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Assessment of urban energy performance through integration of BIM and GIS for smart city planning

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Abstract

Smart city has been becoming nowadays a popular topic that not only in developed countries but also in developing countries. There are variety of definitions for smart city in different fields and regions. Generally, it aims for a sustainable city development through the optimal management of the resources and potential, offering a comprehensively high quality life to the citizens. The planning of area energy system is one of the most important issues, which is related to the energy generation, the energy consumption by facilities, transportation system, and any other city infrastructures. Especially for Japan, one of the countries facing the complex issues of an aging society, disaster management and energy dependency need a new methodologies for optimal urban energy planning that integrates all information from these sectors. Smart city with highly developed information and communications technology (ICT) is considered as such an important approach. To encourage the smart city concept in Japan, this paper proposes a “GIS-BIM” based urban energy planning system to access the optimal technical and policy solution for readjust city infrastructure beyond the integrated analysis. Firstly, it introduces the concept of Japanese smart city which convey the ideas from urban planning to infrastructure. Secondly, the research proposes a GIS-BIM based urban energy planning system including the database construction and analysis using GIS, the optimal energy system design aided by BIM and 3D visualization with user-friendly interface. Finally, center of Tokyo city is adopted as a case study, suggesting the potential to access the optimal technical and policy solution.

Keywords: Smart city, Geographic information system (GIS), urban energy planning, Building information modeling (BIM),

1. Introduction

Smart city is a relevant new concept that has been adopted not only in developed countries but also the developing countries. It has been clarified in many countries and from various fields with their different concerns. Generally, city smartization is intended to dealing with the current rapid urbanization and the increase in population. It is basically implemented by Information and communications technologies (ICT) with the using of big data, IoT(internet of things) and Geographic information system(GIS),e.g. [1], aiming for a sustainable city development though the optimal management of the resources, offering a comprehensive high quality life for the citizens [2].

One of the most serious results of rapid urbanization is the energy shortage caused by the population increase and environmental degradation. According to the existing researches, cities are responsible for approximately two thirds of the global primary energy consumption [1]. Furthermore, there will be a major shift in energy consumption from industry sectors to urban life, with two thirds of CO_2 emission generated by people living and working in the cities. For example in Japan, the statistic in the year 2014 shows that CO_2 emission of industrial sector decreased 6.8% (compared with 1990) while city life increased 6.6% [3]. Cities will thus offer greater opportunities for economic development but meanwhile face to the greater environmental stress [4].

To deal with the environmental and energy problems caused by urbanization, Net-zero energy building (nZEB) is expected as one of the most advanced initiatives to realize additional energy reduction on demand side. However, most of them are individual efforts in a single building. nZEB tends to focus on improving energy using efficiency, renewable energy utilization and energy management in the buildings, overlooking on the effect or limitation of other related elements, such like the conditions of the existing buildings, economic feasibility and city infrastructure [5]. In order to achieve the advanced low energy like nZEB, the large scale construction project will be considered to be easier to prepare enough budget than the small and medium scale buildings owning to the high cost. The current research suggests that even in the large cities like Tokyo, Osaka in Japan, more than 70% of the existing buildings are occupied by the small scale buildings [6]. These small scale buildings are hard to be the target of nZEB.

Urban energy demand and supply is a far more complex system than a single building, which needs to improve the existing system while putting forward new system in a cooperative way. The technologies or policies should be decided based on other related energy elements, like the city infrastructure (the energy supply from the generation to demand side), the distribution of natural energy potential (related to renewable energy) and urban structure (effect to demand side and infrastructure development). Rather than one single solution, urban energy technical packages, dealing with the environmental degradation should be an optimal approach, with synergies among various elements and energy solutions.

Smart city concept used to be considered as an ideal conceptual plan. Nowadays, the development of advanced ICT systems in smart city has enabled us to gather, unify, analyze and manage the related information comprehensively and locally, which impossible in the past. In Japan, Ministry of Economy, Trade and Industry (METI) has defined smart community as "a community that effectively leverages ICT to efficiently operate basic, lifeline and other system in its urban infrastructure and bring greater comfort and convenience to citizens" [7]. From the year 2010, Japanese government has started Four Major Smart Cities Model projects named "smart city initiatives" [8]. Distributed energy generation, renewable energy utilization, Area Energy Network and management, a range of measures have been developed toward achieving the goal for the smart city initiatives. Beside energy system implementation, it also suggests the importance of compact urban structure and infrastructure from the view of the aging society in Japan. However, these model projects usually address the effort of energy or environment on each specific district separately, lacking the overall image and optimal approach form the city level. They proved the effect of latest technologies but cannot give out optimal combination of the technologies based on the features of other districts in the city. A comprehensive package of CO2 reduction measure of cities and the tool that can support the related analysis are necessary.

This paper proposes a "GIS-BIM" based energy planning system to access the optimal technical and policy solution for readjusting city infrastructure. Firstly, it introduces the Japanese model of smart city covering the concepts from urban planning to the multiple infrastructures. Secondly, the research proposes a GIS-BIM based energy planning system including the database construction and analysis by GIS, as well as the optimal urban energy system design aided by BIM and 3D visualization. Finally, center of Tokyo city is adopted as a case study, for suggesting the potential to access the optimal technical and policy solution.

2. Concepts of Japanese smart city

2.1. Paradigms for smart city in Japan–a community based development

From the stand point of sociology and the primitive of urban planning, a city is formed of various communities, the basic and adoptive unit of the city.

One of the goals of smart city development for Japan is to make the urban infrastructure flexible and adaptable in a long-term perspective. Especially for Japan, the rapid aging population poses unavoidable challenges for city planning. It has to consider the travel distance and the suitable travel mode for the seniors in the city. In consideration of the lifestyle and living range, the paradigms of city smartization in Japan is community based, considering aging society, disaster prevention, and energy security.

There are two types of the community planning in the modern age: the neighborhood community and the station centered community. In the urban area, the station centered communities along with transit-oriented development (TOD) is more popular. Its main concept is that houses, commercial facilities, offices, open spaces, public utilities and other various facilities are arranged within a 10-15 minute walking distance, or a radius of approximately 600 meters. This concept effected the expansion of the rail way and urban infrastructure in Japan from the year 1990. Fig. 1 suggests that almost the whole Tokyo city are covered by the TOD communities. Compared with TOD in the US, Japan considers more about infrastructure development instead of the controlling of automobile traffic.

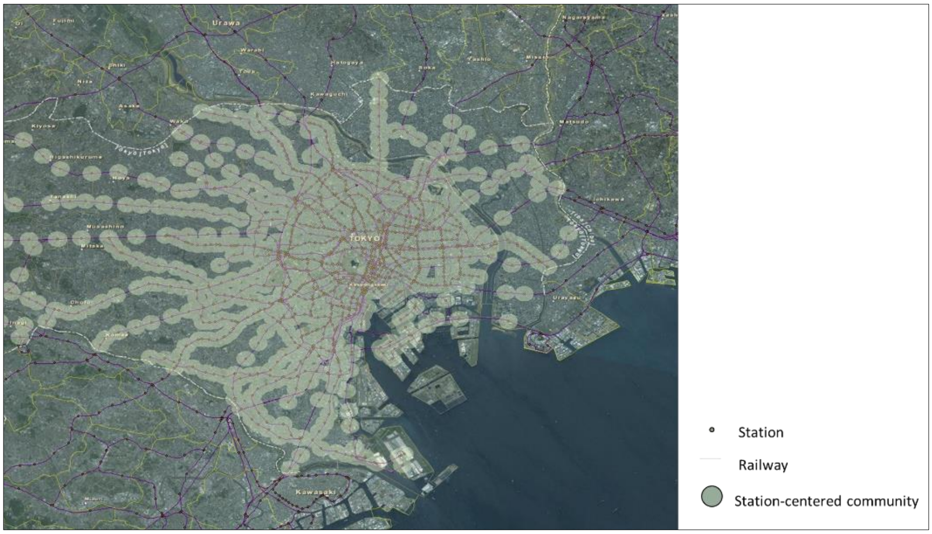

Fig. 1. Station centred communities in Tokyo

2.2. Two core concepts for community smartization

In Japanese smart city planning, a city's infrastructure system ranging from transportation and energy, to water, waste, greenery and information should be thoroughly studied, analyzed and planned. When the particular technology is deployed, the scales and sizes of its component must be sized and planned to suit each infrastructure system. An ideal urban structure for a smart city would be one that optimally combines and integrates all infrastructure system.

Two concepts for urban structure are suggested in Fig. 2: compact development and layer integration.

- Compact development

Compact development means concentrating and combining various urban functions and developing them in a walkable distance. It is based on the concentrations for the population living in urban areas and aging people.

In Japan, the various forms of urban infrastructures that developed during the period of rapid economic growth are requiring for renewal now. For minimizing this infrastructure renewal, the concept of compact development would contributes to reducing costs and accordingly increasing the efficiency of city management.

- Layer integration

Layer integration is a planning approach for extracting various layers on hierarchies that establish urban activities and then integrating them so that those layers are used in an optimal manner. The form of the community is determined through the compact development process, and the layer integration process aims to combine urban function layers, profiting the community from the synergies among all these layers.

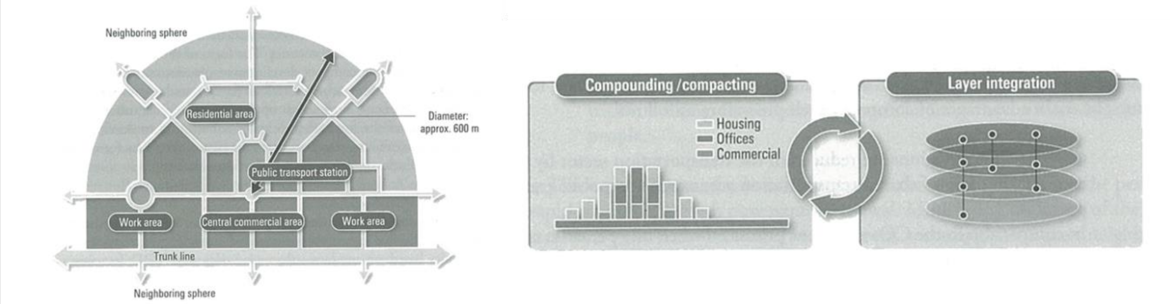

Fig. 2. Two concepts for community smartization in Japan

3. Methodology

Japan states the comprehensive concepts for city smartization, but it still not yet has such planning methodology and tools that able to adopt these concepts. One obstacle is the lack of energy planning tool that can bridge the information between building design and urban planning. The ICT in smartization can visualize the different issues simultaneously and uncover their underlying conditions. This helps the planners prioritize the related issues and find out a cross-domain solution.

3.1. Overall concept

This research proposes a GIS-BIM based urban energy planning tool to support the planning of smart cities.

GIS can interpret the real world by layering the information and integrated with its geographic location. It can describe the community in multi-scale, space-time dimensions with detail information in attribute table. In this research, the data of energy elements and related urban infrastructure are unified by the 3D city model in GIS.

Building Information Modeling (BIM), focus in the building scale, describing the building in a geometrical manner with the detail building information. Recently, BIM are widely cooperatively used with other simulation software that can predict the effect of every measure in the building or among some of the buildings. It can get the infrastructure data from the GIS platform and process the energy simulation by using the existing simulation software. Finally, the result is returned back to the GIS platform to check its effect at the city level.

The integration of GIS and BIM can interpreted the holistic city. The 3D building model built up by BIM is located on the city 3D model set up by GIS. The data of building level that related with energy performance are offered by BIM, while the infrastructure data of city level are offered by GIS. It is the base for energy demand prediction, which is input into the simulation process to test the effect of proposed energy policies and technologies. The result of the calculation for a single building is returned back to the city 3D model that supported by GIS. Comprehensive assessment both in the building and city level is adopted to get the optimal technology package.

3.2. Components and architecture of the tool

Urban energy planning should be based on the information from the city level, offering various policy technology packages to the communities that are with different urban infrastructure conditions. It can be used by various kind of users. For one area energy planning project, the planner can get the urban plan information, the community features and the appropriate energy technology package by inputting the location of the target area. Further, the related urban infrastructure information can also be obtained for further optimal design, combining with other existing simulation software. The averaged users, energy management operators or government can use the 3D platform for the visualization of the energy consumption of the city, district or building.

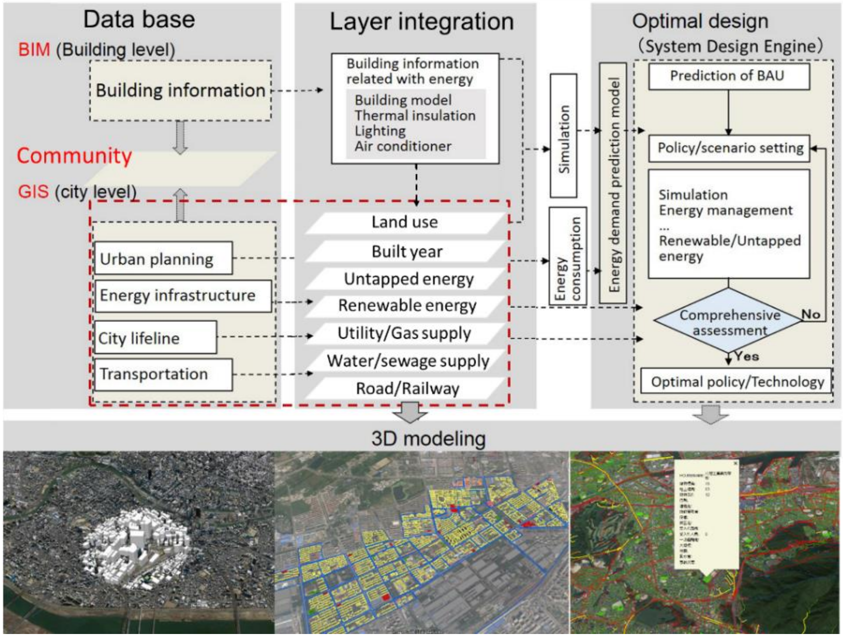

Fig. 3. Structure of the tool

Fig. 3 shows the architecture and components of the tool. It consists four parts: the database sector, layer integration sector, optimal design sector and 3D visualization sector.

Database sector and layer integration sector interpret the city by layered data. The building information related to energy consumption are from BIM, and the other urban infrastructure data are offered by GIS. The simplified building big data from BIM are integrated with the city model that build by GIS. These sectors offer input data for optimal design sector and 3D visualization sector. The users can use the data for energy system optimization or directly visualize the existing condition of the community by 3D visualization sector.

Optimal design sector has the database of various technology packages for different types of community. By inputting the project location, it selects the optimal technology package by the community features offered by database sector. These data is processed into further simulation and analysis, selecting the optimal energy solution when it has a high environmental and economic performance.

Visualization sector adopts the 3D visualization in GIS and BIM to display the existing energy consumption, simulation result, facility operation and infrastructure condition. It can be developed into the user-friendly system that combines with web-GIS.

4. Case study of the communities around JR Yamanote line in Tokyo

The communities around JR Yamanote line (one of the most important circular line in the center of Tokyo) are adopted as case study to suggest the different effect of the technologies in different area.

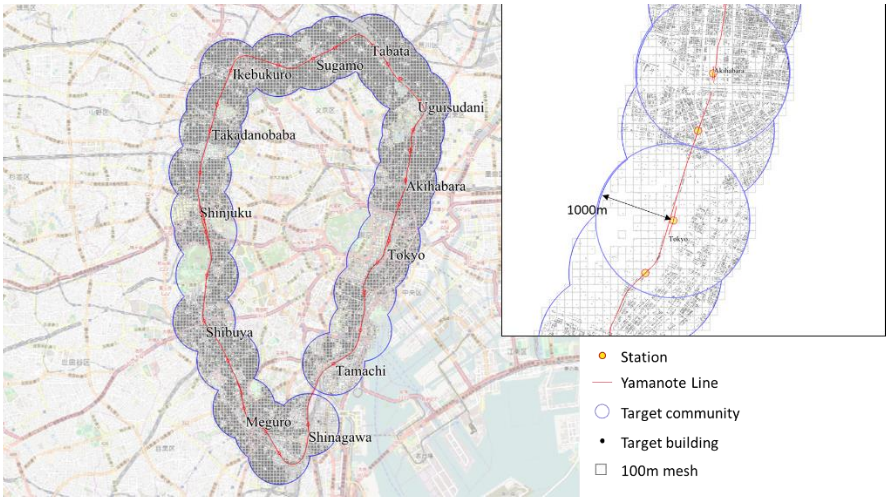

Fig. 4. Target buildings around JR Yamanote line

4.1. Target area

There are 29 stations for JR Yamanote line. Taking the station as center, the buildings within a radius of approximately 1000 meters in 12 TOD communities, which contains all the target building (do not overlap within other community) are selected as targets for case study (Fig. 4). There are around 150,000 buildings in these 12 communities.

The building point data from urban planning which contains the information of location, building type, building area are used for this research. All the selected buildings are distributed, analyzed in 100 mesh (around 17,000 meshes for all the target area).

4.2. Layered community features

- Building scale

In the 12 communities, the total building area is around 156 billion m^2. It is supposed that the buildings with more than 50000m^2 are large scaled buildings (supposed to be the target of nZEB*[1] buildings). Only 28% of the building area is composed with large scaled buildings, the other 72% are small scaled buildings. Fig. 5 shows the distribution of the building area. It also suggests that most of the large scale buildings are around Tokyo and Shinjuku station.

- Building type

Fig. 6 are the constituent of building type. It suggests that the station with more large scaled buildings such like Tokyo, Shinagawa, and Shibuya station have around 50% commercial or office buildings. Other communities have more residential buildings. Large building renovation, like nZEB* are difficult to be implemented into these residential areas.

[1] nZEB* in the case study refers to the buildings with advanced high low carbon technologies which realizes nearly zero energy consumption (60%~70% energy consumption)

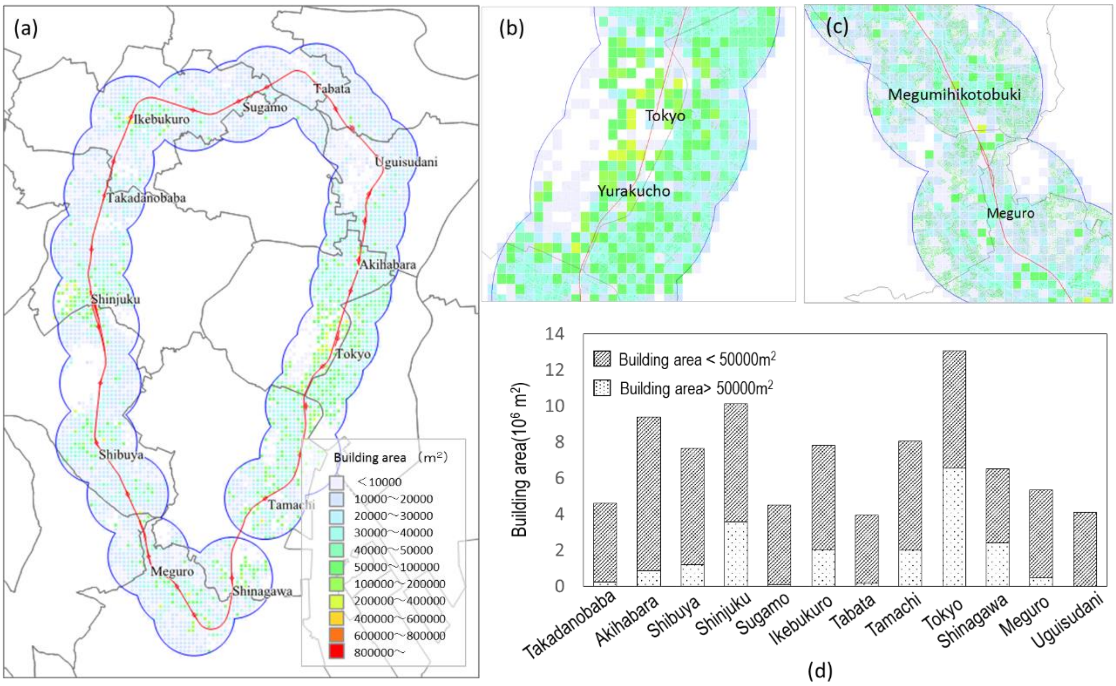

Fig. 5. Building area distribution

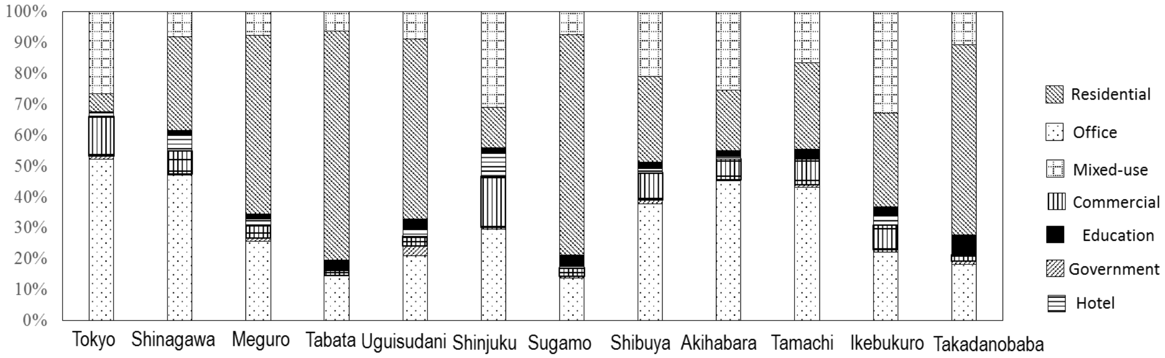

Fig. 6. Building type in target communities

- Existing building energy consumption

In Japan, there is the Data-base for Energy Consumption of Commercial building (DECC) that reports yearly energy consumption unit, the energy consumption of every building types in per unit (m^2) every year [9]. This energy consumption unit and building area are adopted for the estimating existing building energy consumption. It can be calculated as formula (1)

$$\sum_i Building\ energy\ consumption = \sum_i E_i \times S_i \quad \ldots\ldots\ldots\ldots(1)$$

i : Building type

Ei:Yearly energy consumption for building type *i*

Si: Building area for building type *i*
Energy consumption units used in this research are listed in Table 1

Table 1 Yearly energy consumption unit for different type of building

Type	Yearly energy consumption unit(MJ/㎡・Year)
Commercial	4529
Office	1648
Mixed use	1600
Residential	778
manufactory	1297

The existing yearly energy consumption of the community is displayed by 3D modeling (Fig. 7) and values are suggest in Fig8 (Existing case). It shows that the areas around stations where has more large-scaled buildings have high energy consumption density.

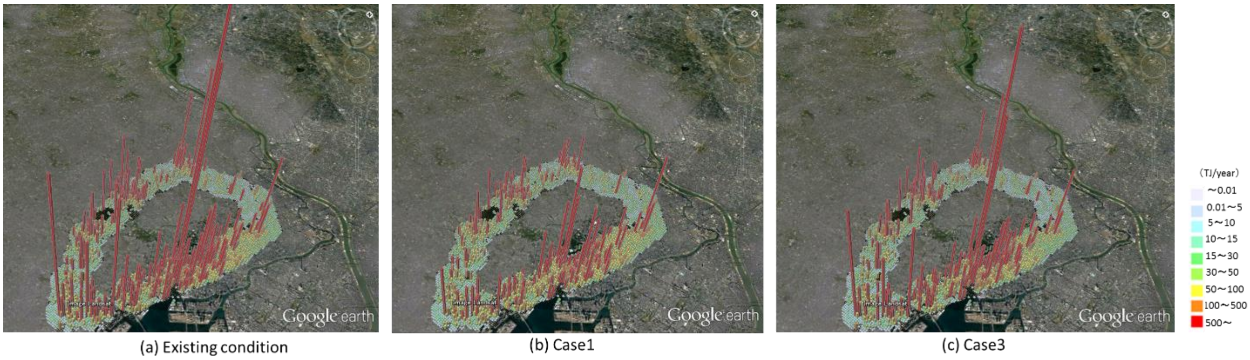

Fig. 7. Annual energy consumption of cases

Table 2 Case setting

Case	Energy conservation measures
Case1 Large-scale development priority model	Over 60% energy-reduction renovation (aiming nZEB*) in case over 50000m^2 No additional measures in cases under 50000m^2
Case2 Long tail method1	Buildings over 50000m^2 renewed to 20% energy-reduction Buildings under 50000m^2 changed lights to LED and use High efficiency air-conditioners（10% reduction）
Case3 Long tail method2	Half of the buildings over 50000m^2 renewed to 20% energy-reduction Buildings under 50000m^2 changed lights to LED, use High efficiency air-conditioners and implement energy management (20% reduction)

- Case setting

The nZEB* building renovation tend to be limited in large scale building construction projects because they usually require the high initial cost. This research suggests tentatively that nZEB* can be only implemented in the buildings that with building area larger than 50000m^2 (considered as the large scale projects). Another method is long tail method which means the large-scaled buildings works on high efficiency method (nZEB*) while low cost energy saving method like implementation of LED, high efficiency air conditioner are supposed to be implemented in small-scaled buildings. This research sets three cases that are listed in Table 2 to compare the energy conservation effects of these communities.

5. Results

- Energy saving effect in community scale

Fig. 9 shows the annual energy consumption and energy saving effect in the target communities. The result suggests that large-scale development priority model are more effective in the communities with more large buildings. In other communities, the long tail method has better effect.

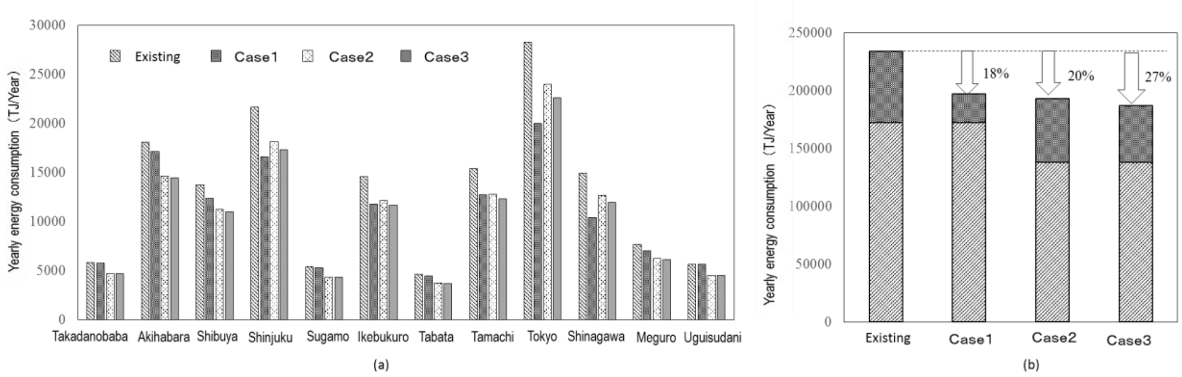

Fig. 8 Annual energy consumption for target communities

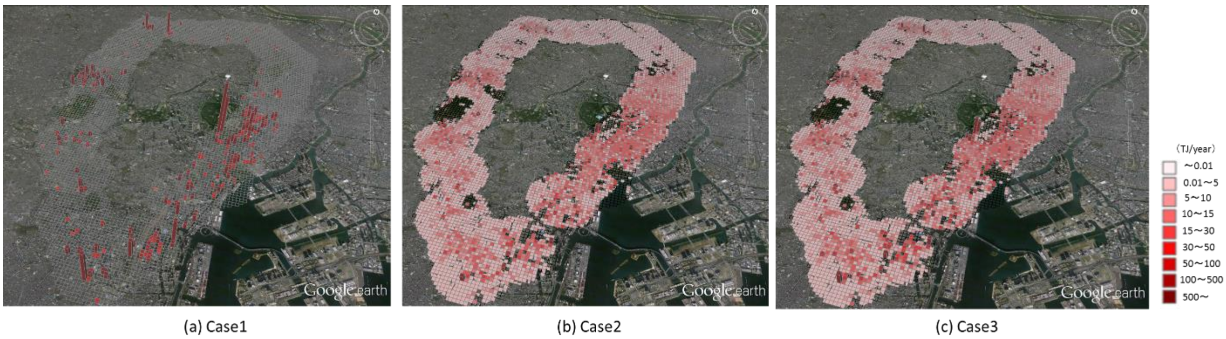

Fig. 9. Annual energy conservation effect of case

- Energy saving effect in city scale

The energy conservation of the whole city, Fig. 8(b), also suggests that long tail method can realize more energy saving effect, especially in the local communities.

6. Discussion and conclusion

For the future transition of urban structure and energy planning, the city management and engineering department need a tool to solve different environmental issues across different scales. This study suggests a GIS-BIM based urban energy planning tool which is able to propose the appropriate solutions for future smart city, considering urban development and infrastructure regeneration for future smart development. It works as a multi-functioned system that can (a) combine GIS based data and other data resources across the city, community and building; (b) model the city with layer integration; (c) predict and simulate the effect of energy conservation technologies in multi-scales by municipalities and developers; (d) visualize by 3D city modeling.

The results of the study are described as below:

(1)It suggested the overview of the urban energy planning tool including its developing concept, architecture and basic function. The collaborative modeling with GIS and BIM, taking communities as immediate scale, unifies data across the city and building to support the comprehensive analysis.

(2)The TOD oriented community area around the stations of JR Yamanote line in the center of Tokyo, the place with high potential of urban development, are adopted as case studies to suggest the feasibility of the tool. In order to clarify the relationship between energy conservation effect and initial cost, nZEB* method (stress on the energy conservation effect) and the long tail method were set in the three cases.

(3)As the result, advanced low energy buildings like nZEB can effectively reduce the big portion of energy consumption in certain buildings (large building), but in a wide range area, the long tail method has shown the potential to realize a higher energy conservation effect. Therefore, with this tool, it is possible to find out the method that can efficiently and economically reduce the energy consumption in a large area.

(4)The result can also suggest that for the whole city, various energy policies and technology packages in consideration of the district features are required to realize the energy conservation in the city level.

(5)The projects in developing or emerging countries do not always start from the appropriate climate, economic and social conditions that would allow cutting-edge technologies or design methods, which is cultivated in advanced countries. It is necessary to propose schemes that combine advanced technologies with the conventional methods that fit to the local conditions of the projects site. Therefore, the tool proposed in this research is more preferable for these countries.

This research generally offers an architecture of the tool as the first step that only GIS is adopted in the analysis. The future work will develop a middle ware for GIS and BIM data integration, query and visualization. More details of technologies and its cost performance should be analyzed and the energy plan support system will be made available to city management and engineering. Furthermore, for implementation of the tool in other developing countries in Asia, the research will conduct widely data collection, case studies and provide different technology packages to these countries.

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