Housing Arrangements in Pursuit of Maximum GFA
Under CO$_2$ Emission Constraint

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Abstract
This paper attempts to develop a management instrument for housing arrangements under given constraints regarding household annual CO$_2$ emissions (HACO$_2$). HACO$_2$ was defined as the sum of the life cycle CO$_2$ emission from house construction and operation (LCCO$_2$) and the CO$_2$ emission from commuting (CTCO$_2$). 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; HACO$_2$; traffic mode; gross floor area (GFA)

1. Introduction
1.1 Background
Global warming can be largely attributed to increased carbon dioxide (CO$_2$) emission induced by human activities (Karl and Trenberth, 2003). A common understanding in controlling CO$_2$ 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. CO$_2$ emission per year (kg-C/yr) is a commonly used measure. We define the household's annual CO$_2$ emission (HACO$_2$) as the sum of all the above impacts. The annual CO$_2$ emission from house construction, operation and demolition throughout the house’s life cycle was defined as LCCO$_2$. The CO$_2$ emission from commuting (CTCO$_2$) was defined as the emissions from traffic occurring on a daily basis. HACO$_2$ can be expressed as:

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

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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 HACO2?
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 LCCO2, 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 LCCO2, 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 CO2 emission at an acceptable level. The CO2 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.

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 $D_{p} = D_{1} + D_{2}$. 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.

2. Materials and Models

2.1 Urban Model and CTCO2

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 $St$.

$$St = a \cdot b \cdot l^2$$ (2)

where,
$St$: 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 $i$ ($N$) is:

$$N = (int)St_i / S_i$$ (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.

Related Studies
House Construction
House Running
House Scrapping
Commuting

This study incorporates both LCCO2 and CTCO2 into the concept of HACO2, 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).
Therefore, \( D_y = \sqrt{D_1^2 + D_2^2} \) (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. CTCO\(_2\) could be expressed as:

\[
T_{i} = \sum E_{j} \times D_{j}
\]

where,

- \( T_{i} \): CTCO\(_2\) (kg-C/yr) value of the grid \( i \)
- \( D_{j} \): commuting distance by vehicle \( j \) (km)
- \( E_{j} \): \( \text{CO}_2 \) emission unit of vehicle \( j \) (kg-C/km.yr.p)

(Note 1.)

2.2 House Model and LCCO\(_2\)

The detached house is of concern in this study. A detailed description of the estimated amount of LCCO\(_2\) 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 138.2m\(^2\). Approximately 96.9% of the houses’ GFA ranges from 80m2 to 200m\(^2\). This range was therefore adopted for this study. A change in GFA will lead to a change in the LCCO\(_2\).

2.3 HACO\(_2\)

Of concern is how much HACO\(_2\) should be determined as a desirable or acceptable level. Until now, no such commonly accepted standard exists. According to formula (1), HACO\(_2\) is determined by LCCO\(_2\) plus CTCO\(_2\). Since LCCO\(_2\) per square meter of a wooden Standard House Model was 3.3(kg-C/m\(^2\)_yr) (Munemoto et al., 2002), LCCO\(_2\) of the whole house is 3.3(kg-C/m\(^2\)_yr)\times125.9(m\(^2\))=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). HACO\(_2\) was then 527.5 (kg-C/yr) and this was used as the constraint level.

Once the traffic mode is decided, the CTCO\(_2\) of a household in a certain grid \( i \) can be estimated. From formula (1), LCCO\(_2\) can then be obtained (LCCO\(_2\)=HACO\(_2\)-CTCO\(_2\)). As stated in section 2.2, for the same type of housing model, LCCO\(_2\) 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.).
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 [156] = 100% means that all the land in one grid is used as residential land. Gene [157] = 200% means that the area of the house lot is the same as the area of the ground floor.

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 evolutional function:

\[
\bar{S} = \frac{\sum_{i=0}^{155} S_i \times n_i \times \text{gene}[i]}{n_i} \rightarrow \text{max}
\]

where,
- \(S_i\): average GFA of each house in the grid \(i\) (m²)
- \(n_i\): a random integer from 1 to \(N_i\)
- \(n_i\): actual number of the total households
- \(\text{gene}[i]\): 0 or 1

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

\[
\bar{n}_t = \sum_{i=0}^{155} n_i \times \text{gene}[i]
\]

where,
- \(n_i\): a random integer from 1 to \(N_i\)
- \(n_t\): actual number of total households
- \(\text{Gene}[i]\): 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 \(\text{gene}[i] = 0\)). If so, the system changed it into "occupied" (change \(\text{gene}[i] = 0\) to \(\text{gene}[i] = 1\)). 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 (4 km²) may not be larger than 4,000 (< 1000 households/km²).
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=1000000 (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 evolutional 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 1x10^5 times. The evaluation value \( \bar{\xi} \) did not change anymore after the 350th generation, which is 147.6(m2). The estimated \( \bar{\xi} \) was 15m^2 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 \( \bar{\xi} \). The configuration of housing arrangements of the 350th generation was cross-shaped along the railway infrastructure.

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 \( \bar{\xi} = 114.7 \) m^2. The configuration of the mixed-mode is in the shape of a rhombus (Fig.9.). The corresponding evaluation value is \( \bar{\xi} = 131.1 \) 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.
The workplace (the nucleus), the larger the GFA. Different the evaluation value. The closer the house was to the mode affected both the housing arrangements and arrangements with better living conditions; even CO2 under the management instrument rule.

The management instrument facilitated of housing configurations of housing 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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