Environmental Performance Evaluation of District Using 4D-GIS

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Abstract

We have developed a model to predict a house-rebuilding trend and to comprehensively evaluate residents' quality of life (QOL), amount of CO_2 emission, and the urban maintenance cost, which is aimed at evaluation of future spatial plans and the environmental performance of the built-up areas on a time-series basis. We used this developed model to perform a case study of the Choja-machi district located in downtown Nagoya City, Japan, and found it possible to reduce CO_2 emissions more at a certain point in the future, as well as over the entire process up to the district's future renewal plan, through an organized renewal of the entire district than through the renewal of each building planned individually, which as a result improved the residents' QOL.

1. Introduction

From the 1950s through the 1970s, Japan experienced rapid urbanization along with a high-rate of economic growth, which widened the urban fringe area and brought about urban sprawl. This has posed such problems as a reduction of amenities for residents and an increase of urban maintenance cost and environmental load. Furthermore, as a rapid population decrease is predicted, there is concern that the urban structure will become environmentally and economically more inefficient.

To tackle such problems, some local governments have proposed a transition to the aggregated-urban-structure (Aomori-city, 1999; Toyama-city, 2008; Nagoya-city, 2011). Its basic concept is to promote relocation of residents from environmentally and economically inefficient districts to more convenient downtown or suburban districts. These local governments, however, have not adequately discussed how to design districts that will attract and encourage settlement of more people. If they promote population transfer without a future plan for the resettlement districts, it is possible that the amenities will deteriorate further. To implement a smooth conversion to the aggregated-urban-structure, it is important to make a spatial design that can surely reduce the environmental load while providing residents with amenities, and it is necessary to make a future spatial plan that can develop the district-level environmental performance in a comprehensive and well-balanced way.

There are two possible cases in redesigning urban districts: the first case is to implement the redevelopment over the entire district at once while in the second case individual buildings are renewed by each owner one–by-one in accordance with the rules of the entire district. However, it is practically difficult to carry out redevelopment of an entire district at once except in the downtown areas of a few large cities, and there is no choice available for most districts but to carry out the spatial plan redesign in several steps. In this case, it takes quite a long time to realize the future plan and the environmental performance could worsen before it is completed. So, it is important to evaluate the entire process of a plan in addition to a certain point in the future before starting to redesign built-up areas.

Taking the above-mentioned points into account, this study works out a model to predict the future state of the building renewal dynamically and to evaluate the environmental performance integrally on a time-series basis, using 4D-GIS data (Sugimoto et al., 2012) having the time axis added to the 3D-geometry data of a city. The model is aimed at enabling discussions on efficient district formation process to go along with the building renewal in several steps. We used the model to conduct a case study of Nagoya City's downtown area, analyzing the differences in the amenities for residents, CO_2 emission and the cost to maintain or renew buildings and infrastructure between the two cases: the case in which individual buildings are renewed without specific rules and the case in which individual buildings are renewed according to the rules of the district.

2. Review of the district's environmental performance evaluation method

Various methods have been developed around the world to perform an integral evaluation of urban environmental performance. Among them, Japan's CASBEE-UD (IBEC, 2011), North America's LEED for neighborhood development (USGBC, 2009) and the UK's BREEAM (BREEM, 2010) are representative examples. These methods use a detailed checklist to evaluate and verify amenities and environmental load generating factors estimated for deciding the design of a district. They are evaluation systems intended to be used mainly during the design phase (by which it has been decided to carry out the development and policy), and they convert output indices such as introduction of individual technologies and consideration in design into scores as the environmental performance (Sharifi and Murayama, 2013). Some of them are certified and used in Japan and can be positively evaluated since they are in practical operation.

In the planning phase of a project, however, it is necessary to judge whether to implement a program, and which programs should be combined. Making such judgments inevitably requires measurement of how much effect can be expected from various environmental conservation measures. Besides, these systems are not applicable to cases in which the built-up areas are redesigned in several steps as studied in this paper, and it is difficult to make the time-series evaluation with these systems.

On the other hand, there have been many researches to calculate individual environmental performance (duration of daylight for a house or energy consumption of a house, for example) from relatively simple data as the simulation technology has developed. For example, for calculation of the duration of daylight, which is regarded as one of the house performances, it is already possible to conduct a detailed analysis of complicated buildings and terrain in an wide area (Miguet and Groleau, 2002), and various programs for wind environment simulation are being developed (Blocken et al., 2008; Mochida et al., 2011). There are also many studies of energy simulation in progress, in which a simple database per floor area (JSBC, 2013; AIJ, 2006) has already been developed and a complicated one dealing with 3-D-geometry of buildings (IBEC, 2013) is being prepared. Nevertheless, there are few studies that try to calculate various evaluation indices regarding environmental performance from a single database, because the level of input data required by each index is different. While it is very important to reach an agreement with residents and interested parties in the actual process to prepare a district plan, it is necessary to quantitatively evaluate how effective and efficient the approved plan is.

To achieve this, it is necessary to have a method that can use simple data in the planning phase in which no specific information is clear, in order to evaluate integrally the interrelation between the environmental factors or to make an overall evaluation in a relatively easy way.

3. Preparation of the model to integrally evaluate the district's environmental performance

3.1. Entire structure of the evaluation model

Figure 1 shows the entire structure of the model to integrally evaluate the district's environmental performance. In order to evaluate the district's environmental performance comprehensively and easily from 4D-GIS data from past to present, the environmental performance integral evaluation model developed in this study consists of three elements: 1) the building renewal prediction model to process buildings' renewal time in future and to store 4D-GIS database, 2) the living environment simulation that uses the 4D-GIS data to calculate the physical amount in the residential environment of the district, and 3) the triple-bottom-line (TBL) (John, 1992) evaluation system to integrally evaluate the district's environmental performance from the aspects of society, economy and environment.

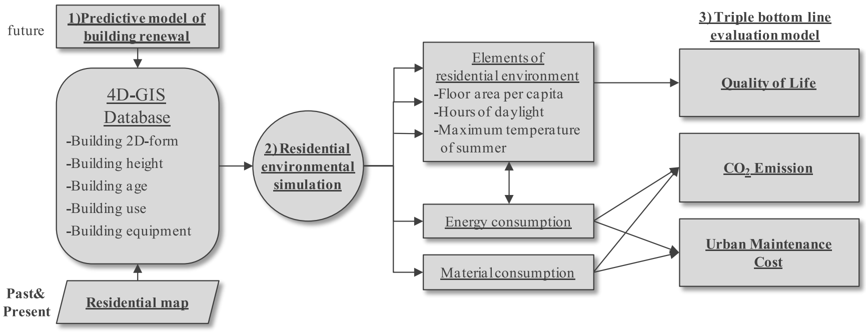

Fig. 1. Overall structure of evaluation system

3.2. 4D-GIS database

4D-GIS arranges the spatial data with the height information (3D-GIS) on a time-series basis (Figure 2), and the 4D-GIS databases have been built up by the cities of Manchester, UK (Tanikawa et al., 2009); Kyoto, Japan

(Yano et al., 2011) and others. In Japan, the housing maps with such information as owner and level of each individual building have been prepared annually since the 1950s, even in areas without specific historical importance, and it is possible to know changes in special design over a period of time. The databases are also built up by adding such information as the construction year and number of levels to complement the building structure and building performance information, which will be necessary for simulation in future.

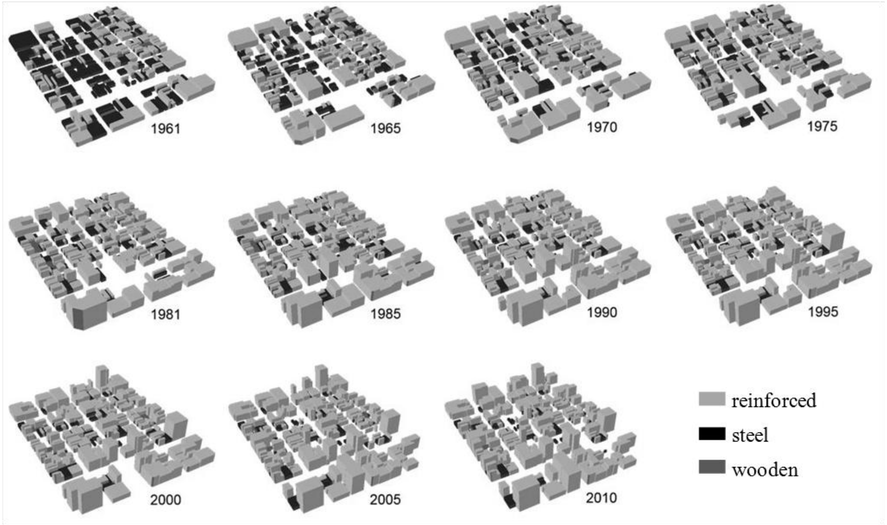

Fig. 2. A case of 4D-GIS (1961 – 2010, building construction)

3.3. Future prediction of building renewals

To further evaluate the time-series environmental performance from present to future, it is necessary to predict when the existing buildings will be renewed. Nevertheless, since it is difficult to predict when each building will actually be renewed, this study used the Monte Carlo method to prepare a renewal prediction model. To be more specific, the loss rate function $f_i(t, t_i^0, c)$ of a building structure c having the construction year t_i^0 as an explanatory variable is set as in the formula (1) using the form of normal distribution function (Komatsu et al., 1992). Simulations for each year are performed using the formula.

$$f_i(t, t_i^0, c) = \frac{1}{\sqrt{2\pi}\sigma_c} \exp\left\{ -\frac{((t - t_i^0) - l_c)^2}{{\sigma_c}^2} \right\} \tag{1}$$

The average life l_c and standard deviation ${\sigma_c}^2$ of the loss rate function are set based on the residual rate between the time points in a survey by Mr. Komatsu and others (Komatsu, 2008) (Table 1). Status of replacement buildings (such as form, volume, height) is determined exogenously by each scenario.

Table 1. Function of building renewal according to structure and use

	Average			Variance		
Construction	DH	CH	BO	DH	CH	BO
RC	56.2	46.7	47.1	15.3	5.3	11.4
S	48.6	44.5	41.5	14.3	5.9	9.9
W	50.7	41.8	-	16.6	9.6	-

The following abbreviations are used in Table 1:

Construction:	Use:
RC.......Reinforced Concrete	DH ....Dedicated dwelling House
S ....Steel	CH ....Cooperative House
W ....Wooden	BO ....Business Office

3.4. Residential environment simulation

This, based on the 4D-GIS, calculates the residential environment elements that comprise amenities, and the amount of resources necessary for living.

3.4.1. Sunlight simulation

To calculate the duration of sunlight DT_i to each building, the duration of sunlight to 3D box models from the 4D-GIS per hour at the spring equinox is calculated according to the formula (2).

$$DT_i = \sum_h \frac{LA_i^h}{A_i} \tag{2}$$

Where LA_i^h represents the area to receive the sunlight in the period h, and A_i represents the building's ceiling area.

3.4.2. Ambient temperature simulation

To calculate temperature changes in a city's downtown area, CFD (Computational Fluid Dynamics) simulation was used because it can consider the ventilation and thermal diffusion of various spatial designs. The analysis method followed the preceding study by Mr. Mochida et al. (2011), and the unit of analysis was an analysis model represented by a building block corresponding to every 1/4 of district (50 m (x_1) × 50 m (x_2) × each height) based on the 4D-GIS data (Figure 3).

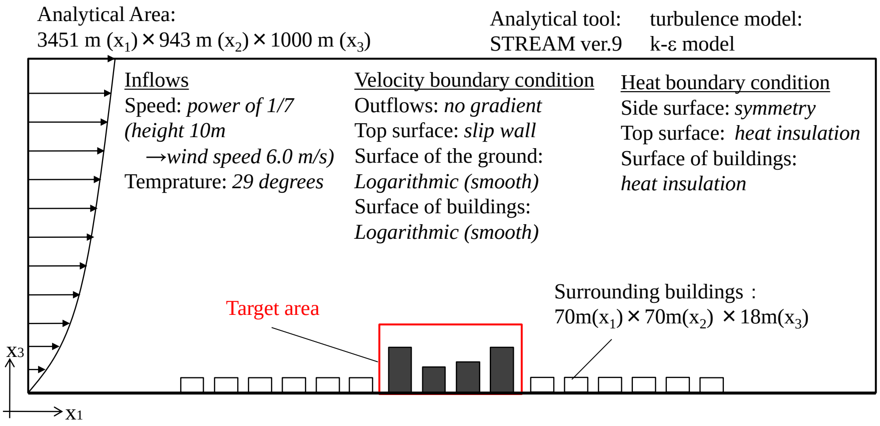

Fig. 3. Calculation condition of temperature simulation

3.4.3. Energy simulation

The duration h of social activities in the district and the energy consumption $ec_{i,h,m}$ of an energy type m are calculated by a simulation of each building's energy balance in each hour of each month. To be more specific, by taking account of the recycled energy supply $ec^r_{i,u,h}$ and the facilities' energy conversion efficiency $\eta_{i,u,h,m}$ in addition to the energy demand quantity $q_{u,h}$ per floor area a_i in each application u (electricity, hot water supply, heating and cooling), they are calculated according to the formula (3).

$$EC_{i,h,m} = \sum_{u} \frac{(q_{u,h} \cdot a_i - ec^r_{i,u,h} + ec^s_{i,u,h})}{\eta_{i,u,h,m}} \tag{3}$$

Where $ec^{s}_{i,u,t}$ represents the battery's charging and discharging amount as well as the thermal storage tank's (or the hot water storage tank's) heat charging and discharging amount at the time. If these facilities are introduced, it is possible to use the surplus electricity and exhaust heat under the conditions of the formula (4) depending on the maximum capacity $C^{s}_{i,u}$ of the facilities.

$$0 \le \sum_{h} e^{s}_{i,u,h} \le C^{s}_{i,u} \tag{4}$$

3.4.4. Material simulation

The amount of material $M_{i,k,l}$ necessary to rebuild, maintain and renew the buildings in the district is calculated by multiplying the unit consumption of each building by the total floor area. The unit consumption $m_{c,k,l}$ in each stage of individual buildings l (construction, maintenance and disposal) and of each material k are calculated according to the formula (5) based on the integrated amount of the materials thought to be necessary from standard design examples of each building structure.

$$M_{i,k} = \sum_{l} m_{c,k,l} \cdot a_i \tag{5}$$

3.5. Triple-bottom-line (TBL) evaluation system

Of the residential environment elements and the necessary resources for living calculated above, the TBL evaluation system is prepared to integrate social aspects into the residents' QOL, the economic aspects into the urban maintenance cost, and the environmental aspects into CO_2 emission.

3.5.1. Quality of life (QOL) evaluation model

Good residential environment that residents can enjoy from their residential area is determined by the physical performance of the residential environment and subjective sense of value held by the residents there. It is integrated as "Quality of Life (QOL) for evaluation. In determining the QOL measurement index AM_j, three axes of domain, value and environment are set to keep the independence of each index. In reference to a study by Kachi et al (2008), eight indices were selected (Table 2).

Table 2. View of QOL measured index

Field	Subject	Value	Measured Index
Private	Artificial	Direct	Total floor area per capita (m^2)
		Indirect	Noice level (dB)
	Nature	Direct	Private garden (dummy)
		Indirect	Hours of daylight (hr)
Public	Artificial	Direct	Number of store within walking distance
		Indirect	Unity of buildings (%)
	Nature	Direct	Rate of open-space (%)
		Indirect	Maximum temperature of summer (degree)

The QOL values are defined as a linear sum calculated by multiplying these indices by the weight of value to each index w_j, and is expressed in the formula (6).

$$\begin{aligned} QOL &= f(\mathbf{w}, \mathbf{AM}) \\ &= \sum_j w_j \cdot AM_j \end{aligned} \tag{6}$$

The weight representing the residents' sense of value w_j was estimated through conjoint analysis. A questionnaire-based survey (Table 3) was conducted to ask the residents to choose one of two residential areas with different attribute profiles, from which their preference was gained as a result. Afterward, $\mathbf{w}$ is calculated by the maximum-likelihood estimation on the assumption of a binominal logit model. Besides, by informing the death risk from earthquake in each residential area as well, the weight of each $\mathbf{AM}$ factor in relation to their survival time was estimated. In this way, the QOL values are integrated to the unit, “Quality Adjusted Life Year (QALY)” (Kachi et al., 2007), for use (Table 4).

Table 3. Summary of questionnaire

Item	Content
Timing	2012/12/19〜21
method	WEB
Region	Nagoya urban area
Sample number	1,000 (Age: twenties to sixties)
Content of questionnaire	Ranking of alternatives, individual attribute

Table 4. Result of adjusted life year

Measured Index	Unit (#)	Adjusted life year (year/#*year)	t-value
Total floor area per capita	m^2	0.037	21.66***
Noice level	dB	-0.022	9.87***
Private garden	Dummy	0.002	1.64
Hours of daylight	Hour	0.101	13.34***
Number of store	number	0.020	15.01***
Unity of buildings	%	0.296	8.67***
Rate of open-space	%	3.079	10.54***
Maximum temperature of summer	degree	-0.125	-24.36***

*10%, **5%, ***1%

3.5.2. CO_2 emission evaluation model

As the environmental aspects, the amount of CO_2 emitted in an entire life cycle through activities necessary to live in and maintain the district to be surveyed shall be subject to evaluation. Specifically, the amount of CO_2 emission through consumer activities (of households and businesses) $E^e_{CO_2}$ shall be calculated from the energy consumption estimated in the previous section, and the amount of CO_2 emission in each phase from the building and infrastructure construction to the disposal shall be calculated from the material consumption. Each unit consumption shall be further calculated based on the statistical data (JEMAI, 2007; Shibahara et al., 2008). In addition, it shall be considered that the environmental load is generated in each stage of the buildings' and infrastructure's life cycle, and that the environmental load can be calculated according to the formula (7).

$$\begin{aligned} E_{CO_2} &= E^b_{CO_2} + E^e_{CO_2} \\ &= \sum_{i,k} e^b_k \cdot M_{i,k} + \sum_{h,i,m} e^e_m \cdot EC_{i,h,m} \end{aligned} \tag{7}$$

Where e^b_k represents the amount of CO_2 emitted per consumption unit of an infrastructure material k over its life cycle, and e^e_m represents the amount of CO_2 emitted per consumption unit of an energy type m.

3.5.3. Urban maintenance cost evaluation model

As the economic aspects, the cost caused by activities in the district in the entire life cycle shall be subject to evaluation. Like the amount of CO_2 emission, the cost caused by activities from the building and infrastructure construction to disposal C^b as well as the cost to be paid for the consumed energy in consumer activities (households and businesses) C^e are studied to specify their unit consumption (MLIT, 2011), and shall be calculated according to the formula (8).

$$\begin{aligned} C &= C^b + C^e \\ &= \sum_{i,k} c_k^b \cdot M_{i,k} + \sum_{h,i,m} e_m^e \cdot EC_{i,h,m} \end{aligned} \tag{8}$$

Where c_k^b represents the cost per consumption unit of a building or infrastructure material k, and c_m^e represents the cost per consumption unit of an energy type m.

4. Case Study : District Planning of Choja-machi

4.1. Outline of the district subject to the case study

We used the prepared models to carry out a case study of the Choja-machi district (2 Nishiki, Naka-ku, Nagoya City, Figure 4), a downtown area in Nagoya City, Japan. While the district once developed with the textile wholesale business, the small business offices, restaurants and condominiums are increasing in the district in recent years. Even so, the district is not in a desirable state as a residential area with many buildings constructed on small sites.

The Choja-machi district prepared the program called "Urban Planning Concept of Future Nishiki Nichome (2 Nishiki) " (Nishiki 2-Chome liaison council on Town Planning, 2011) and is working on an improvement in the residential environment of the district and others over the next 20 years. Nagoya City, to which Choja-machi belongs, also encourages people to live in districts close to train stations, and it is expected that the provision of a comfortable residential environment will bring more residents into such districts as a result.

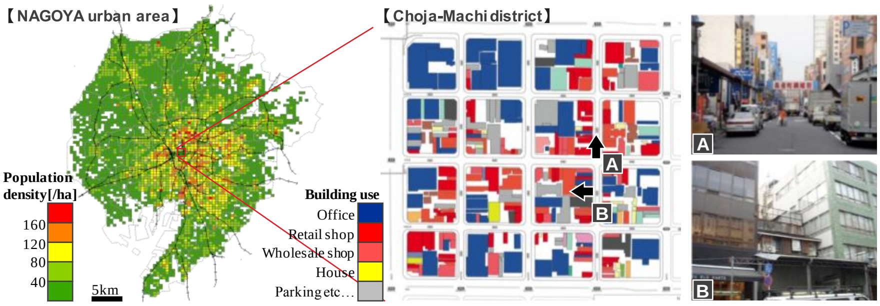

Fig. 4. Summary of Choja-machi district

4.2. Analysis scenario setting

Table 5. Configuration of each scenario

Items	BAU(Business as Usual)	DRP(District Renewal Plan)
Building equipment	All renewal building wills be equipped with solar-power system, fuel-cell cogeneration system and battery.	Same as on the left
Land-use	The status quo. (All blocks use mixed)	Rezoning as 10 blocks of external side use office and shop, 6 blocks of internal side use mixed.
Renewal scale	All buildings will be rebuilt individually	All buildings will be rebuilt collectively in units of from 1/4 to 1 blocks
Renewal timing	Following the prediction result.	Midterm in renewal timing of each building
Open space	The status quo.	Buildings FAR is within 300% are courtyard apartment type, those FAR is bigger 300% are tower type.
Street	The status quo.	Widening of a sidewalk.

For analysis, two scenarios were set: one is "BAU (business as usual) scenario" in which the existing buildings will be freely rebuilt as before; and the other is the "DRP (District Renewal Plan) scenario" in which buildings of similar age will be renewed together in each block in the district.
Figure 5 shows an outline of DRP scenario, and Table 5 shows the conditions of each scenario setting.Both cases followed the future prediction that

the number of households will be 1.8 times more and the working population 1.4 times more than the year 2010 while the predicted technology level of the building facilities was adopted as that of the reconstructed buildings in order to agree with the technology innovation road map (NEDO, 2009a; NEDO, 2009b; Agency for Natural Resources and Energy, 2008) prepared by the Japanese government.

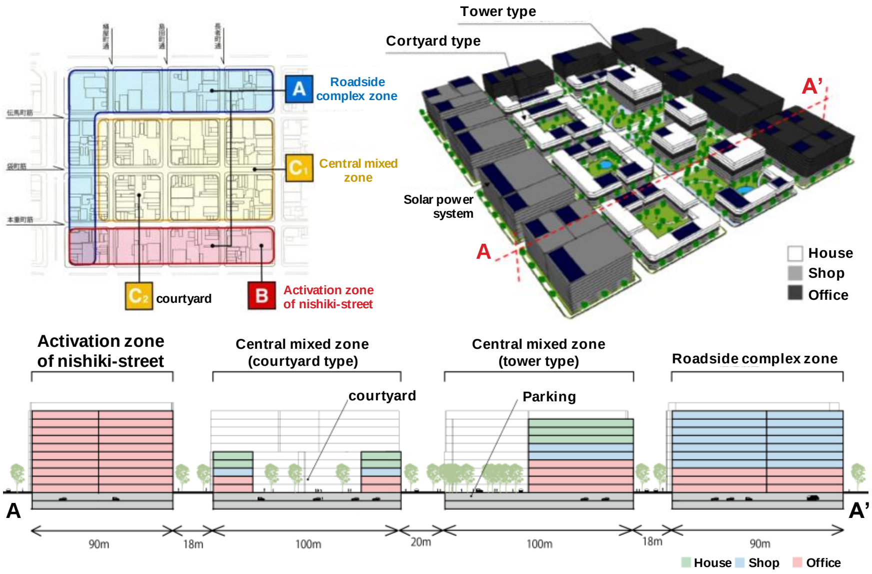

Fig. 5. Summary of DRP scenario (2050)

4.3. Result of building renewal prediction

Figure 6 shows prediction examples of renewal at 10 year intervals in each scenario. In the BAU scenario, buildings are constructed on the same sites even after renewal and reconstruction continues in steps over 40 years. In order to secure larger floor areas than now, the building volume varies from one building to another, which could create a special design having a large difference in height among the buildings. In DRP scenario, on the other hand, since it takes a certain period to secure large construction sites, it is predicted that only the loss of buildings will happen for 10 years from 2020 and the building renewals will concentrate from 2020 to 2030 or so.

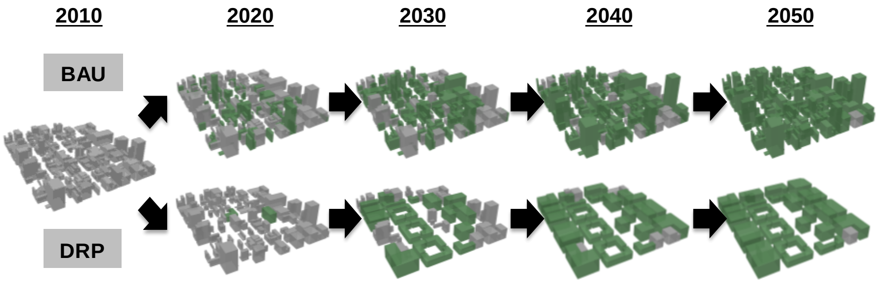

Fig. 6. Example of prediction results (decade after decade from 2010 to 2050)

4.4. Result of living environment simulation

Figure 7 shows results of sunlight, ambient temperature (summer) and energy simulations in each scenario. In the BAU scenario in which a large difference in height is found among the buildings, more than half of the buildings get sunlight for not more than six hours, and many get sunlight for two hours or less. By contrast, individual buildings become larger in DRP scenario with more space provided between the buildings and a smaller difference in height among them. This enables more than 80% of the buildings to get sunlight for eight hours or more.

The summer-time ambient temperature simulation revealed that there is the heat accumulation in many spots in the BAU scenario in which buildings are small. The concentration of heat accumulation is also found in some spots in DRP scenario, but places in the center of the perimeter-block buildings are designed to be in the shade with good ventilation. The temperature in many of these places is relatively low; this design is expected to create a comfortable outdoor space.

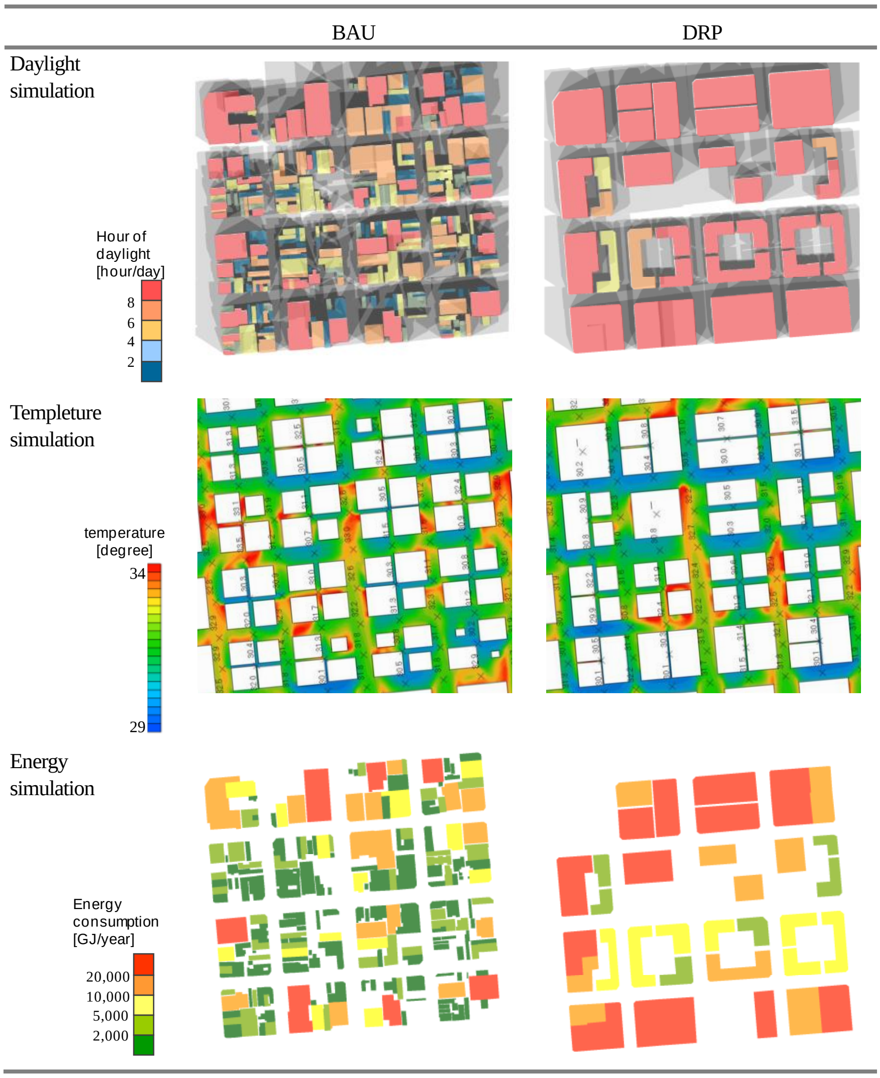

Fig. 7. Example of simulation results (2050)

4.5. Overall evaluation of the environmental performance

4.5.1. Result of the quality of life (QOL) calculation

Figure 8 shows a change in the QOL value from 2010 to 2050 of both the BAU and redesign-plan scenarios. While the BAU scenario shows a trend of gradual decrease in the QOL value from now, down 0.03 (day/year) in 2050 on 2010, DRP scenario shows a sharp increase in the QOL value from about 2020, up 4.39 (day/year) in 2050. The QOL value was decreased largely by the shorter duration of sunlight in particular. Unorganized renewal reduces the living comfort ability of the entire district to a large extent. DRP scenario provides open spaces, greenery, well-balanced landscapes and more time for sunlight through an organized spatial plan. It revealed that the effect of facilities was quantitatively indicated in the QOL value of the residents.

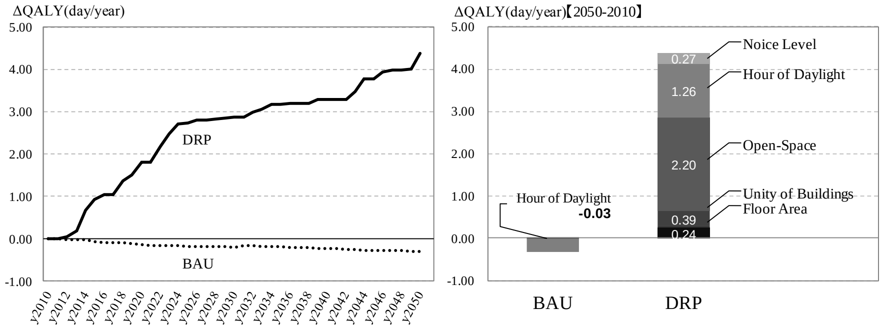

Fig. 8. Transition of QOL-value from 2010 to 2050 (left) and breakdown of 2050 (right)

4.5.2. Result of CO_2 emission amount and urban maintenance cost calculation

Figure 9 shows the calculation result of both BAU and redesign plan scenarios from 2010 and 2050 (businesses and construction industry are excluded from the calculation). It is expected that even in the BAU scenario, CO2 emission will be significantly reduced in the consumers' activities as well as in traffic through the introduction of low carbon technologies. Energy savings of approximately 59% in comparison to 2010 are expected. Besides, the energy demand can be leveled and become more efficient by taking advantage of multiplicity in building application and renewing buildings together, which further saves energy, by 23% respectively, in comparison with the BAU scenario.

The urban maintenance cost more or less follows the trend of CO2 emission. The cost in the BAU scenario remains almost the same from 2020 on, achieving a reduction of only about 4% from 2010 to 2050. The extent of reduction is also small in DRP scenario, with only a 13% reduction from 2010. It is considered that the construction accounts for a larger ratio in the maintenance cost than the energy and this explains the smaller reduction in the cost than in CO2 emission.

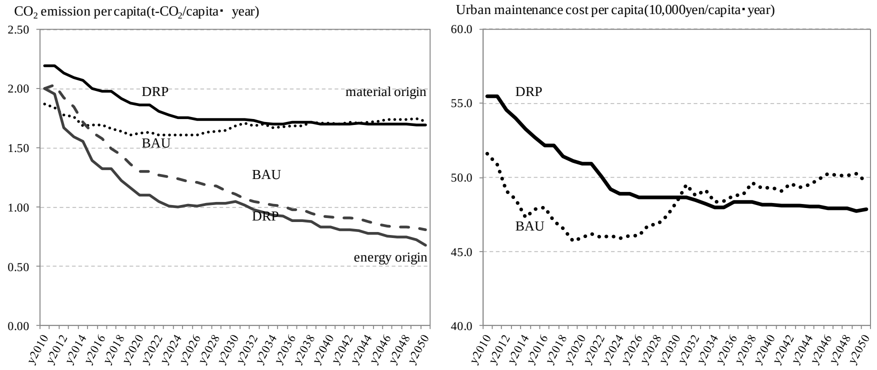

Fig. 9. Results of CO_2 emission per capita(left) and urban maintenance cost per capita (right) (from 2010 to 2050)

4.5.3. Comparison between eco-efficiency and cost efficiency

The eco-efficiency Ef and cost efficiency Cf are the indices that represent environmental and economic efficiency in relation to the services provided by the district, or the QOL value. They are defined by the formulae (9) and (10) respectively.

$$Ef = QOL / E_{CO_2} \tag{9}$$

$$Cf = QOL / C \tag{10}$$

Figure 9 shows the change in the eco-efficiency and cost efficiency from 2010 to 2050 in each scenario. Although the eco-efficiency is increased in the BAU scenario by reduction of CO_2 emission through technology introduced by 2050, the efficiency in DRP scenario is further improved by an increase in the QOL value, which reveals that the district develops to be more eco-efficient. From the viewpoint of cost, DRP scenario shows that the district also becomes more cost-efficient with an improvement trend from 2020 on following the eco-efficiency although its performance is temporarily poorer than that of the BAU scenario due to slow renewal in the district between 2010 and 2020.

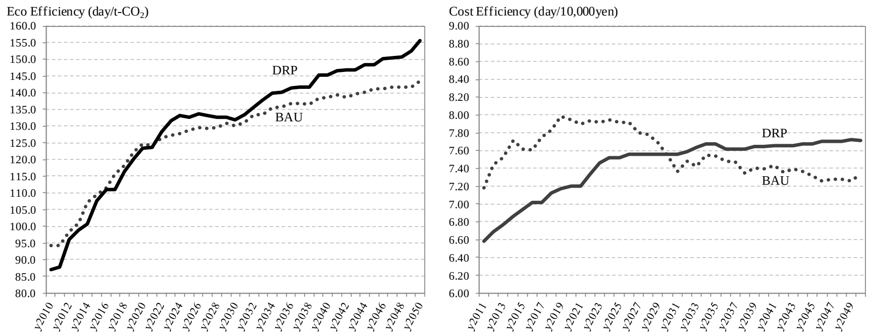

Fig. 10. Results of Eco Efficiency (left) and Cost Efficiency (right) (from 2010 to 2050)

5. Conclusions

This study has presented a model that uses the 4D-GIB database and evaluates the environmental performance of districts regarding TBL, through prediction of annual building renewal based on such practical data as construction year and detailed environmental simulations taking account of sunlight. It has enabled us to present designs on the time-series basis necessary to change the built-up areas into low-carbon communities, or to indicate the effect quantitatively for consideration of district planning. The following points have been clarified by the case study.

1. The introduction of new technologies, such as solar power generation and cogeneration, contributes significantly to the reduction of CO_2 emission. Besides, further reduction can be expected depending on the spatial design and the arrangement of buildings.
2. When each building is rebuilt individually, comfortability in the outdoor space, sunlight or landscape, for example, could deteriorate. On the other hand, when the buildings are renewed in an organized way as well as in accordance to the rules of the district, a significant improvement in comfortability can be expected.
3. Particularly in the case of downtown areas, it is more beneficial to an improvement of the residents' QOL to renew the buildings in each block together for an enlargement of each building and diversification of building application, rather than rebuilding buildings on each site individually. This method can reduce CO_2 emission as well as the cost in terms of energy consumption.

4. This model is effective as information tool to facilitate consensus-building on redevelopment efforts among each stakeholder in district such as city counsil, residents, land owner and so on. For the future, it is will need to discuss the scheme to gain win-win outcome for each stakeholder.

Acknowledgements

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