Time-series Analysis and Prediction of Building Material Stock and Flow Using 4d-GIS

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Abstract

We developed 4d-GIS, which is a database of spatial 3D GIS data with a time scale, to estimate building material stock and flow and visualize the transition of buildings in urban districts for contribution to spatial designs. By utilizing 4d-GIS, it was found that steel buildings initially accounted for 60%, but the number of reinforced concrete buildings increased. As for building material stock, it has increased from 0.35 million ton in 1961 to 97.5 million tons in 2010, because of the increase of RC buildings and virtualization. We predicted the building renovation for Business As Usual (BAU) and District Renewal Plan (DRP) scenarios up to 2050. The results show that building material stock does not differ much between BAU and DRP scenarios in 2050, but it was observed in the DRP scenario, building material stock increased by 0.2 million ton because buildings will be rebuilt collectively in units.

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1. Introduction

Dealing with global warming has become a major challenge in developed countries, including Japan, and the reduction of greenhouse gas emissions by introducing low-carbon technologies has become the urgent need of the hour. However, it is difficult to achieve reduction targets via initiatives such as electric vehicles and solar power generation systems in the separate fields of residence, business, and transportation. Therefore, it is necessary to study the links between the infrastructure systems that form the foundation of urban activities as well as the introduction of technologies and policies that support the renovation of urban structures (Sunikka, 2006; Lehmann, 2013). In particular, the life span of buildings is short in Japan compared to the United States and European counties (Johnstone, 1994; Komatsu, 2008), and so district renovations are carried out much earlier.

In addition, as the population decreases, it cannot be assumed that the demand for buildings will remain similar to what it has been historically. Because of this, it is difficult to develop new urban areas. Therefore, it is desirable to carry out the renovation of city blocks in a phased manner to match the pace of building renovation in existing urban areas, and at the same time, introduce low-carbon technologies to match the characteristics of the regions. Furthermore, to help form a consensus among the local residents in the redevelopment of existing urban areas, it is also necessary to visualize and simulate a concrete urban planning image of urban structures and transportation infrastructure by using GIS (Geographic Information System).

In developed countries, there is a responsibility to create not just a low-carbon society but also a sound material-cycle society. Until now, socio-economic development has been accomplished by harvesting a large amount of resources from nature; processing them into various forms of social infrastructure such as buildings, roads and bridges; and using the services thus obtained. Manufacturing construction materials is accompanied by energy expenditure and CO_2 emission. Furthermore, when the structures reach the end of their service life, they are disposed of as trash at the time of demolition.

In view of the limits of natural resources, it is indispensable to construct a sound material-cycle society that efficiently utilizes resources by improving resource productivity and the cycling utilization rate. For this purpose, it is necessary to quantitatively understand the amounts of resources harvested, accumulated, and disposed of in the course of human activities. In this context, MSFA (Material Stock and Flow Analysis) was developed to quantify the amount of material that is harvested from nature by human society and its life cycle.

So far, previous studies related to MSFA such as Gordon *et al.* (2006) , Daigo *et al.* (2007), Hashimoto *et al.* (2007), and Schandl and West (2012) have been carried out at national, prefectural and regional scales. By using MSFA, the environmental load that occurs at each stage of material circulation from the initial resource investment to disposal is estimated, enabling more efficient and sustainable material utilization. However, the estimations in these previous studies have relied on aggregate units of data based on spatial resolution. Therefore, analysis of the districts at the micro-scale level is difficult. On the other hand, in Tanikawa and Imura (2001), Tanikawa and Hashimoto (2009) and Yasumoto *et al.* (2012), not only is a MSFA with a high level of detail in the space-time scale possible, but also a historical visualization of the cityscape is possible by building a 4d-GIS (four dimensional - GIS) where spatial data that contain information about height (3d-GIS) are arranged in a chronological order. However, these studies have so far been limited to hind casting and have not reached a stage where they are used to form the foundation of predictions for the future.

As described above, in the introduction of low-carbon technologies that conform to the renovation cycle at the district level, it is necessary to form a consensus among the stakeholders by presenting a concrete design that includes the study of not only efficient technologies and policies according to regional characteristics but also spatial structures. Therefore, in this study, we order structural and spatial data representing the heart of Nagoya City from the past to the present and aim to build a foundational dataset that will contribute to the reconstruction of existing urban areas and is also of use for the renovation of buildings in the future. Furthermore, we create visualizations of the structures for the case where reconstructions are left to take their own course in the usual manner and the case where we assume an “urban development plan" that is under study in this region. At the same time, we estimate the amounts of material stocks and flows.

2. Establishment of 4d-GIS

2.1 Summary of Case Study Area

We focused on the Choja-machi district in central Nagoya city (16 city blocks of Nishiki 2 chome-Nagoya City, Fig.1) as the target for our case study. Historically, this district once flourished as center for wholesale textile shops. However, due to changes in industrial structures and the impacts of recession, the wholesale stores went out of business and this area now faces increasing problems with vacant buildings, vacant lands, and parking lots. On the other hand, as this district has the convenience of being close to the main arterial highways and subways and because it is sandwiched between the city center of Nagoya city and the Sakae station, there is pressure to develop offices and restaurants on these blocks.

In the context of these socio-economic pressures on the land in the Choja-machi district, an urban development committee including representatives of local residents, businessmen, and academic experts was established. An urban development plan was adopted to work towards the planning of a thriving district. The zoning of land use and the skeletal structure of the urban infrastructure were included in this urban development plan. Regarding the specific policies in the urban development plan, it plans for six roads in the area, each with a distinct trait, along with maintenance policies for each road route.

In the plans for the future, based on the age distribution of the present buildings, it is assumed that very old buildings would either be individually reconstructed or would be jointly reconstructed along with the surrounding buildings. Therefore, by creating the building 4d-GIS in this district, it is possible not only to understand the current situation but to present a design for the city blocks based on the trends so far. It is further possible to present a conceptual plan that introduces environmental technologies that are based on that design. Moreover, based on the reconstruction period of each building, it is possible to estimate the amounts of raw materials used for construction and of waste produced during demolition.

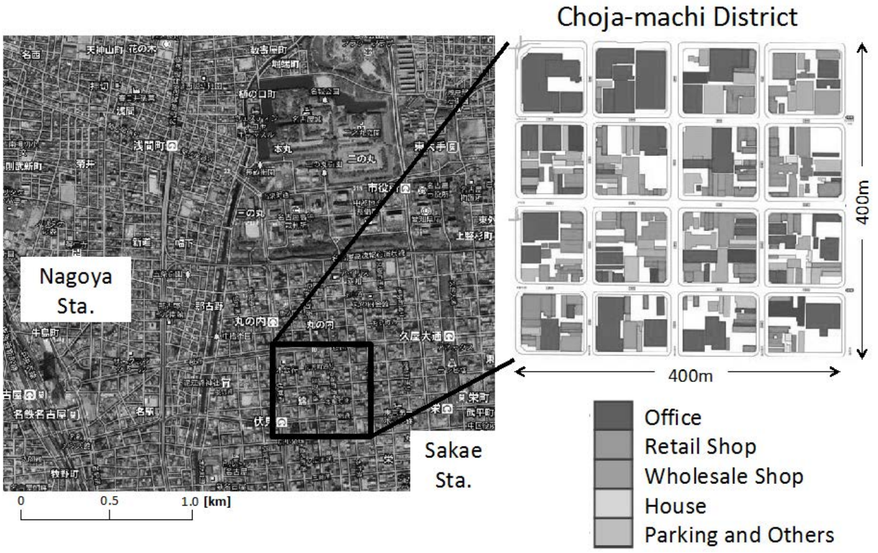

Fig.1 Summary of the Choja-machi District (Nagoya City, Japan)

2.2 Creating of Spatial Buildings Data

The building 4d-GIS in the Choja-machi district was constructed by integrating residential maps, aerial photographs and the structural GIS data of the past, thereby creating structural data for each period, and by arranging those data into a time series. The timeframe used was 1961 onward, as we could obtain residential maps of the district for that period. We then created the data at temporal intervals of almost every five years. We describe the structural data creation method below.

First, let us look at the structural data for the current year (2010). Based on the residential map database "Zmap TOWN II 2008/2009 edition" (hereinafter called as Zmap), which consists of the building GIS data created by Zenrin, we digitized the printed version of the "Zenrin Residential Map", superimposed the same, and corrected the building polygons where there were changes. Next, based on the current structural data created in this way, we worked backwards sequentially in time and edited and created polygons to match historical conditions based on the residential maps and aerial photographs. While doing so, if there was any change in the name or the building shape listed in the residential map or if there was any major change in the shape of the roof in the aerial photograph, we considered that to be a reconstruction, created a new polygon, and assigned attributes such as the years of construction and demolition to the polygons representing the building before and after reconstruction.

In the 4d-GIS created using the above method, there was insufficient information related to the structure of buildings and number of floors, which are required for the estimation of the amount of material stock, i.e., the amount of raw materials used for construction. We could estimate the number of floors from the shadow of the building in aerial photographs. Although it would be desirable to determine the building type by referring to the fixed assets register, doing so is difficult from the perspective of protection of personal information. Furthermore, using that method, we would not realistically be able to confirm the information on the buildings that no longer exist.

Therefore, we described the building types based on conditions such as building names and number of floors, as shown in the sequence below.

1) In the residential maps, if it is clear that the building is a wooden structure or an individual house with the name of a temple or shrine or of an individual person: *W (Wooden)* Structures
2) Among the buildings other than the wooden ones, the structures that have fewer than four floors: *S (Steel)* Structures
3) Other buildings: *RC (Reinforced Concrete)* Structures

Here, in condition 2), the S and RC structures are differentiated by a threshold of four floors because based on data aggregated and compiled by the Construction Research Institute on the number of floors and building type for new buildings (Construction Research Institute, 2009), approximately 70 percent of buildings with up to three floors (excluding the wooden structures) are S structures, and if the number of floors is more than three, the proportion of RC structures increases. This is because RC structures are adopted for high-rises owing to their strength and rigidity. In this study, we have determined structure of building by using only floor numbers due to the luck of observations, but regression analysis considering other building attributes such as floor space or usage would be needed to improve the accuracy of estimation.

2.3 Visualization of Building Transition

Let us describe the buildings 4d-GIS created based on the sequence mentioned in the previous section. Fig.2 shows the 3d image generated based on the number of floors during 1961 to 2010. Table 1 shows the transition in the number of buildings of each building type in the same period. First, let us look at the building types. In the 1960s, the S structure buildings accounted for more than half the number of buildings. However, the proportion of RC structures increased after that period, and by 2010, RC structures accounted for 73% of the total number of buildings. There was no large change over time in the number of W structures. This is because there are many buildings in the Choja-machi district that serve as both businesses and residences; so the number of individual residences is smaller. The existence of ancient temples and shrines also has an influence on the stability of the number of W structures.

Next, looking at the total number of buildings, we see an overall downward trend except for a period of slight increase in the 1980s. In 2010, there were 273 buildings, approximately two-thirds of the number in 1961. Considering the abovementioned increase in RC structures, it is apparent that at times several buildings were replaced with single, much taller high-rise RC structures.

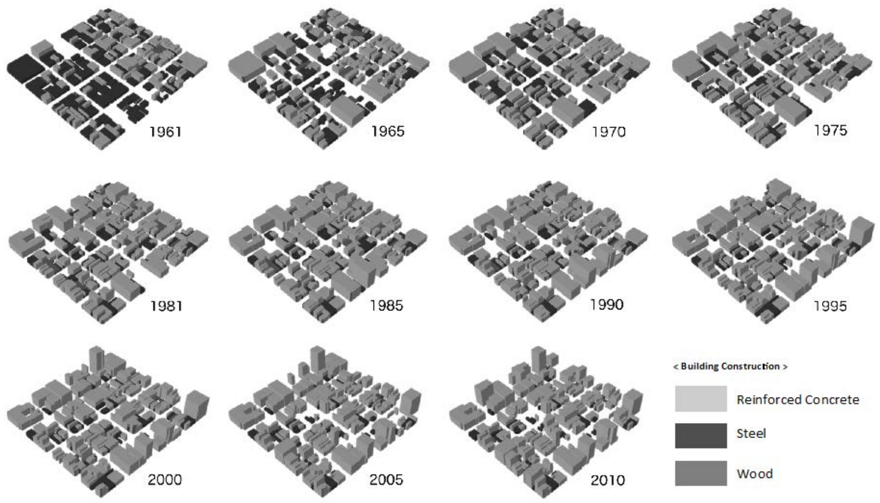

Fig.2 Transition of Buildings (1961 - 2010)

Table 1 Number of Buildings by Construction Type (1961-2010)

year	by structure Wood	Steel	RC	Total
1961	16	248	147	411
1965	18	199	178	395
1970	13	149	200	362
1975	13	136	211	360
1981	15	133	219	367
1985	15	125	225	365
1990	15	102	222	339
1995	14	85	220	319
2000	14	82	220	316
2005	9	75	204	288
2010	9	65	199	273

2.4 Estimation of Building Material Stock and Flow

We used the basic unit output method to estimate the amounts of material stocks and flows using the 4d-GIS that we constructed. In the basic unit output method, we estimate the amounts of stock by multiplying the amount of construction materials invested per unit area (hereinafter referred as material invested per unit) by the total floor space area of each building. In other words, the amount of stocks $MS_{i,t}$ of the building that occurs in the year t is estimated as follows:

$$MS_{i,t} = H_{i,j} \times I_j \tag{1}$$

Here, H = the total floor space area of the building [m^2], I = material invested per unit corresponding to the building age and the building type [kg/m^2], i = building, and j = building type. We used the values shown in Table 2 as the material invested per unit. Table 2 shows the values organized in chronological order based on the paper by Tohgishi *et al.* (2008). These values are calculated by computing the amount of material invested during construction using either statistical values or the general design diagram of each building type and then dividing the value obtained by the total floor space area.

We calculated the amounts of stocks in each building in the Chojamachi district using the 4d-GIS attribute information and the basic unit output method given by equation (1). Fig.3 shows the transition in the amounts of building stocks from the year 1961 to 2010. The stocks increased consistently within this time period. What was 355 [10^3 tons] of stock in 1961, increased 2.5 fold in a span of 50 years, reaching 975 [10^3 tons] of stock in 2010. This degree of increase in stocks can be attributed to factors such as the increase in the total floor space area due to the vertical expansion of buildings (high-rise multistoried buildings) and the increase in the number of RC structures, for which the amount of material invested per unit is very high compared to other building types.

Furthermore, Fig.4 illustrates the amount of change in the stocks that occurs in each period. That is, it shows the amount of increase in stocks due to new constructions and the amount of decrease in stocks due to demolitions. Here, the amount of increase signifies that the building stocks increased due to new constructions, and the amount of decrease signifies that the building stocks decreased due to demolitions.

When we look at the amount of increase, we see that there was a large increase in 1961-1965, whereas there was a decrease in the following time period. After that time period, there were intermittent increases. In particular, there was a rapid increase from 131 to 156 [10^3 tons] after the year 2000. On the other hand, when we look at the amount of decrease, before 2000, the transition was in the range of 97 to 329 [10^3 tons], but after the year 2000, similar to the amount of increase, the amount of decrease rapidly increased to 100 [10^3 tons]. Because the net increase is not very large, we can consider the amounts of increase and decrease to have increased due to active reconstruction of deteriorated buildings.

Table 2 Material Stock Intensity (by construction type, by built year)

[unit: kg/m^2]

construction type	built year				
	1959	1971	1974	1981	2000
Wood	369.4	443.3	→	450.5	487.5
Steel (2 floors)	751.9	890.3	891.7	→	961.0
Steel (3 floors)	850.9	850.9	872.8	→	957.6
RC	1840.5	1843.7	→	→	→

Source) Tohgishi *et al.* (2008)

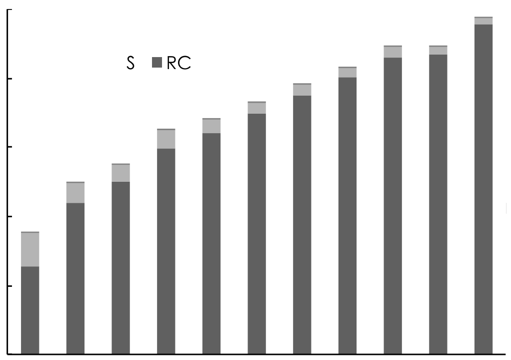

Fig.3 Building Material Stock Changes (1961 - 2010)

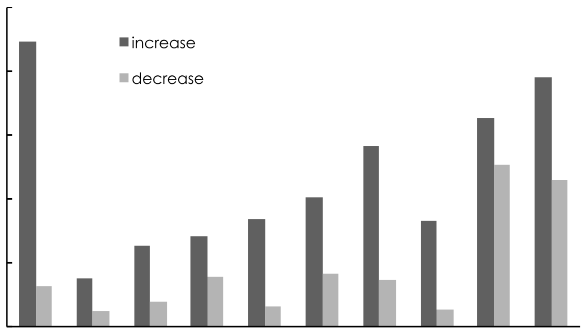

Fig.4 Building Material Flow Changes (1961 - 2010)

3. Future Prediction Using 4d-GIS

3.1 Assumption of the Building Renovation Scenario

We used the building 4d-GIS time series constructed in the previous section to make predictions out to the year 2050 in accordance with a future building renovation scenario that included assumptions about the renovation patterns and time periods. As described above, because the development of new urban areas is difficult in Japan, where the population is declining, we assume that individual or collaborative renovations take place within the districts of the existing urban areas. We set up two renovation scenarios, namely, (a) building renovations that are left to take their own course and (b) a collaborative renovation scenario.

(a) *BAU (Business As Usual) scenario*: Renovations are performed individually for each building. The renovation time period is based on the results of a Monte Carlo method (number of trials = 1,000) using a demolition rate function that is based on the historic trends.

(b) *DRP (District Renewal Plan) scenario*: In accordance with the urban development plan that was adopted in the Choja-machi district, collaborative reconstructions are carried out for units of 0.25-1 city blocks. The reconstruction time period is based on the demolition rate function, similar to (a). However, the buildings are maintained until they are demolished for collaborative renovation.

Assume the building to be *i* and the building type to be *c* in both the scenarios. The demolition rate function is set as a normal distribution function where t_i^0 is taken as the explanatory variable:

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

Here, μ = the average life span of a building and σ = the standard deviation of the building life span. In addition, the data obtained from a survey conducted on the survival rates of different construction ages based on Komatsu (2008) are used as the parameter. Moreover, after the reconstruction, according to the scenario, it is assumed that the buildings are demolished and that the demolished sites do not become parking lots or vacant lands.

During the estimation of the amount of building stocks, we used the recent standards (corresponding to the year 2000) for material invested per unit after reconstruction. Regarding the population and the number of households in the district, we used the concept of the Nagoya city master plan that states “stations near residences”. As for the population, we referred to the future predictions for the Nagoya city center, which state that in 2050, the population and the number of households will be 1.8 times the values for the year 2010, and so we assumed that the total floor space area of the residential buildings will also increase by 1.8 fold.

3.2 Simulation Results of Building Renovation

Fig.5 shows the prediction of reconstruction for each renovation scenario. In the scenario where the building renovations are left to take their own course, from the year 2020, renovations will progress gradually from the old buildings in the central regions of the district towards the roadside city blocks. As this progresses, because the floor space index will increase along with the increase in the resident population, the variation in the height of buildings will increase. On the other hand, in the collaborative renovation scenario, even in the areas where demolition is faster, there will not be many building demolitions up to the year 2020 because a consolidated land site could not be secured within the district. After that, it is estimated that renovations will be concentrated during the years 2030 to 2040. In addition, because the floor space will be controlled, hardly any increase in the variation in building heights will be observed.

Furthermore, we estimated the material stocks and flows up to the year 2050 using the basic unit output method in equation (1). Fig.6 shows the scenario where the transition in the amount of material stocks is estimated for each year, and Fig.7 shows the transition in the amount of material stocks flow, which was aggregated every five years. The amount of building stocks in the year 2050 will be 1.316 million tons in the scenario where building renovations are left to take their own course, and in the District Renewal Scenario, it is 1.331 million tons. Though the difference between these two values is not large, more of a difference can be seen in the process by which these values are attained.

To be specific, because reconstruction progresses individually in the renovation scenario where the building renovations are left to take their own course, there is a consistent increase in stocks with no large, sudden changes. However, in the collaborative renovation scenario, the increase and decrease in stocks vary greatly depending on the time period. For example, between 2045~2050, there is an increase in stocks of approx. 87 [10^3 tons]. On the other hand, it is not more than 8 [10^3 tons] in 2030~2035. This is because reconstruction of an area follows the demolition period of the same area with a delay between the two events. Thus, the larger increase in 2045-2050 is due to new construction.

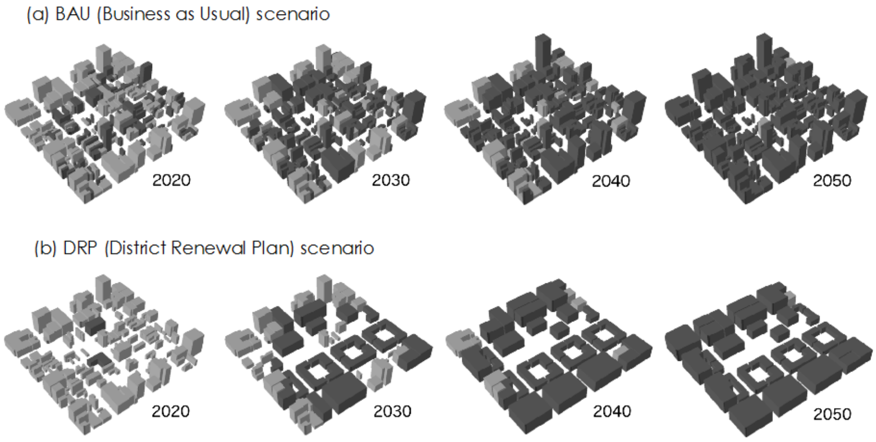

Fig.5 Simulation Results of Building Renovation (2010 - 2050)

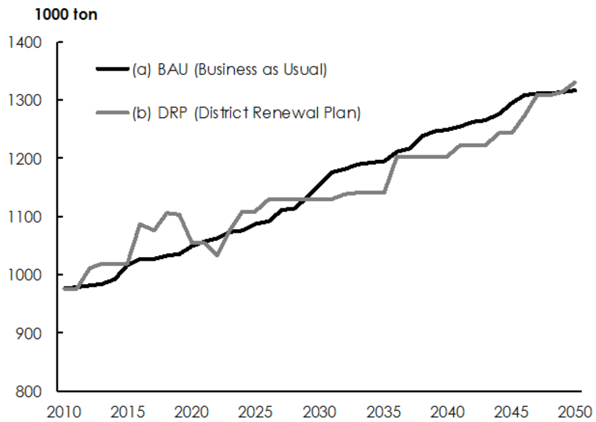

Fig.6 Prediction of Building Material Stocks (2010 - 2050)

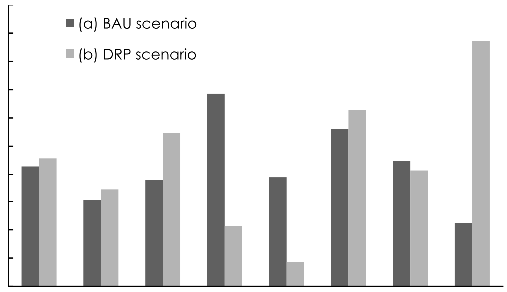

Fig.7 Prediction of Building Material Flow (2010 - 2050)

3.3 Accuracy of Predictions

It should be noted that there are a number of uncertainties in the future building renovation scenario that is assumed in this study as well as in the estimation results of the amounts of stocks and flow. First, the basic unit output of raw material invested that is used in this estimation is based on the generic value representing present circumstances, and the technological progress that may be available during future construction has not been taken into account. Particularly in Japan, where large amounts of damage are caused by earthquakes, revisions have been made to the Building Standards Act and initiatives are being taken to reduce the damage.

Though the basic unit output that we used in this study also intends to achieve the same, it can be considered that the material invested per unit floor space will change depending on the time of construction. Furthermore, the collaborative renovation scenario is only a concept that was proposed during the committee meetings in the district, and the plan by itself does not have any legal basis. Thus, the district images shown in this study can be expected to be utilized in the formation of consensus among the residents and the landowners.

4. Conclusions

In this study, we carried out an investigation into the urban planning that results from the introduction of low-carbon technologies in urban centers, and we constructed a database that can become the information base for contributing towards the quantification of the material stocks and flows that accompany the above urban planning. The database includes a time series of data on architectural structures. Furthermore, based on those data, we predicted the material stocks and flows until the year 2050 based on historic trends for the case where building renovations are left to take their own course and for the case where it is assumed that buildings are renovated based on collaborative low-carbon urban development plans that are being studied in various districts.

We present our findings below.

1) Over time, the amount of building stocks has consistently increased. The main causes for this increase are the increase in floor space due to urban vertical expansion (high-rise multistoried buildings) and the increase in the amount of RC structures, for which the amount of construction materials per area is comparatively large.
2) In the future predictions, the building stocks consistently increase in the usual scenario when building renovations are carried out independently for each structure. However, in the collaborative renovation scenario, because the building renovations are carried out collectively, larger increases and decreases in the amount of building stocks are seen at specific points in time.
3) Though there are a number of uncertainties in the predictions based on the simulation results of building renovation, it is expected that the predictions can be used as visualizations of the district during the process of forming a consensus.

Acknowledgements

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References

Construction Research Institute (2009) Building Construction Statistics. [in Japanese]

Daigo, I., Y. Igarashi, Y. Matsuno and Y. Adachi (2007) Accounting for steel stock in Japan. *ISIJ International*, 47(7), 1065-1069.

Gordon, R. B., M. Bertram and T. E. Graedel (2006) Metal stocks and sustainability. *Proceedings of the National Academy of Sciences of the United States of America*. 103(5), 1209-1214.

Hashimoto, S., H. Tanikawa and Y. Moriguchi (2007) Where will large amounts of materials accumulated within the economy go? - A material flow analysis of construction minerals for Japan. *West Management*, 27(12), 1725-1738.

Johnstone, I. M. (1994) The mortality of New Zealand housing stock. *Architectural Science Review*, 37(4), 181-188.

Komatsu, Y. (2008) Life time estimations of Japanese buildings and houses at the years of 1997 and 2005. *Journal of Architecture and Planning (Transactions of AIJ)*, 73 (632), 2197-2205. [In Japanese]

Lehmann, S. (2013) Low-to-no carbon city: Lessons from western urban projects for the rapid transformation of Shanghai. *Habitat International*, 37, 61-69.

Schandl, H. and J. West (2012) Material flow and material productivity in China, Australia and Japan. *Journal of Industrial Ecology*, 16(3), 352-364.
Sunikka, M. (2006) Energy efficiency and low-carbon technologies in urban renewal. *Building Research & Information*, 34(6), 521-533.

Tanikawa, H. and S. Hashimoto (2009) Urban stock over time: Spatial material stock analysis using 4d-GIS. *Building Research & Information*, 37(5-6), 483-502.

Tanikawa, H. and H. Imura (2001) Quantification and evaluation of total material requirement related to the urban construction - Case study for residential development. *Japan Society of Civil Engineers*, 671, 35-48.

Tohgishi, Y., R. Inadu, M. Naito, H. Tanikawa and S. Hashimoto (2008) Study on estimation of material stock intensity of urban structure. The 19th Annual Conference of The Japan Society of Waste Management, P2-A5-1. [in Japanese]

Yasumoto, S., A. Jones, K. Yano and T. Nakaya (2012) Virtual city models for assessing environmental equity of access to sunlight: a case study of Kyoto, Japan. *International Journal of Geographical Information Science*, 26(1), 1-13.