10^5 times. The evaluation value $\bar{S}$ did not change anymore after the 350th generation, which is 147.6(m²). The estimated $\bar{S}$ was 15m² larger than the value in 0th generation. Under the restriction of $N_i < 4000$, the land-use parameters were: $a=20\%$, $b=70\%$. The average number of households living in a grid now is 3,904.

The configuration of housing arrangement in the corresponding generation is shown in Fig.8. The houses tended to be located in the grids close to the workplace and the railway, maximizing $\bar{S}$. The configuration of housing arrangements of the 350th generation was cross-shaped along the railway infrastructure.

Fig.7. Evaluation Process

Fig.8. Transition of the Best Arrangement

3.2 Simulations on Three Different Traffic Modes

Evaluations by GA of the other two traffic modes were made as the same workflow mentioned above. The results show that the configuration of housing arrangements of the self-mode is circle-shaped, with value $\bar{S} = 114.7\text{m}^2$. The configuration of the mixed-mode is in the shape of a rhombus (Fig.9.). The corresponding evaluation value is $\bar{S} = 131.1\text{m}^2$. The values of a and b were, $a=20\%$, $b=50\%$ and $a=20\%$, $b=60\%$, respectively.

Under the same conditions, the self-mode resulted in a lower GFA than the other two modes. The CO₂ emission unit of a motorcar is higher than that of public vehicles. Although at the same location, the value of CTCO₂ in the self-mode is higher. In order to minimize the commuting distance, more houses were located closer to the workplace, which increased the population density. For this reason, the land-use parameters were lower than that of public-mode and mixed-mode.

Fig.9. Results in the Case of Different Traffic Modes

4. Conclusions and Perspectives

To explore different housing arrangements, a methodology was established using GA. The results demonstrated the applicability of GA in searching for a housing arrangement with the goal of approaching the maximum average GFA, under the constraint of constant CO₂ emission.

This study revealed that the location and traffic mode affected both the housing arrangements and the evaluation value. The closer the house was to the workplace (the nucleus), the larger the GFA. Different traffic modes may lead to different patterns of housing arrangement. The self-mode had high-energy demand resulting in the lowest evaluation value, and was the least efficient in obtaining better living conditions under the management instrument rule.

The management instrument facilitated understanding of the spatial configuration of housing arrangements with better living conditions; even CO₂ emission was given at a constraint level. This may help to develop environmental policy with a new point of view, and guide household activities in relation to location and choice of traffic mode.

Of further interest is what the household prefers to do under the management instrument and how the individual activities of households affect the housing arrangements. These will be investigated in a future study.

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Notes

1. Unit of energy consumption of vehicles from EDMC (2000), pp. 116-117

vehicle	unit (kcal/p.km)
train	50
car	575
bus	160

Note: the above are data of 1998

2. An implement for function optimization based on genetic search techniques, provided by John J. Grefenstette, October 1990.

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