A STUDY ON 3-DIMENSIONAL COMPACTNESS OF BUILDINGS IN NAGOYA CITY

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Urbanization has been causing various environmental problems such as heat island and energy consumption which are associated with spatial structure of urban land use. Based on 3-Dimensional building information, this study developed a new Distance-Height Index (DHI) to describe the compactness of urban buildings. DHI values were calculated for Nagoya City in 1991, 1996 and 2001 to evaluate the temporal variation and spatial distribution of building compactness. The characteristics of subway stations were also assessed using DHI values. Finally, DHI was related to land surface temperature (LST) to show the relationship between human activity and urban thermal environment.

Key Words: *compactness, height, DHI, building, LST, Nagoya City*

1. INTRODUCTION

Urbanization and human activity have reached the limitation of land environmental burden that arousing urban heat island, transportation problem, energy consumption and other environmental deterioration problems. It is important to optimize the spatial structure of urban land use to improve the urban environment. Under this background, Nagoya City aims to be a 'low-carbon and comfortable city' by introducing 'close-to-station' policy, which redesign the city by establishing compact residence and convenient lifestyle around a station of the public transport.

This study intends to evaluate the urban building compactness by involving height of buildings and distinguishing the uses of the buildings. The urban compactness has been described by many authors at urban scale[1)], block scale[2)] or pixel scale[3)], and the compactness of land use has been related to transportation[4)] or land surface temperature (LST)[5)]. However, these researches focused on the agglomeration or compactness of land uses at 2-Dimension, e. g. a building distance compactness index, the Distance Index (DI) was created by summarizing the distance between central point and neighboring pixels within a given range[6].

Considering the necessity of incorporating height to describe the compactness of building[7)-9)], in this study, a new 3-Dimensional Distance-Height Index (DHI) was proposed based on DI and incorporating height of buildings to evaluate the 3-Dimensional building compactness in Nagoya City. The values of DHI were calculated in 1991, 1996 and 2001, and the relationships between DHI and subway stations and land surface temperature (LST) were evaluated.

2. MATERIALS AND METHODS

(1) Materials

Nagoya City building GIS data[10] were collected, including 1991, 1996 and 2001. The attributes of the building GIS data involve numbers of floor, the uses of the building, area, etc. The spatial accuracy of the data is very high (<1 m); however, in order to calculate the urban form index, the vector data was degraded to 10m spatial resolution raster data and only kept the attributes of numbers of floor, the uses of the building and areas of buildings. Here we used numbers of floor as the height of the buildings. The uses of the buildings were categorized by all buildings and specific uses of commerce, residence, education, entertainment, industry, hospital and park.

The subway stations GIS data[11] was also used to analyze the location of subway stations. Totally there are 129 subway stations in Nagoya City (with some missing stations), and shortest distances between stations are averaged as 721m.

(2) Concept of Distance-Height Index (DHI)

Based on concept of DI[5),6)], the Distance-Height Index (DHI) integrates the uses of buildings, the distance between one location (I, J) and neighboring buildings (with different uses), and the height of the buildings. The calculation of DHI is given by:

$$\mathrm{DHI}_{I,J} = \frac{\sum_{i=0,j=0}^{i=M,j=M} U_{i,j} \times D'_{i,j} \times H_{i,j}}{\sum_{i=0,j=0}^{i=M,j=M} D'_{i,j}} \qquad (1)$$

where (i, j) is the location of neighboring pixels, M is the size of a window centered by (I, J), $U_{i,j}$ is the binary variable indicated the specific uses, e.g., when analyzing commercial buildings, the pixel with commercial use will be assigned a valid value of 10, and 0 for non-commercial uses. $H_{i,j}$ is the height of the pixel. Considering the non-linear distance decay[12], the distance between central pixel and any neighboring pixels was computed by logistic model[13] as the following function:

$$D' = \frac{1}{1+e^{-(a+b\times D)}} \qquad (2)$$

where D is the Euclidean distance (in unit of pixel) between point (i, j) and central point (I, J), D' is the distance value converted by logistic model (logit distance), and a and b are parameters of logistic model. Here we used a 101×101 window (i.e. M=101, and real size of the window is 1.01km×1.01km) to generate the template of logit distance (**Fig. 1**), with a and b values of 5.0 and -0.2, respectively.

(3) Land surface temperature (LST) estimation

The DHI index is associated to land surface temperature (LST) to evaluate the relationship between height of buildings and temperature. We used Landsat 7 EMT+ band 6 (TIR) data on July 4 2001 to derive LST. The raw ETM+ digital number (DN) values were converted to radiance for band 6 and reflectance for band 3 (red) and 4 (NIR), and the latter two bands were used to calculate normalized difference vegetation index (NDVI). The method for estimating LST was the mono-window algorithm[14]. The emissivity of each

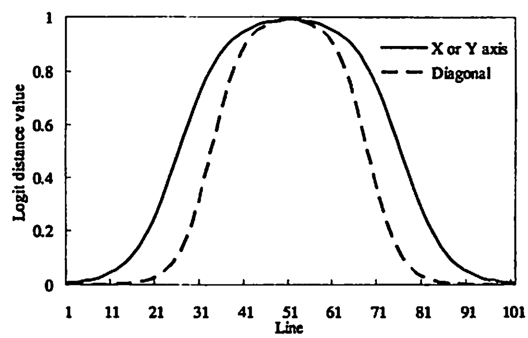

Fig. 1 Logit distance in a 101×101 window. The figure shows the variation of logit distances at X (or Y) axis and diagonal direction.

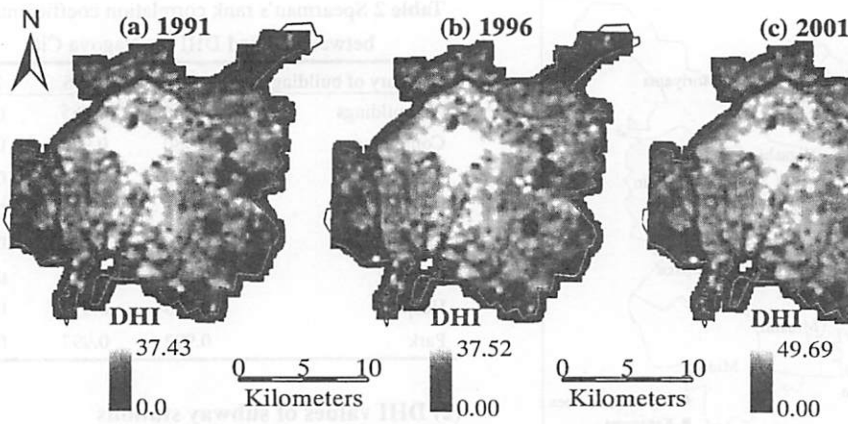

Fig. 2 DHI index (all buildings) of Nagoya City in 1991, 1996 and 2001

land cover was assigned to 0.99 for water and 0.956 for urban land use. For vegetated area, the emissivity was estimated based on the ratio of vegetation and bare ground[15]. For high density vegetation (NDVI > 0.72), the emissivity was set as 0.985. We didn't validate the LST result using measured LST because we just intended to find out the qualitative relationship between height of buildings and temperature.

3. RESULTS

(1) DHI results and comparison with DI index

We calculated DHI values of Nagoya City in 1991, 1996 and 2001 for all buildings (**Fig. 2**) and 7 categories of uses, and **Table 1** shows the temporal variations from 1991 to 2001 for all buildings, commerce, residence and industry in each administrative ward of Nagoya City.

We can observe an increase of maximal DHI (all buildings) index values from 1991 to 2001 in **Fig. 2**, which is mainly induced by building heightening in central area, yet the spatial structure of DHI during the period does not change. **Table 1** indicates the comparison among wards (see **Fig. 3**) and the temporal changes of DHI values. It is found that DHI of all buildings, commerce and residence basically increase during 1991~2001; however, the values of industry decrease within the period for all the wards. This variation could be explained by higher buildings for commercial or residential uses

Table 1 Temporal DHI variation and comparison among administrative wards of Nagoya City

	All buildings			Commerce			Residence			Industry		
	1991	1996	2001	1991	1996	2001	1991	1996	2001	1991	1996	2001
Moriyama-ku	2.55	2.77	3.05	0.12	0.14	0.17	1.70	1.85	2.08	0.26	0.25	0.22
Kita-ku	5.55	5.85	6.09	0.45	0.54	0.51	3.83	4.02	4.16	0.35	0.28	0.28
Nishi-ku	5.48	5.81	5.97	0.62	0.76	0.76	3.28	3.30	3.42	0.70	0.60	0.55
Higashi-ku	8.42	8.72	9.22	1.73	2.10	2.19	3.90	4.03	4.39	0.73	0.72	0.58
Meito-ku	4.10	4.45	4.92	0.30	0.37	0.41	3.24	3.50	3.88	0.04	0.02	0.02
Chikusa-ku	5.66	5.93	6.43	0.52	0.56	0.62	3.82	3.95	4.37	0.09	0.08	0.05
Nakamura-ku	7.13	7.48	7.85	1.76	1.95	2.20	3.82	3.69	3.76	0.38	0.36	0.18
Naka-ku	12.77	13.69	14.58	6.37	6.97	7.25	3.29	3.56	3.94	0.25	0.19	0.18
Nakagawa-ku	4.07	4.38	4.64	0.30	0.34	0.36	2.36	2.58	2.81	0.51	0.48	0.48
Showa-ku	6.67	7.12	7.72	0.57	0.69	0.74	4.17	4.43	4.97	0.19	0.16	0.16
Tempaku-ku	3.57	4.02	4.35	0.21	0.26	0.27	2.57	2.94	3.25	0.14	0.14	0.14
Atsuta-ku	6.74	7.13	7.62	0.99	1.16	1.34	2.93	3.15	3.57	1.11	1.00	0.94
Mizuho-ku	6.64	6.95	7.03	0.42	0.46	0.54	4.17	4.42	4.65	0.70	0.66	0.54
Minato-ku	3.02	3.39	3.60	0.22	0.27	0.33	1.31	1.44	1.58	0.69	0.69	0.66
Minami-ku	5.80	6.04	6.24	0.38	0.46	0.51	3.29	3.42	3.60	1.00	0.98	0.92
Midori-ku	2.82	3.14	3.55	0.14	0.19	0.22	1.98	2.26	2.62	0.27	0.25	0.26

Fig. 3 The administrative wards of Nagoya City and the locations of selected subway stations

and decentralization of industry in Nagoya City. Among the wards, Naka-ku has the highest DHI (commerce) value, which means the height or compactness of commercial buildings are concentrated in this district. For residential use, the DHI values are homogeneous, but also we can find the main residential regions as Showa-ku, Mizuho-ku and etc. DHI (industry) values are very low for all the wards. The all buildings' DHI indicates the overall building compactness in Nagoya City. Naka-ku and Nakamura-ku are the most compact wards, while Moriyama-ku and Midori-ku are the most low density wards.

We also calculated the DI (2D) for Nagoya City during 1991, 1996 and 2001, and then compared it with DHI (3D) by Spearman's rank correlation coefficient (ρ^2)[16]:

$$\rho^2 = \frac{\left(\sum_{i=0}^{N-1}\left(Rx_i-\overline{Rx}\right)\left(Ry_i-\overline{Ry}\right)\right)^2}{\sum_{i=0}^{N-1}\left(Rx_i-\overline{Rx}\right)^2\sum_{i=0}^{N-1}\left(Ry_i-\overline{Ry}\right)^2} \qquad (3)$$

where N is the total number of pixels, Rx_i and Ry_i are the magnitude-based ranks among X (DI) and Y (DHI), respectively. The Spearman's rank correlation coefficient (ρ^2) results are shown in **Table 2**. Generally DHI and DI have high Spearman's rank correlation coefficients, yet the decrease among years indicates the enhancement of impact of height. The low ρ^2 of residence shows the high heterogeneity of residential building's height.

Table 2 Spearman's rank correlation coefficients (ρ^2) between DI and DHI for Nagoya City

Category of building	1991	1996	2001
All buildings	0.906	0.885	0.870
Commerce	0.980	0.976	0.974
Residence	0.899	0.874	0.850
Education	0.971	0.970	0.972
Entertainment	0.974	0.971	0.969
Industry	0.990	0.990	0.989
Hospital	0.973	0.970	0.967
Park	0.992	0.997	0.994

(2) DHI values of subway stations

In order to analyze the 'close-to-station' policy in Nagoya, some subway stations were selected (Nagoya, Sakae, Kanayama, Motoyama, Higashiyama Koen and Yagoto, see **Fig. 3**) and evaluated their DHI values. **Fig.4** shows the temporal variations of DHI (all buildings) for these subway stations. It is observed that Nagoya and Sakae have the highest compactness index values for all buildings; specially, the DHI in Nagoya station has significantly increased during 1996~2001. The similar increments are also found in Kanayama and Yagoto, which means the centralization or heightening of buildings around these subway stations. **Table 3** indicates the specific uses' DHI values of these stations in 2001. Nagoya and Sakae are commercially compact stations whose DHI (commerce) values are 36.62 and 20.71, respectively. Kanayama is also compact for commercial use buildings. Motoyama and Higashiyama Koen are relatively compact for residential buildings. Around Yagoto, however, the commercial, residential and educational uses buildings all have relatively high compactness. The

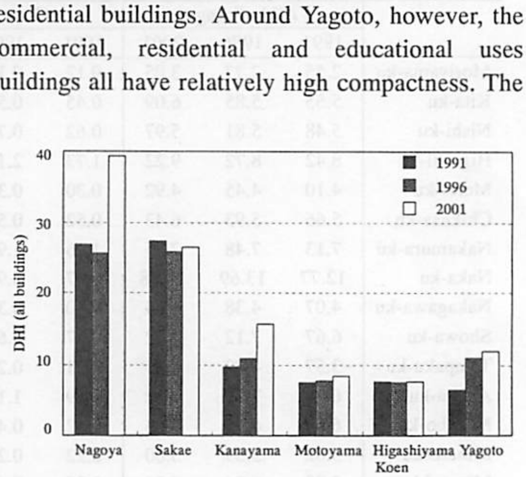

Fig. 4 DHI variations from 1991 to 2001 for selected subway stations

Table 3 DHI values for subway stations (2001)

Subway station	Commerce	Residence	Education	Entertainment	Industry	Hospital	Park
Nagoya	36.62	0.29	0.47	0.34	0.02	0.07	0.01
Sakae	20.71	0.23	3.40	0.41	0.00	0.33	0.00
Kanayama	9.81	2.72	0.84	0.72	0.03	0.19	0.00
Motoyama	1.43	5.82	0.15	0.20	0.02	0.24	0.00
Higashiyama Koen	0.62	6.28	0.18	0.00	0.10	0.13	0.00
Yagoto	3.91	3.90	2.64	0.01	0.07	0.03	0.00

DHI value for each station suggests the possible purpose of population flow, and it has the potential to be used to evaluate the 'close-to-station' policy.

(3) DHI index and LST

In order to analyze the reflection of DHI on unban environment, the LST is related to DHI to evaluate the relationship between temperature and compactness of all buildings. Because of neighboring effect on DHI, the correlation between temperature and DHI at pixel level is very low. Thus we calculated the average DHI (all buildings) and average LST for each administrative ward in 2001, and found the significant correlation between DHI and LST at district level (N=16, R^2=0.4317, p<0.01, **Fig. 5** a). It should be noted that the DHI and LST values of Naka-ku is obviously outside the cluster of the other wards, with the highest DHI value and lower LST. Naka-ku is the most commercially compact ward (**Table 1**), while there is also large area of vegetation (parks) which will dramatically reduce the average LST of this ward. If remove Naka-ku and then correlate DHI and LST using the other wards, the correlation coefficient (R^2) will significantly increase up to 0.7786 (N=15, p<0.01). A comparison was also performed by analyzing the relationship between building coverage and LST. Here the building coverage equals to total area of buildings in each ward divided by total area of each ward. The low and insignificant correlation coefficient (N=16, R^2=0.182, p>0.05, **Fig. 5** b) suggests that the building coverage are less sensitive to human activity associated urban environment than 3D compactness of buildings.

4. CONCLUSIONS AND DISCUSSION

In this study, a new DHI index was developed to describe the 3D compactness of buildings in urban area. The concept of DHI is based on DI with involving the height of buildings and the distance of neighboring buildings. The DHI values of all buildings and 7 categories of uses are calculated for Nagoya City in 1991, 1996 and 2001. The 3D compactness for each ward was evaluated and compared, and the commercially and residentially

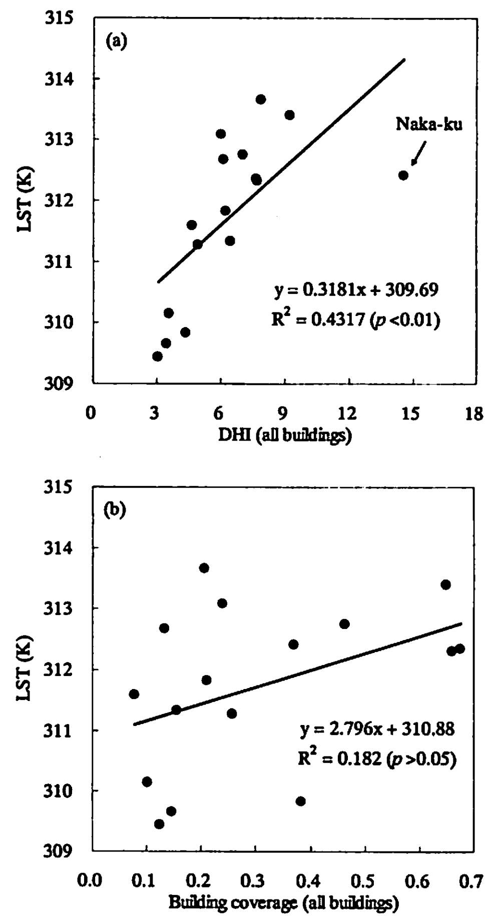

Fig. 5 Relationship between LST and (a) DHI values, and (b) building coverage; the point indicates the average value for each ward.

compact wards were found to be Naka-ku and Showa-ku. For all the buidings, Naka-ku and Nakamura-ku are the most compact wards, and Moriyama-ku and Midori-ku are the least compact wards. DHI values of subway stations were also evaluated. In the selected stations, the temporal variation and the specific uses compactness were analyzed, and Nagoya and Sakae were found to be commercially compact stations, while Motoyama and Higashiyama Koen are relatively compact for residence. Finally, DHI was associated with LST, and it was observed a good correlation between DHI and LST at ward level.

Although DHI has the potential to analyze urban environment related to human activity, it is not evaluated the impact or sensitivity of parameters in DHI calculation. On the other hand, the relationship between DHI and LST were evaluated at ward level, which is the administrative boundary without physical definition. To study the lower scale of this correlation will be helpful to understand the impact of buildings, especially the 3D compactness of buildings, on LST or urban heat island.

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REFERENCES

1) Huang, J., Lu, X. X., and Sellers, J. M., A global analysis of urban form: applying spatial metrics and remote sensing, *Landscape and Urban Planning*, 82, pp. 184-197, 2007.

2) Turskis, Z., Zavadskas, E. K., and Zagorskas, J., Sustainable city compactness evaluation on the basis of GIS and Bayes rule, *International Journal of Strategic Property Management*, 10, pp. 185-207, 2006.

3) Yoshikawa, T., A method to analyze characteristics of agglomeration of the same and different kinds of land use using grid data, *Journal of Architecture, Planning and Environmental Engineering, Transactions of AIJ*, No. 520, pp. 227-232, 1999.

4) van de Coevering, P., and Schwanen, T., Re-evaluating the impact of urban form on travel patterns in Europe and North-America, *Transport Policy*, 13, pp. 229-239, 2006.

5) Onishi, A., Hirota, F., Yoshikawa, T., Morisugi, M., and Imura, H., Analysis of urban heat environment by utilizing fine land cover information, *Environmental Systems Research*, 31, pp. 357-365, 2003.

6) Mochizuki, F., Shimizu, H., Ariga, T., and Minami, J., Grasping method of the pattern and level of the agglomeration of land use using remote sensing data: case of West Aichi, *Journal of Architecture and Planning*, No. 617, pp. 47-54, 2007.

7) Taguchi, A., Urban traffic distribution and elevator capacity in supper high buildings, *Journal of the Operations Research*, 40 (4), pp. 536-545, 1997.

8) Gaubatz, P., China's urban transformation: patterns and processes of morphological change in Beijing, Shanghai and Guangzhou, *Urban Studies*, 36 (9), pp. 1495-1521, 1999.

9) Luckman, A., and Grey, W., Urban building height variance from multibaseline ERS coherence, *IEEE Transactions on Geoscience and Remote Sensing*, 41 (9), pp. 2022-2025, 2003.

10) City of Nagoya: Fundamental investigation for urban planning of Nagoya City.

11) Digital Map 2500 (Spatial Data Framework): Geographical Survey Institute.

12) Tiefelsdorf, M.: Misspecifications in interaction model distance decay relations: a spatial structure effect, *Journal of Geographical Systems*, 5, pp. 25-50, 2003.

13) Harrell, F. E: *Regression modeling strategies: With applications to linear models, logistic regression, and survival analysis*, Springer series in statistics. New York: Springer, 2001.

14) Qin, Z., Karnieli, A., and Berliner, P., A mono-window algorithm for retrieving land surface temperature from Landsat TM data and its application to the Israel-Egypt border region. *International Journal of Remote Sensing*, 22 (18), pp. 3719-3746, 2001.

15) Valor, E., and Caselles, V., Mapping land surface emissivity from NDVI: Application to European, African and South American areas. *Remote Sensing of Environment*, 57 (3), pp. 167-184, 1996.

16) Myers, J. L., and Arnold, D. W., *Research Design and Statistical Analysis*, second edition, Lawrence Erlbaum, pp. 508, 2003.