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Compact development and energy consumption: Scenario analysis of urban structures based on behavior simulation

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HIGHLIGHTS

- Individual consumption behaviors are simulated under urban structure scenarios.
- Increased consumption of the non-mobility goods and mass transit trips are found.
- Energy is estimated based on demand of non-mobility and mobility goods.
- Concentrating all population in one city center increases energy consumption.
- Polycentric urban structure shows effect on energy consumption reduction.

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ABSTRACT

This study investigates the relationship between compact development and energy consumption by simulating individual consumption behaviors in monocentric and polycentric urban structures in Kumamoto in 2030. A model is developed to estimate individual consumption behaviors and demand of mobility goods and non-mobility goods at micro level. By considering the economic factor of income, the energy consumption is calculated based on demand of goods under Business as usual scenario, Central Core City scenario, and Multi-pole structure scenario. Results indicate the urban structure influences individual consumption behaviors and energy consumption. Increased consumption of the non-mobility goods and mass transit trips is shown in Central Core City scenario and the Multi-pole structure scenario. Monocentric urban structures as shown in Central Core City scenario show less effect on energy consumption than the polycentric urban structure in Multi-pole structure scenario. The findings suggest that the multi-pole urban structure is a better choice for compact development in Kumamoto based on less energy consumption. The method in this study provides a new approach to analyze the influence of urban structure on energy consumption at micro level. Findings give good suggestions for planning policy making regarding to compact development in Kumamoto.

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1. Introduction

1.1. Context and literature review

The magnitude and speed of urban growth makes urban sustainable development a crucial element affecting the long term outlook of humanity. High levels of fossil fuel consumption and environmental problems have aroused great attention of governments worldwide. Many studies have searching for countermeasures leading to urban sustainable development. Compact city is recommended [1–3]. Compact city is a relative high density and mixed land use city, which is based on efficient public transport system and dimensions that encourage walking and cycling [1]. It is suggested as an urban form for sustainable development [4]. Two major environmental benefits from compact city are less private car dependency and preservation of green fields and arable land [5]. However, limitations have been argued for too compact development, including road congestion, reduced access to green and natural areas, higher housing prices, and reduced living space [6,7].

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The debate on sustainable city is fraught with interests on what kind of urban form should be and how urban living environment strongly influences residents' behaviors [8]. It argued that there does not exist one ideal urban form for all cities, depending on the local context, existing urban structure, and political possibilities [9]. Based on a review of existing planning strategies throughout cities worldwide, traditional monocentric urban structures have being substituted by 'wisely compact cities' of polycentric urban organization [10]. Considerable attention has been focused on assessing urban structures for compact development by analyzing energy consumption [11]. The amount of energy consumption is a very important and effective index for evaluation of urban structures. First, urban spatial configuration and land use affect the density and intensity of activities thus energy consumption. Second, growing environmental awareness requires urban development not only minimize the use of resources and the spatial displacement of environments, but also improve energy efficiency.

There is a wide spectrum of research for evaluating the effect of urban structures on energy consumption, and exploring opportunities to reduce energy consumption from the viewpoint of compact development. Broadly speaking, two major streams of studies could be classified. The first stream of studies investigates the relationship between compact urban structures and energy consumption by comparing energy consumption in different urban structures at city and regional scales. Most of them focus on the energy consumption in transport sector [12–15]. Yao analyzed the impact of population density and energy consuming density to space within urban districts of Beijing. Results indicated that compact urban structure was the most efficient way to reduce energy use in urban areas [16]. Liu and Sweeneya investigated the relationship between household space heating energy use and urban form for the Greater Dublin Region. The results illustrated that the compact urban structure scenario was likely to decrease the domestic heating energy consumption per household by 16.2% compared with the dispersed city scenario [17]. Schwanen et al. analyzed the impact of territorial structures upon energy consumption in the Walloon Region (Belgium). Dense urban settlements were found be more efficient in both mobility and building [18].

Although these studies explored the relationship between urban form factors and energy consumption, some have heavily relied on the cross-sectional statistical data of fuel or electricity, which may not satisfactorily address the country or city specific issues, such as different stages of economic development. Academic research investigating into the connections between urban structures and energy consumption has been inconclusive. The results obtained differ depending on the methodology used, data limitations, and spatiotemporal settings [19–21]. Moreover, it fails to consider social and economic factors and lacks deep investigation on the influence of urban structure on resident behaviors at micro level. Social economic factor are found influential to household energy consumption behaviors. As income increased the proportion and absolute amount of energy consumption and CO_2 emissions decreased for food, and increased for education, cultural and recreation services in China [22].

Increasing studies are tending perform simulation analysis by considering social economic attributes. The other stream of studies developed models to simulate the impact of urban structures on behaviors thus energy consumption. Feng et al. developed a new integrated model and applied it in Indonesia. Results suggested that the polycentric urban structure with proper control of urban growth and an efficient public transport system would be promising for energy saving in Jabodetabek [22]. Yamagata and Seya developed a land use-transportation model to analyze the energy of future compact and dispersion city scenarios for the year 2050 in Toyo metropolitan area. Results suggested that compact urban structure may contribute to the reduction of electricity demand from the residential sector [23]. Besides, other models that integrated land use, transportation, and residential location choice have been built to analyze the effect of the compact development policies on resident behaviors thus energy consumption, such as UrbanSim. It is a software-based simulation system for supporting planning and analysis of urban development, incorporating the interactions between land use, transportation, the economy, and the environment [24]. It allows us to explore the effects of infrastructure and policy choices on housing affordability, greenhouse gas emissions, protection of open space, and environmentally sensitive habitats. However, the system requires extensive data which limit its practical use widely.

Robust suggestions can be drive from model simulation results by considering social economic factors. However, most studies focuses on household energy use in residential and transportation sectors (space heating and cooling, appliances and lighting, domestic hot water and private cars) [25]. Energy for commercial and public services is rarely considered. Actually, it is very important to consider the energy for commercial and public service because of big contribution to all energy use. According to statistic data from Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry, energy use in the commercial sector accounts for 25.07% of that consumed by all sectors in Kumamoto prefecture in 1997, compared to 23.07% of residential sector [26]. Furthermore, it has been found that energy requirements for heating, cooking, and driving only increase weakly, while energy requirements for industrial production and services increase strongly with rising income [27,28].

On the whole, three main challenges highlighted in the literatures are often neglected or considered individually: (i) the effect of social economic factor on energy consumption; (ii) the importance of investigating the behaviors of citizens at the micro level in different urban structures; (iii) the consideration of all energy use that related to the everyday life of residents, including energy use in transport, residential, and commercial and services sector. Raising awareness of these challenges in academic studies, and providing local authorities and policy makers with practical advice adapted to their own planning situation is crucial. This could lead to successful policy making toward to compact development and significant reductions in the total energy consumption of the city.

1.2. Aim of this study

This paper presents an approach dedicated to the energy estimation of transport, residential, and commercial sectors under urban structure scenarios in Kumamoto (Japan) at micro level. Major objectives of the study are: (i) to identify the methodology details for estimating individual energy consumption under three kinds of urban structures in Kumamoto by considering the influence of social economic factors; (ii) to investigate the effect of urban structures on behaviors of residents at micro level; (iii) to summarize the important findings arising from energy evaluation and behavior analysis, which could be used to assist policy making and urban planning in achieving to a sustainable compact development.

2. Materials and method

2.1. Kumamoto context and urban structure

2.1.1. Kumamoto development context

The Kumamoto metropolitan area is located in the Kumamoto prefecture on the island of Kyushu (Fig. 1). The population of the Kumamoto prefecture is 1,812,255 in 2010, ranking 23rd in Japan.

The Kumamoto metropolitan area is undergoing a transition to new development because of the promotion of national position and improvement of traffic accessibility. The bullet train, called Shinkansen in Japanese, has operated between Kumamoto and Tokyo since March, 2012. Moreover, Kumamoto has become a city designated by government ordinance since April, 2012. It is a city that has a population greater than 500,000 and has been designated by an order of the cabinet of Japan under Article 252, Section 19 of the Local Autonomy Law. There are 20 government ordinance cities in Japan. Designated cities are performed many of the functions normally run by prefectural governments in fields as public education, social welfare, sanitation, business licensing and urban planning. The Kumamoto city government is generally delegated the various minor administrative functions while the Kumamoto prefectural government retains authority over major decisions. For instance, pharmaceutical retailers and small clinics are licensed by Kumamoto city government, but pharmacies and hospitals are licensed by the Kumamoto prefectural government.

In spite of beneficial news, there are challenges in addressing the development in Kumamoto, such as decreasing and aging population. A decreasing population has been observed in Kumamoto. Although the population increased slightly from 2005 to 2010, a decreasing trend is forecasted over the next thirty years. Kumamoto city is predicted to lose more than ten thousand of the population every five years after 2020. Accompanied with a decreasing population, aging is another problem. The ratio of elders (older than 65) increases year by year. Elders accounted for 18.7% of the population in 2005. The ratio is projected to increase to 29.7% in 2030. Higher proportion of elders brings more pressure on the financial and the infrastructure system of the city, partly caused by less taxpayers and increased welfare output. To ensure the quality of life, easy access to facilities and living services are essential for the growing number of elders. Public transport and car rental become important for the mobility of elders due to the limitation of driving licenses. In Japan, residents who are older than 75 need retest for driving licenses. In 2030, more than 17.6% of the population in Kumamoto are forecasted to be older than 75.

Suburbanization is another challenge. Kumamoto is proceeding on a process of urban growth and sprawl. Attracted by low rent, more shopping centers are located in the suburban area. Meanwhile, cars become affordable for ordinary people due to the economic development. These factors together attribute to the booming activities for shopping and recreational in suburban area. According to a survey by the Kumamoto government, shopping walkers in the city center decreased sharply in recent years. The number declined from 797,624 in 2003 to 569,171 in 2008. The city center is losing attraction. To reactivate the city center, the Kumamoto government has carried out a plan called the "Basic plan for activating the Kumamoto city center". The plan has been effective, shown as the increasing number of walkers as 585,507 in 2009.

Facing the challenges of declined population and urban sprawl, the Kumamoto prefecture government made a plan for compact development for the future planning. Although a compact urban structure is recommended by scholars, the question as to what type of compact urban structures is suitable for Kumamoto remains unanswered. It is expected the right compact urban structure will increase the energy efficiency of the city and preserve more green land and agricultural land.

2.1.2. Urban structure scenarios

The term urban structure covers aspects of density, geometric shape, use of land (residential, industrial), and infrastructure (road, rail, waterway), it refers to the arrangement of the larger functional units of a city, reflecting both the historical development of the city and its more recent planning history [29]. Urban structures are summarized as monocentric and polycentric types [30]. Corresponding to the plan of compact development in Kumamoto, three kinds of scenarios are set based on current urban structure and desired structures, either monocentric or polycentric types. One scenario is based on the polycentric urban form, called the Multi pole structure scenario. The Central core city scenario is based on a monocentric strategy. A Business as usual scenario (BAU scenario) is used for comparison.

Although more complex land use indicators would be desirable, population density can serve as a useful indicator of urban structure [25]. Scenarios of urban structures are set based on different population distribution strategies. The influence of land use and economic activities could be reflected by the population distribution. The total population of the region is assumed to be the same in all scenarios, which is estimated be 942,233 in 2030. The total energy consumption of the Kumamoto metropolitan area is estimated in 2030. The base year is 2010.

2.1.2.1. Business as usual scenario (BAU scenario). The urban structure is characterized by one main center and several sub centers, which is same as the urban structure of 2010. Urban is sprawled within the urban boundary of 2010. The living area and the location of facilities in the community remain stable as the base year of 2010. However, the number of population changes. The population in 2030 is distributed among zones according to the zone population ratio. We use zone population ratio in Personal Trip Survey (PTS) conducted in 1997 due to the lack of accurate data of zone population ratio in latest year. The population distribution result is shown in Fig. 2.

2.1.2.2. Central core city scenario. This classical monocentric urban structure is characterized by one main city center. The total population is concentrated on the city core by two strategies. In the Central core city scenario (1), the population is distributed in urbanized zones by the zonal population density ratio of 1997. Residents are distributed to living circles in the Central core city scenario (2). Living circles are area mapped at radius of 3, 6, 9, 12, 15 km around the city center (Tsuruya Department Store). The population is distributed in these living circles with the ratio of 40%, 24%, 18%, 12% and 6%, respectively. Zone population of each living circle is estimated by the zonal population ratio of 1997 and the total population of the living circle. Fig. 3a and b presents the population distribution results of the Central core city scenario.

2.1.2.3. Multi pole structure scenario. A multi-pole urban structure is designed as one city core and several living circles (Fig. 4). The city core marked in red[1] is the center of services and facilities of the whole area. It is connected with the living circles by highways and mass transit lines. Residents live in living circles, which is marked in green. Regional cores (pink) and living cores (yellow) are included in the living circles. Facilities and services are supposed located in the region core. Living cores are dispersed yellow points which accommodate residents. The region core and living cores are connected by highways and public transit lines.

Based on the urban structure in Fig. 4, the population is distributed to the poles, which are called cores in Fig. 5a. In the Multi-pole structure scenario, two types of cores are defined as the center core and the living core. The center core is the center of the district both politically and economically. It is located within the bureau of administration, main stations, department stores and other facilities. The living core is the second level core, which provides services for residents' living, such as supermarkets, schools, gyms, and community parks. Zones around cores are called living

[1] For interpretation of color in Figs. 4 and 5, the reader is referred to the web version of this article.

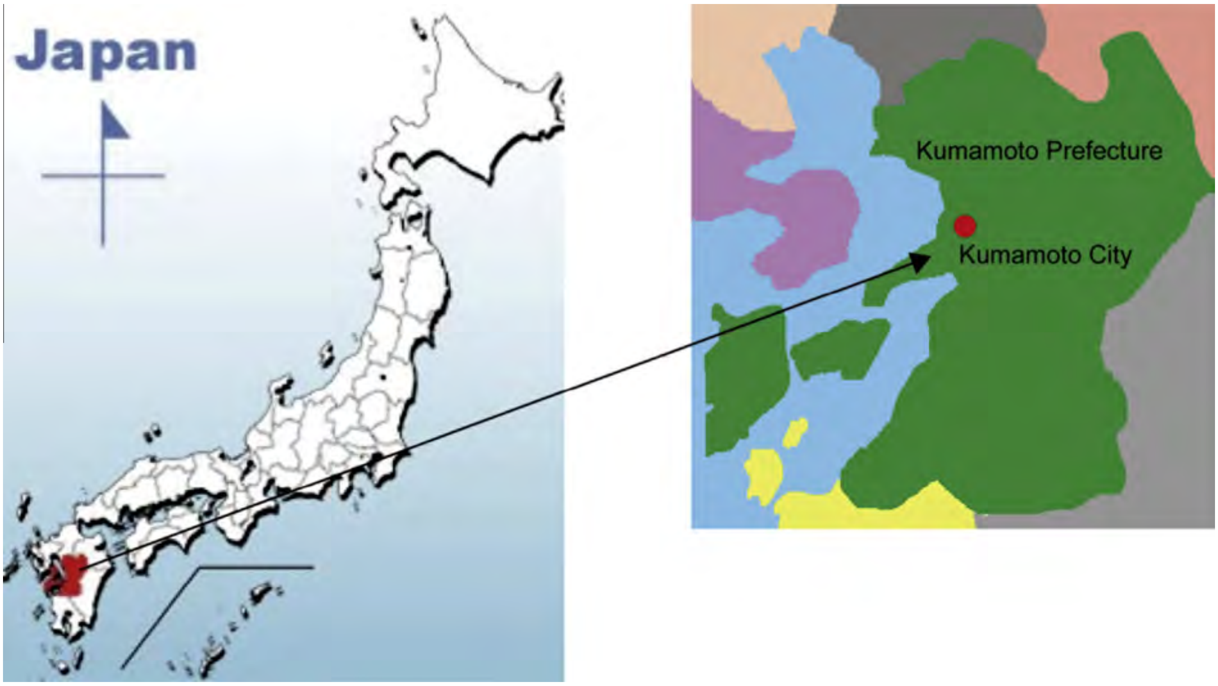

Fig. 1. The location of the Kumamoto metropolitan area.

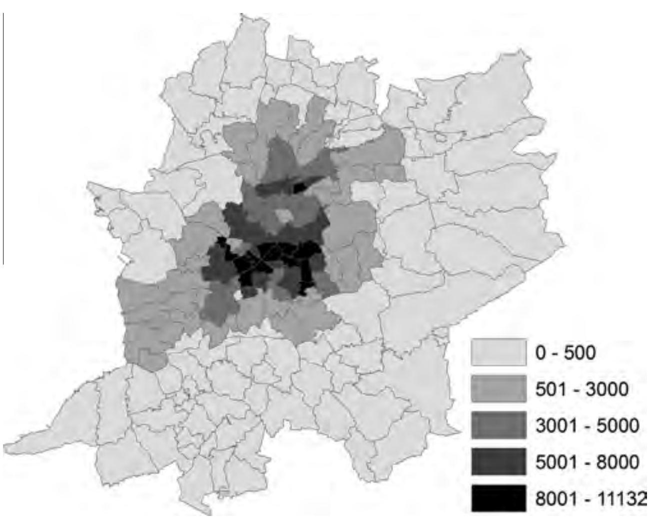

Fig. 2. Population density of the BAU scenario in 2030 (person/km^2).

space areas, which accommodate the population. In Fig. 5a, the population is distributed in zones that located in the center core area (red), living core area (yellow), and living space area (green). The zone population of the center core area and living core area is assumed be 1.5 times of population of the same zone in the BAU scenario. The remaining population is distributed to zones in the living space area by the zone population ratio in 1997. It is assumed that there are no residents living in zones outside of the core and living space areas. The population distribution result is shown in Fig. 5b.

2.2. Energy estimation method

From a consumption perspective all economic activities and the related energy use at all the stages of the economic process can be understood as being ultimately aimed at final consumption [31,32]. Based on this concept, energy consumption could be estimated through the estimating the good consumption. Utility theory is chosen as the basic theory for energy estimation approach for two reasons. Firstly, it is a developed theory that focuses on consumption behaviors and demand of goods in microeconomics. Utility is a term to describe the satisfaction experienced by a person through the consumption of commodities. In microeconomics, residents are assumed to make decisions based on their preferences of goods, the cost of goods, and budget constraints to maximize their utility. Solutions of maximum utility could give answers to the demand of goods. Secondly, social economic factor is included into consideration in utility theory, such as income. Three sub sections are included to introduce the approach to estimate individual demand of goods based on utility theory and calculation method of energy consumption.

2.2.1. Assumptions

All consumption behaviors of residents are classified as consumption behaviors for non-mobility goods and mobility goods. Mobility goods include car trips and mass transit trips. Non-mobility goods are defined as all other goods except mobility goods. Specially, non-mobility goods include goods in the Residential and Commercial sectors, such as heating, cooling, food and recreation. Following assumptions are essential parts for developing the approach to estimate demand of goods: (a) Consumption preference of the "representative individual" is applied as a representation of all individuals' behaviors in each zone. (b) The "representative individual" is assumed to consume two types of goods: non-mobility goods and mobility goods. (c) The demand of mobility goods is a function of car trips and mass transit trips. (d) Individuals are supposed to achieve maximum utility and mobility at same time. The demand of goods on maximum utility and maximum mobility is assumed be equal to the real demand of goods. (f) All income is spent on consuming without saving.

2.2.2. Mathematical model for demand of goods

A two order Constant Elasticity of Substitution (CES) function are applied to express the relationship between utility, mobility,

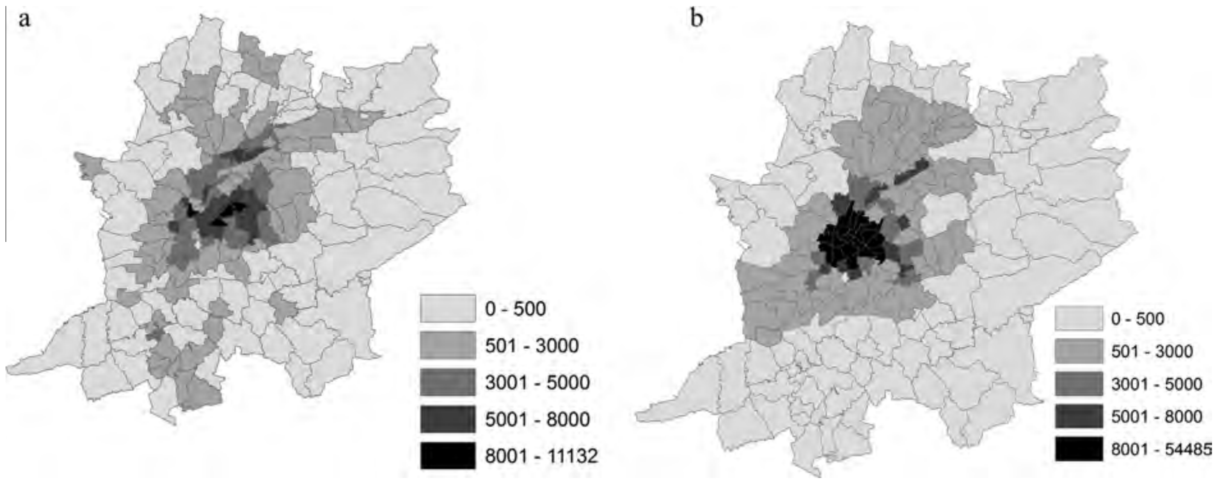

Fig. 3. (a) Population density of the Central core city scenario (1) in 2030 (person/km^2). (b) Population density of the Central core city scenario (2) in 2030 (person/km^2).

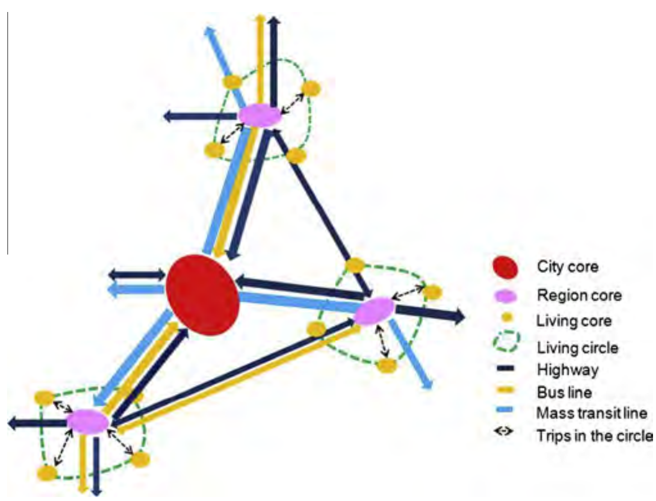

Fig. 4. Concept structure of Multi-pole urban structure scenario.

and demand of goods. Utility is determined by the consumption of non-mobility goods and mobility goods. The constant elasticity of substitution between non-mobility goods and mobility goods is represented by a CES function at the first order (Eq. (1)). Mobility is determined by car trips and mass transit trips. The substitution relationship between car trips and mass transit trips is expressed by CES function at the second order (Eq. (2)).

$$u_i(x_{1i}, x_{2i}) = \left\{\alpha_1 x_{1i}^{(\sigma_1-1)/\sigma_1} + \alpha_2 x_{2i}^{(\sigma_1-1)/\sigma_1}\right\}^{\sigma_1/(\sigma-1_1)} \tag{1}$$

$$x_{2i}(x_{2Ci}, x_{2Mi}) = \left\{\alpha_{2C} x_{2Ci}^{(\sigma_2-1)/\sigma_2} + \alpha_{2M} x_{2Mi}^{(\sigma_2-1)/\sigma_2}\right\}^{\sigma_2/(\sigma_2-1)} \tag{2}$$

where u_i indicates utility level; x_{1i}, x_{2i} are demand of non-mobility goods and mobility goods, respectively; x_{2Ci}, x_{2Mi} are demand of car trips and mass transit trips, respectively; σ_1 represents substitution elasticity between non-mobility goods and mobility goods; σ_2 is substitution elasticity between car trips and mass transit trips; α_1, α_2 are expenditure share of non-mobility goods and mobility goods to income, respectively; α_{2C}, α_{2M} are expenditure share of car trips and mass transit trips to traffic budget, respectively.

The demand of goods in reality is estimated by solutions of maximization problems of utility and mobility. Firstly, maximum mobility is determined by car trips and mass transit trips subject to the transportation budget (Eq. (3)). Secondly, maximum utility is determined by non-mobility goods and maximum mobility under the income constraint (Eq. (4)).

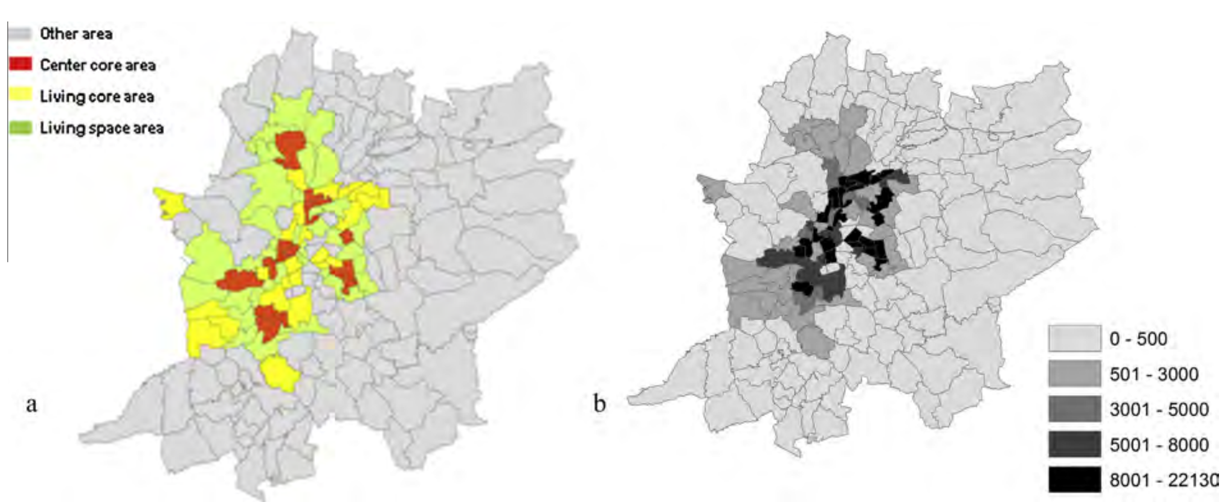

Fig. 5. (a) Cores and living space area in the Multi-pole structure scenario. (b) Population density of Multi-pole structure scenario in 2030 (person/km^2).

$$\max_{x_{1i},x_{2i}} : u_i = \left\{\alpha_1 x_{1i}^{(\sigma_1-1)/\sigma_1} + \alpha_2 x_{2i}^{(\sigma_1-1)/\sigma_1}\right\}^{\sigma_1/(\sigma_1-1)} \quad s.t. \quad p_{1i}x_{1i} + p_{2i}x_{2i} \leqslant I_i \tag{3}$$

$$\max_{x_{2Ci},x_{2Mi}} : x_{2i} = \left\{\alpha_{2C} x_{2Ci}^{(\sigma_2-1)/\sigma_2} + \alpha_{2M} x_{2Mi}^{(\sigma_2-1)/\sigma_2}\right\}^{\sigma_2/(\sigma_2-1)} \quad s.t. \quad p_{2Ci}x_{2Ci} + p_{2Mi}x_{2Mi} \leqslant I_{2i} \tag{4}$$

where in zone i, p_{1i}, p_{2i}, p_{2Ci}, p_{2Mi} represent price of non-mobility goods, mobility goods, car trips, and mass transit trips, respectively; I_i is income (person per day); I_{2i} indicates traffic budget (person per day).

The solutions of the maximum mobility problem at the second stage shows the optimal number of car trips and mass transit trips as Eqs. (5) and (6). The maximum mobility and corresponding price of mobility goods are shown in Eqs. (7) and (8), respectively.

$$x_{2Ci} = (\alpha_{2C}/p_{2Ci})^{\sigma_2}\left(I_{2i}\Big/\left(\alpha_{2Ci}^{\sigma_2}p_{2Ci}^{(1-\sigma_2)} + \alpha_{2Mi}^{\sigma_2}p_{2Mi}^{(1-\sigma_2)}\right)\right) \tag{5}$$

$$x_{2Mi} = (\alpha_{2M}/p_{2Mi})^{\sigma_2}\left(I_{2i}\Big/\left(\alpha_{2Ci}^{\sigma_2}p_{2Ci}^{(1-\sigma_2)} + \alpha_{2Mi}^{\sigma_2}p_{2Mi}^{(1-\sigma_2)}\right)\right) \tag{6}$$

$$x_{2i} = \left(\alpha_{2C}^{\sigma_2}p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2}p_{2Mi}^{1-\sigma_2}\right)^{1/(\sigma_2-1)} \cdot I_{2i} \tag{7}$$

$$p_{2i} = \left\{\alpha_{2Ci}^{\sigma_2}p_{2Ci}^{(1-\sigma_2)} + \alpha_{2Mi}^{\sigma_2}p_{2Mi}^{(1-\sigma_2)}\right\}^{1/(1-\sigma_2)} \tag{8}$$

The maximum utility problem is solved based on the maximum mobility and price of mobility goods. The optimal demand of non-mobility goods and mobility goods is shown as Eqs. (9) and (10). The traffic budget is calculated as Eq. (11). Substituting I_{2i} with I_i, the optimal demand car trips and mass transit trips on maximum utility and maximum mobility could be express as Eqs. (12) and (13), respectively.

$$x_{1i}^* = (\alpha_1/p_{1i})^{\sigma_1}\left\{I_i\Big/\left[\alpha_1^{\sigma_1}p_{1i}^{1-\sigma_1} + \alpha_2^{\sigma_1}\left(\alpha_{2Ci}^{\sigma_2}p_{2Ci}^{(1-\sigma_2)} + \alpha_{2Mi}^{\sigma_2}p_{2Mi}^{(1-\sigma_2)}\right)^{\frac{(1-\sigma_1)}{(1-\sigma_2)}}\right]\right\} \tag{9}$$

$$x_{2i}^* = (\alpha_2/p_{2i})^{\sigma_1}\left(I_i\Big/(\alpha_1^{\sigma_1}p_{1i}^{1-\sigma_1} + \alpha_2^{\sigma_1}p_{2i}^{1-\sigma_1})\right) \tag{10}$$

$$I_{2i} = p_{2i}x_{2i}^* = p_{2i}(\alpha_2/p_{2i})\left(I_i\Big/\left(\alpha_1^{\sigma_1}p_{1i}^{1-\sigma_1} + \alpha_2^{\sigma_1}p_{2i}^{1-\sigma_1}\right)\right) \tag{11}$$

$$x_{2Ci}^* = (\alpha_{2C}/p_{2Ci})^{\sigma_2}\alpha_2^{\sigma_1}\left(\alpha_{2C}^{\sigma_2}p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2}p_{2Mi}^{1-\sigma_2}\right)^{((\sigma_2-\sigma_1)/(1-\sigma_2))} \times \left\{\alpha_1^{\sigma_1}p_{1i}^{1-\sigma_1} + \alpha_2^{\sigma_1}(\alpha_{2C}^{\sigma_2}p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2}p_{2Mi}^{1-\sigma_2})^{((1-\sigma_1)/(1-\sigma_2))}\right\}^{-1} I_i \tag{12}$$

$$x_{2Mi}^* = (\alpha_{2M}/p_{2Mi})^{\sigma_2}\alpha_2^{\sigma_1}\left(\alpha_{2C}^{\sigma_2}p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2}p_{2Mi}^{1-\sigma_2}\right)^{((\sigma_2-\sigma_1)/(1-\sigma_2))} \times \left\{\alpha_1^{\sigma_1}p_{1i}^{1-\sigma_1} + \alpha_2^{\sigma_1}(\alpha_{2C}^{\sigma_2}p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2}p_{2Mi}^{1-\sigma_2})^{((1-\sigma_1)/(1-\sigma_2))}\right\}^{-1} I_i \tag{13}$$

2.2.3. Energy estimation function

Individual energy consumption in zone i is calculated based on demand of goods, energy unit, and trip time (Eq. (14)). E_i is the energy consumption of a "representative individual" in zone i. E is the total energy consumption of the region, which depends on E_i (energy consumption of a "representative individual") and P_i (population) in zone i. x^*_{1i}, x^*_{1Ci}, x^*_{1Mi}, are demand of non-mobility goods, car trips, and mass transit trips on the maximum utility (u_i^*), respectively. e_1, e_2, and e_3, are energy units of non-mobility goods, car trip, and mass transit trip, respectively. Energy units are used to evaluate the energy needed of each goods, which are important constants in the function. t_{2Ci}, t_{2Mi}, are trip time of car trip and mass transit trip. The trip time is introduced into the function to consider the influence of traffic congestions on energy consumption. Serve traffic congestion means longer travel time, thus more energy consumption.

$$E = \sum_i E_i P_i = \sum_i \left(e_1 x_{1i}^* + e_2 t_{2Ci}(x_{2Ci}^*, x_{2Mi}^*)x_{2Ci}^* + e_3 t_{2Mi}(x_{2Ci}^*, x_{2Mi}^*)x_{2Mi}^*\right) \cdot P_i u_i(x_{1i}^*, x_{2Ci}^*, x_{2Mi}^*) = u_i^*, \forall_i \tag{14}$$

2.3. Data source

2.3.1. Energy unit

According to the data from Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry in Japan, the energy unit of goods in the Residential and Commercial sector is 17.47 kJ/yen in the Kumamoto prefecture in 2010, including energy for residential, water supply, sewage and waste disposal, trade and finance service, public service, commercial service, retail servicers [26]. Non-mobility goods include goods in the Residential and Commercial sector. Energy unit of non-mobility goods is assumed to be same as the energy unit of goods in the Residential and Commercial sector, which equals 17.47 kJ/yen.

The energy unit of a trip is determined by the running fee unit, which measures the cost of one vehicle running one kilometer, including fees for oil, tires, tubes, and vehicle maintenance and depreciation. Based on the data of the running fee unit from a report titled "A method to calculate unit value of time and running fee unit in 2003" from Ministry of Land, Infrastructure and Transport (MLIT) in Japan, the running fee unit in 2003 is used to calculate the energy unit of a car trip and a mass transit trip due to lack of latest data [33]. The energy unit of a trip is calculated as following: energy unit of trip (kcal/trip min) = the energy unit of trip distance (kcal/trip min) × average speed (km/min). Based on the running fee unit of a trip, the trip distance, and the trip time, the energy unit of a car trip is estimated be 825.4 kJ/trip min (equals to 197.18 kcal/trip min), and 76.01 kJ/trip min (18.16 kcal/trip-min) for a mass transit trip (1 cal = 4.186 J).

2.3.2. Primary trip data

The Personal Trip Survey (PTS) is a person-based travel survey conducted every ten years by Ministry of Land, Infrastructure and Transport (MLIT) in Japan. The data are aggregated by traffic zones. Although the latest PTS was carried in 2012 in Kumamoto, the data is not available. Most of the data used for parameter estimation are from the PTS in 1997, which is provided by the Urban Transport Planning and Consultation Council of the Kumamoto metropolitan region. Car trips and mass transit trips are aggregated from the original PTS dataset. Trips only for the purposes of commuting, business, shopping, and returning home, are taken into consideration.

2.3.3. Price of goods

The price of non-mobility goods is set to one. The price of mobility goods is determined by the price of car trip and mass transit trip. The price of car trip is measured by the speed of a trip and the running fee unit. It is calculated as follows: p_{2Ci} (yen/trip) = [(running fee unit (yen/km vehicle) × minimum distance from zone i to j (km/trip))]/average number of passengers (trip/vehicle). The number of passengers in a car is 1.21 according to the report from MLIT [26]. The price of a mass transit trip is determined by the mass transit fare based on the trip assignment result.

2.3.4. Income

It is difficult to estimate the household income in each zone in Kumamoto in 2030. First, we forecast the total income of all residents in Kumamoto metropolitan region in 2030 according to the history income data of each administrative district from the homepage of the Kumamoto prefecture. The total income of each administrative district in 2030 is calculated by multiplying the average increasing ratio and the income of 2010. The increasing ratio of income is the averaged value of increasing ratios of income from 2000 to 2010 [34]. Because a positive relationship between land price and income is assumed, the zone income ratio is supposed to be equal to the land price ratio of main roads in each zone. Then we distribute the total income of each administrative district among zones according to the land price ratio of main roads in 2010. The data of land price of main roads are available from the Japanese National Tax Agency [35].

2.3.5. Trip time

Trip time is estimated by assigning car trips and mass transit trips on the maximum utility on the network by software, which is called JICA System for Traffic Demand Analysis (JICA STRADA). It is a package system for forecasting transport demand, traffic mode choice, traffic distribution, and traffic assignment. The software was used to estimate the trip time of all zone pair (trips from zone i to zone j) by assigning estimated demand of trips to the network of Kumamoto. For zone i, there are many trips from zone i to the different destination zone j. Trip time of all trip pair from zone i is averaged weighted by number of trips. The averaged value of trip times is used in the energy estimation function for zone i.

2.4. Parameter Estimation

The values of elasticity of substitution, σ_1 and σ_2, could be estimated if values of self and cross demand elasticity of car trips and mass transit trips, ε_{2mmi} and ε_{2mci}, are estimated according to Eqs. (15) and (16) [36].

$$\varepsilon_{2mmi} = ((\partial x_{2mi}/x_{2mi})/(\partial p_{2mi}/p_{2mi})) = -\sigma_2 + (\sigma_2 - \sigma_1)(p_{2mi}x_{2mi}/I_{2i}) + (\sigma_1 - 1)(p_{2mi}x_{2mi}/I_i) \quad (15)$$

$$\varepsilon_{2mci} = ((\partial x_{2mi}/x_{2mi})/(\partial p_{2ci}/p_{2ci})) = (\sigma_2 - \sigma_1)/(p_{2ci}x_{2ci}/I_{2i}) + \sigma_1 - 1(p_{2ci}x_{2ci}/I_i) \quad (16)$$

An aggregated logit-type model is introduced to estimate the values of ε_{2mmi} and ε_{2mci}, shown as Eqs. (17) and (18). G_{2Mi} and G_{2Ci} are the generalized cost of a car trip and a mass transit trip. D_i is the city center zone dummy variable. It takes the value of 1 for center zone and 0 in other cases. The self and cross demand elasticity of car trips and mass transit tips, ε_{2mmi} and ε_{2mci}, are calculated based on Eqs. (19) and (20). The values of ε_{2mmi} and ε_{2mci} are calculated zone by zone. The average value of all zones is applied for model parameters of ε_{2mm} and ε_{2mc}. It is easy to calibrate the allocation parameters α_1, α_2, α_{2C}, α_{2M}, if the value of σ_1 and σ_2 are determined by Eqs. (21) and (22).

$$W_{2Ci} = \exp(\xi + \delta \cdot D_i + \gamma \cdot G_{2Ci})/\{\exp(\xi + \delta \cdot D_i + \gamma \cdot G_{2Ci}) + \exp(\gamma \cdot G_{2Mi})\} \quad (17)$$

$$W_{2Mi} = \exp(\gamma \cdot G_{2Mi}) \Big/ \{\exp(\xi + \delta \cdot D_i + \gamma \cdot G_{2Ci}) + \exp(\gamma \cdot G_{2Mi})\} \quad (18)$$

$$\varepsilon_{2mmi} = ((\partial W_{2Mi}/W_{2Mi})/(\partial p_{2mi}/p_{2mi})) = \gamma \cdot G_{2Mi} \cdot (1 - W_{2Mi}) \quad (19)$$

$$\varepsilon_{2mci} = ((\partial W_{2Mi}/W_{2Mi})/(\partial p_{2ci}/p_{2ci})) = -\gamma \cdot G_{2Ci} \cdot W_{2Ci} \quad (20)$$

$$\alpha_{ki} = \left(\left(p_{ki}x_{ki}^{1/\sigma_1}\right) \Big/ (p_{1i}x_{1i}^{1/\sigma_1} + p_{2i}x_{2i}^{1/\sigma_1})\right) \quad (k = 1, 2) \quad (21)$$

$$\alpha_{2mi} = \left(p_{2mi}x_{2mi}^{1/\sigma_2} \Big/ \left(p_{2Ci}x_{2Ci}^{1/\sigma_2} + p_{2Mi}x_{2Mi}^{1/\sigma_2}\right)\right) \quad (m = C\, or\, M) \quad (22)$$

3. Results

3.1. Parameters and sensitivity analysis

As shown in Eqs. (12) and (13), it is essential to estimate the parameters in utility and mobility CES functions for estimating the demand of goods, thus energy consumption. σ_1, the elasticity of substitution between non-mobility goods and mobility goods, is estimated be 0.6577. σ_2, the elasticity of substitution between car trips and mass transit trips, is 1.0787. The value of the expenditure share parameter, α_1, is 0.9995, indicating that residents spend most of their income on non-mobility goods. In contrast, α_2 is indicated as 0.0005. Eighty percent of the transport fare is spent for car trips, shown by the value of 0.8040 of α_{2C}. Less than twenty percent of the traffic budget is spent on mass transit trips, shown as the value of α_{2M} as 0.1960.

We also analyzed the sensitivity of input variables on output variables. In this methodology, the output variable is the amount of individual energy consumption. As parameters and energy units are fixed constant, input variables include prices of goods, income, and trip time. Energy consumption is most sensitive to income. It increases 1.00% as income increases by 1.00%. Price of non-mobility goods also shows strong influence on energy consumption. The amount of energy reduces 0.58% as the price of non-mobility goods improves 1%. Increasing 1% of the price of car trips would result in 0.17% reduction of energy consumption. Energy only increases 0.01% when the price of mass transit trips improves by 1%. If the trip time of car trips increases 1%, energy consumption would increase 0.23%. However, there is very limited effect of trip time of mass transit trips. Energy increases 0.003% as trips time of mass transit trips increases by 1%.

3.2. Demand of Goods

As shown in Table 1, a total of 6.48 billion units of non-mobility goods are needed for all residents in Kumamoto each day in the BAU scenario. Compared to BAU scenario, monocentric and polycentric urban structure scenarios show higher demand of non-mobility goods. A mild increase trend is shown in the Central core city scenario (1), totally 6.62 billion units of non-mobility goods are needed. The lowest increase demand of non-mobility goods is shown in the Multi-pole structure scenario, which is 6.51 billion units, 1.01 times of the BAU scenario's. The highest demand of non-mobility goods is found in the Central core city scenario (2). More than 6.87 billion units of non-mobility goods are expected, which is 1.1 times of the result of the BAU scenario.

By contrast, the demand of car trips shrinks in monocentric and polycentric urban structure scenarios. Reduced car trips are found in all scenarios compared to the BAU scenario. Both Central core city scenario (1) and (2) show smaller number of car tips, indicated as 1.71 million and 1.73 million, compared to 1.76 million of the BAU scenario. The lowest demand of car trips is observed in the Multi-pole structure scenario, which has 1.64 million car trips each day in Kumamoto. However, an increasing trend is suggested for the result of mass transit trips. The number of mass transit trips is expected to increase to 99.9 thousand, 109 thousand, and 102 thousand in the Central core city scenario (1), the Central core city scenario (2), and the Multi-pole structure scenario, respectively. In BAU scenario, 88.3 thousand of mass transit trips are estimated per capita per day.

3.3. Energy Consumption

Table 2 lists the detailed information of energy estimation. 151 billion kJ of energy is needed for all residents per day in Kumamoto in the BAU scenario, compared to 149 billion, 154 billion, and 146 billion kJ in the Central core city scenario (1), the Central core city scenario (2), and the Multi-pole structure, respectively. A decreasing trend of energy consumption is shown in both the Central core city scenario (1) and the Multi-pole structure scenario. However, the result of the Central core city scenario (2) indicates increased total energy consumption. An increasing trend of energy use for non-mobility goods is indicated in the results of monocentric and polycentric urban structure scenarios. The highest value of energy consumption for non-mobility goods is found in the Central core city scenario (2), which is 120 billion kJ per day. The lowest value is shown in the BAU scenario, as 113 billion kJ per day. Energy consumption for non-mobility goods in the Multi-pole structure scenario increases a little compared to the BAU scenario,

Table 1
Daily demand of goods in Kumamoto.

	BAU scenario	Central core city scenario (1)	Central core city scenario (2)	Multi pole structure scenario
Non-mobility goods (yen/day)	6.48×10^9	6.62×10^9 (1.02)	6.87×10^9 (1.10)	6.51×10^9 (1.01)
Car trips (trip/day)	1.76×10^6	1.71×10^6 (0.97)	1.73×10^6 (0.98)	1.64×10^6 (0.93)
Mass transit trips (trip/day)	8.83×10^4	9.99×10^4 (1.13)	1.09×10^5 (1.23)	1.02×10^5 (1.16)

Note: The number in ( ) indicates the increased ratio compared to the data of the BAU scenario.

Table 2
Estimated energy consumption in Kumamoto in 2030.

	BAU scenario	Central core city scenario (1)	Central core city scenario (2)	Multi pole structure scenario
Total energy consumption (kJ/day)	1.51×10^{11}	1.49×10^{11}	1.54×10^{11}	1.46×10^{11}
Energy consumption for non-mobility goods (kJ/day)	1.13×10^{11} (74.72%)	1.16×10^{11} (77.61%)	1.20×10^{11} (77.98%)	1.14×10^{11} (77.66%)
Energy consumption for car trips (kJ/day)	3.75×10^{10} (24.82%)	3.26×10^{10} (21.90%)	3.30×10^{10} (21.51%)	3.19×10^{10} (21.84%)
Energy consumption for mass transit trips (kJ/day)	6.99×10^8 (0.46%)	7.24×10^8 (0.49%)	7.74×10^8 (0.50%)	7.37×10^8 (0.50%)

Note: The number in ( ) indicates the energy share.

amounting 114 billion kJ per day. It is of note that more than 20% of the total energy is used for the consumption of mobility goods in all scenarios. Energy consumption for car trips reaches 37.5 billion kJ per day in the BAU scenario, accounting for 24.82% of the total energy consumption. Energy consumption for car trips in the Central core city scenarios shows lower values of 32.6 billion and 33 billion kJ per day in the Central core city scenario scenarios (1) and (2), respectively. Energy for car trips in the Multi-pole structure scenario reduces to 31.9 billion kJ. Less than 0.5% of the total energy consumption is consumed for mass transit trips. In the BAU scenario, 699 million kJ of energy is estimated for mass transit trips each day. Other scenarios show increased energy for mass transit trips. In the Central core city scenario (2), the value reaches 774 million kJ.

4. Discussion

Facing the magnitude and speed of urban growth, it is important to evaluate the environmental impacts of urban structures, and to reduce their environmental impacts for urban sustainable development. Previous works focused on energy efficiency of compact urban structures in the traffic sector. Little attention has been focused on energy consumption in other sectors. This study analyzed the energy consumption by simulating the consumption behaviors of residents, both traffic behaviors and non-traffic behaviors, in urban structure scenarios named Business as usual scenario, Central Core City scenario and Multi-pole structure scenario from a microeconomic viewpoint.

It found that compact urban structures are influential on energy consumption behaviors thus energy use. Residents are estimated to increase the energy use for non-mobility goods in compact urban structure scenarios. More energy consumption is found in the monocentric urban structures than polycentric structures. The energy consumption is effectively reduced in the Multi-pole structure scenario. This polycentric urban structure disperses activities to several poles, decreasing the complexity of the traffic. Moreover, shorter trips could be encouraged in dense pole areas because of high facility availability and employment opportunities. Concentration of employment around the poles would reduce commuting trips. Enough services and facilities together with expanding mass transit infrastructure ensure the high accessibility and mobility of residents who live in the poles. Individuals have easy access to services and goods related to daily life, such as supermarkets, hospitals, schools, and gyms.

On the other hand, different population distribution methods in monocentric urban structures show different influence on energy consumption. Less energy consumption is found in the Central core city scenario (1), in which the population is distributed in the urbanized area of Kumamoto. The development of the city center probably stimulates the use of public transport. The increase of mass transit usage could reduce the expenditure on mobility goods, and in return promote the consumption of non-mobility goods. As a result, small number of trips is found in the Central core city scenario (1). Even though the strict compact urban structure of the Central core city scenario (2) shows some positive outcomes in terms of travel patterns as less car trips as well as a higher number of mass transit trips, more energy use is identified in the results of Central core city scenario (2). It could be explain by the less beneficial effects on energy saving in the long term. Concentration of residents in the city center would result in longer travel distance and traffic jams in the city center for all residents. Although most of the living space in the Central core city scenario (2) is urbanized area, there are still residents in the suburban area. People who live in the suburbs and outside of the city center need to travel far and frequently to obtain services in the city center. This of course would increase the trips and lead to a more complex traffic condition in the city center. Consequently, more traffic jams and more energy consumption are expected.

5. Conclusion

This study showed a quantitative approach to simulate consumption behaviors of residents and estimate energy consumption under three urban structure scenarios for the Kumamoto metropolitan region in 2030. The simulation results of the BAU scenario, the Central core city scenario, and the Multi-pole structure scenario indicate two major findings. Firstly, urban structure is influential on energy consumption behaviors thus energy use. More energy use for non-mobility goods is found in Central core city scenario and the Multi-pole structure scenario. Secondly, more energy consumption is found in the monocentric urban structure. Multi-pole structure is recommended as a better choice of urban structure for compact development in Kumamoto due to energy saving.

The study provides deep insights into individual energy use at a zone scale, and included a holistic perspective on energy use by goods. It extends the concept of compact development analysis to a very small aggregated level and then compares rather extreme urban structures in Kumamoto. To the authors' knowledge, there are no other models that attempted to quantify total energy consumption for an individual at the zone scale as this work. The new approach for energy estimation by an innovative idea of utility enriches the knowledge of energy estimation models at micro level. Unlike previous studies which took in a limited view of energy in transportation or residential sector, this approach enables us to estimate not only the energy consumption for transportation, but also energy for other goods and services. Moreover, the methodology of this paper evaluates the effect of urban structures on energy consumption through personal consumption behaviors from a new viewpoint. It takes the advantage of consideration of social economic factors. Such results provide a context for evaluating the impacts of urban structures on energy saving and allow a more quantitative comparison of energy use across different urban form environments. The study could not only give suggestions for urban planners in Kumamoto, but also expand the field of analysis tool of policy making for governments aiming for compact development.

Our paper provided deeper understanding of consumption behaviors in the context of compact cities at a micro level, and give suggestions for the successful implementation of compact policy in Kumamoto. However, following points should be taken into consideration for the future work. Firstly, more urban structure scenarios should be set based on not only the population distribution but also physical elements of urban structures. Secondly, the modeling assumptions are still in need of further refinement as more and better information of consumption behaviors becomes available. For instance, the paper is not specific in transport goods. The analysis of trips of particular purposes by other transport modes, such as walking, gives more explanation of traffic behaviors of residents. Last but not least, land could be analyzed as special goods into the model because compact development is closely related to the use of land. All three points would benefit future academic study by deeply investigating on the relationship between consumption behaviors, energy use, and compact development. Useful findings could be drive form to give suggestions for urban planners, transport planner, and energy saving policy making.

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