Air Pollution Control and Climate Change Measures in Fuxin City, Liaoning Province, China

都市の大気汚染問題は喫緊の課題。遼寧省阜新市での各種エネルギー政策分析を通して、環境共生都市への道を探る。

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Abstract Nonindustrial energy consumption has been increasing rapidly in China with economic development. Household energy demand is increasing for heating, cooking, and other uses. In the cities in China's colder regions, approximately 80% of energy supply is dependent on coal. Therefore air pollution control and CO_2 emissions reduction is an urgent environmental challenge. For this purpose district heating is installed and modernized with the heating demand growth of housing and buildings.

In this study, we investigated actual household energy consumption using official surveys and statistics as well as our original questionnaire. Based on this data, we conduct a quantitative analysis on the relationship between the expenditure of energy and household income, the housing environment, lifestyle, and other factors. Using the results of this analysis, we consider the major factors behind increased household energy consumption. We also conduct a quantitative evaluation of the air pollution control measures (e.g., introduction of flue-gas desulfurization equipment and promotion of district heating systems) taken by the central and city governments, as well as improvements for enhancing the environmental functions of district heating systems. Our quantitative evaluation further highlights Fuxin's potential to become a low-carbon city by expanding the use of methane gas from the city's coal fields and promoting the introduction of renewable energy.

Keywords Air pollution; District heating systems; Household energy consumption; Flue-gas desulfurization equipment; Low-carbon city

Introduction

China's 12th five-year plan, adopted by the National People's Congress in March 2011, identifies environmental problems as more important policy challenges than in the previous plan. The nation now must tackle a number of environmental issues simultaneously including air pollution, water pollution, global warming, and ecosystem preservation.

Energy consumption in the nonindustrial (household/commercial) sector has been surging; household energy consumption per person increased rapidly from 42.4 kWh in 1990 to 132.4 kWh in 2000 and then to 274.9 kWh in 2007. In addition to electric power, households are also demanding more heat for heating, cooking, and other uses.

Amidst the rapid increase in household energy consumption and the changing housing environment in urban areas, controlling air pollution and CO_2

emissions resulting from heating demand in the cold regions, which depend on coal for approximately 80% of their energy, is an urgent environmental challenge.

The nation’s air pollution regulations have been tightened since 2000; installation of desulfurization equipment, electric precipitators, and other flue-gas treatment equipment is now mandatory. As the height of residential buildings continues to rise, cities in the cold regions have been actively promoting the introduction of district heating systems to reduce air pollution and modernize their living conditions.

District heating systems, an important piece of infrastructure for improving urban environments, are classified into two types based upon the method of heat supply employed: systems where power plants supply heat along with electricity and systems where dedicated boilers supply heat. Neither system unconditionally reduces regional air pollution and CO_2 emissions. District heating systems can be effective only after fuel choice, overall system efficiency, and antipollution technology have been designed appropriately. Therefore, it is important to quantitatively evaluate the effectiveness of district heating systems in reducing air pollution.

2. Research Methods and Purposes

We studied changes in energy demand composition and the state of air pollution in Fuxin City, Liaoning Province, and identified the city’s energy consumption characteristics based on statistical data for the period from 1996 to the latest years.

We also investigated actual household energy consumption using official surveys and statistics as well as a questionnaire we administered to residents. Based on this data, we conducted a quantitative analysis of the relationship between the cost of household energy and household income, the housing environment, and other factors. We also conducted a quantitative evaluation of the air pollution control measures (e.g., introduction of flue-gas desulfurization equipment and promotion of district heating systems) taken by the central and city governments as well as clarified the limitations and potential of such measures as well as the prerequisites for and obstacles to enhancing the environmental functions of district heating systems.

Our quantitative evaluation also highlights Fuxin’s potential to become a low-carbon city by expanding the use of spotlighted methane gas or coal-seam gas from the city’s coal fields and promoting the introduction of renewable energy.

3. State of the Environment and Energy in Fuxin City

3.1 Outline of the Environment in Fuxin City

Fuxin City (see Table 1), which was once one of China’s major coal-producing areas, has faced a number of serious environmental problems including air pollution, water pollution, and ground subsidence as a result of having served as a host to the coal industry.

Table 1 Overview of Fuxin City

Location	Northwest quadrant of Liaoning, China's northeastern province
Area	10,355 km^2
Population	1.93 million (approx. 0.78 million in urban areas and approx. 1.148 million elsewhere)
Number.,of Households	643,000
Administrative Divisions	Five districts (Haizhou, Xihe, Taiping, Xinqiu and Qinghemen) and two counties (Fuxin Mongol Autonomous and Zhangwu)
GDP(2009)	14,880 yuan per capita (urban areas: 0.78 million, 27,732 yuan per capita)
Climate	Continental climate typical of the north temperate zone: sufficient sunlight, frequent winds, and low rainfall
Mean Annual Temperature	8.06°C (1997 to 2000)
Coldest Month	-15.9°C (January)
Hottest Month	29.5°C (July)
Mean Annual Precipitation	420 to 540 mm
Mean Annual Humidity	61%

Table 2 State of Air Pollution in Fuxin City during the Period of 1996 to 2000

(a) Seasonal Changes of Air Pollution (unit:mg/ m^3)

Pollutant	Winter	Spring	Summer	Autumn
TSP	0.33	0.41	0.23	0.34
SO_2	0.12	0.03	0.01	0.03
	(0.042 ppm)	(0.011 ppm)	(0.004 ppm)	(0.011 ppm)
CO	1.7	0.9	1.1	1.3
	(1.36 ppm)	(0.72 ppm)	(0.88 ppm)	(1.04 ppm)
NOx	0.03	0.03	0.02	0.03
	(0.015 ppm)	(0.015 ppm)	(0.010 ppm)	(0.015 ppm)

(b) Annual Averages of Air Pollution by District (unit:mg/m^3)

Pollutant	Industrial District	Residential District	Transport District	Clean District
TSP	0.3	0.33	0.4	0.29
SO_2	0.03	0.04	0.08	0.03
	(0.011 ppm)	(0.014 ppm)	(0.028 ppm)	(0.011 ppm)
CO	1.2	1.3	1.6	0.9
	(0.96 ppm)	(1.04 ppm)	(1.28 ppm)	(0.72 ppm)
NOx	0.03	0.03	0.04	0.03
	(0.015 ppm)	(0.015 ppm)	(0.019 ppm)	(0.015 ppm)

Source: Fuxin Environmental Observatory

The decline of the coal industry, which began in the 1990s, forced the city to transform its industrial structure and make efforts to restore the environment. The city is in the process of implementing a plan to end its heavy dependence on coal, reduce environmental pollution, restore the surrounding ecosystem, and create a balanced industrial structure. As the city depends on coal for 80% of its energy needs, reducing air pollution caused by substances such as particulate matters (PM), sulfur oxides (SOx) and nitrogen oxides (NOx) as well as reducing CO_2 emissions by increasing energy efficiency are important goals. In addition to these environmental problems, Fuxin must solve a problem particular to coal-mining cities, namely disposing of the spoil heaps scattered around the city. The city's mining district has as many as 240 spoil heaps large and small, covering a total area of 2,885 ha with a volume of 1.2 billion m^3.

Adjacent to Inner Mongolia, residents of Fuxin suffer from the dust from the spoil heaps blown about by strong winds as well as the dry spring weather. In 1996-2000, Fuxin's TSP (total suspended particles) concentration was highest in spring (0.41 mg/m^3), which is a value much higher than the ambient air environmental quality standard. Fuxin's SO_2 and CO concentrations were both highest in winter, when heating demand is large, reaching 0.12 mg/m^3 and 1.7 mg/m^3, respectively, in 1996-2000 (see Table 2). The reason for these high concentrations was that until 2000, dust collectors and desulfurization equipment were not mandatory for thermal power stations and many houses used individual coal-burning heating systems.

3.2 Structural Changes in the Energy Consumption in Fuxin City

In Fuxin City, most of the primary energy is supplied by coal, and consumption of energy has been increasing rapidly. While the industrial sector continues to be a major energy consumer, the residential sector has been consuming energy at an accelerated rate. Particularly since 2006, Fuxin's electric power consumption has been surging (see Fig. 1). Some power stations use low-quality coal because they must dispose of the resulting spoil.

As Fuxin's coal reserves have already started to become depleted, the city must secure new sources of energy in order to handle the expected increase in demand for power. Fuxin, which will likely procure the necessary coal from Inner Mongolia for the time being, has begun a large-scale renewable energy development project in order to diversify its energy sources.

Potential energy sources include the carbon contained in spoil, coal-seam gas (gas consisting primarily of methane from coal fields), biofuels, large-scale wind power generation that takes advantage of the area's strong winds, and liquefied petroleum gas (LPG). Among these, the city's rich coal-seam gas reserves of 11.6 billion m^3 (3.48 billion m^3 as potential reserves) are drawing international attention. Its

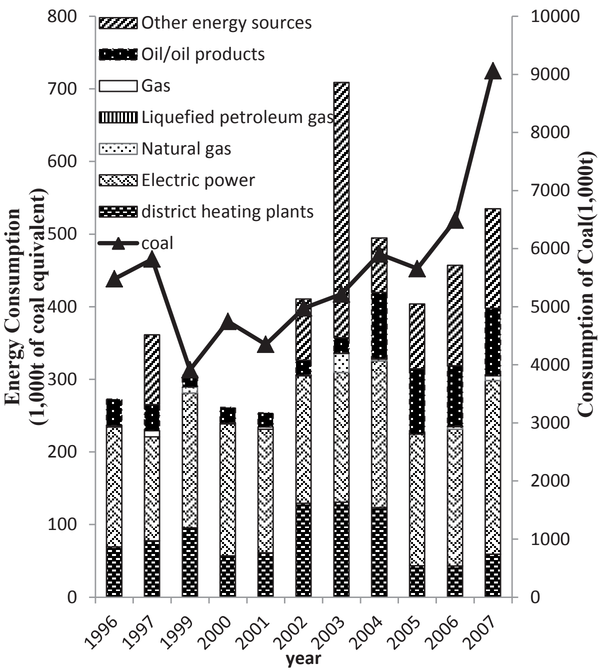

Fig. 1 Composition of Energy Consumption for Fuxin City (Coal and others are shown separately)

use of coal-seam gas has been increasing year after year, reaching 70 million m^3 in 2009. Coal-seam gas is used in various fields, including large-scale power generation and industrial facilities, residences, and light duty vehicles. In 2010, the number of power plants in the city burning only coal-seam gas had a total rated output of 29,600 kW and a total annual output of 176 million kWh.

The city is also in the process of implementing a large-scale wind power generation project, which as of April 2010 had a rated output of 725,000 kW. The annual output was 1,282.38 million kWh for 2010, accounting for 13% of the total power generation capacity of all power plants in the city. The city plans to quintuple the rated output of wind power generation to 3.6 million kW by the end of 2015. Given that the current operating rate of the wind power plants is approximately 20%, their total annual output is estimated to reach approximately 6.3 billion kWh in 2015. These efforts to diversify energy sources will be able to further reduce air pollution and CO_2 emissions.

3.3 Survey of Household Energy Consumption in Fuxin City

In China, where there is still a great economic gap between rural and urban areas, the living standards in urban areas have improved significantly. Typical housing has been shifting from individual houses to apartments. In the 1990s, Fuxin City began supplying gas to kitchens and introducing district heating systems as the number of apartment units increased. In recent years, electrical home appliances (e.g., televisions, refrigerators, and water heaters) have rapidly been adopted in residences in Fuxin. While the city's population has remained nearly constant since the 1990s (see Fig. 2), the one-child policy and the shift to apartments have encouraged families to become more nuclear (see Fig. 3). This trend has boosted household energy consumption, but the city currently places more importance on housing construction; neither the government nor the residents are particularly conscious of the need for energy conservation.

To ascertain the actual household energy consumption of urban residents and to look for clues on how to promote energy conservation, in November 2009 we conducted a door-to-door questionnaire of residents in two of Fuxin's residential districts (Haizhou and Xihe).

1) Outline of the Survey

Number of target households: 68 (194 residents) in two of Fuxin's residential districts (Haizhou and Xihe)

Housing conditions: All surveyed residences were apartments equipped with district heating and supplied with coal-seam gas (fuel consisting primarily (90%) of methane from coal mines) for their kitchens

Survey period: November 1 to 30, 2009

Survey items: Number of family members, floor area, household income, energy consumption, gas rate, district heating rate, fuel consumption of personal vehicles, use of clean energy, and ownership of electrical home appliances

Survey method: Door-to-door distribution and collection of questionnaires.

2) Questionnaire Survey Results

We were able to collect answers on family size, floor area, household income, electricity and heating costs from all 68 surveyed households. However, we received answers regarding ownership of electrical home appliances from only 20 households. Table 3 summarizes the survey results. Family sizes ranged from one to five (average: 2.9), with the largest group (35 households) consisting of families of three. Floor areas ranged from 43 to 164 m^2, with 55 households (80%) having a floor area in the range of 50 to 100 m^2. Annual household incomes spanned a twentyfold range from 7,200 to 150,000 yuan (average: 35,400 yuan). The average annual income per urban Chinese resident was 11,300 yuan in 2008, indicating that the average annual income of the 68 households was at the same level as the national average for urban households.

Annual electricity and heating costs (the total of electricity, gas, and heating costs) per household

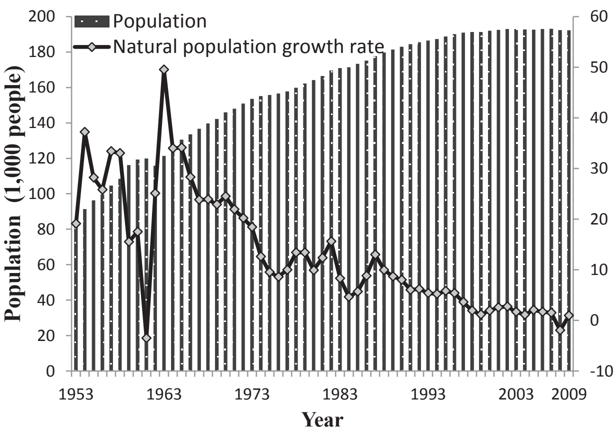

Fig. 2 Population and Population Growth Rate in Fuxin City

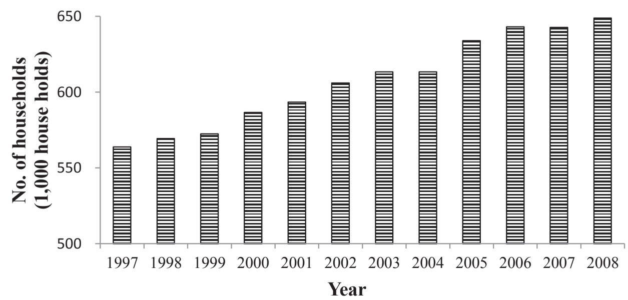

Fig. 3 Increase in the Number of Households in Fuxin City

Table 3 Summary of Questionnaire Survey Results

Survey Item	Basic Information			Electricity		District Heating Rate (yuan/year)	Gas Rate (yuan/year)	Total Electricity and Heating Costs
	Family Size	Floor Area (m2)	Annual Income (yuan)	Electricity Usage (kwh/year)	Electricity Rate (yuan/year)			
Highest	5	164	150,000	3,400	1,680	4,264	1,220	5,944
Lowest	1	42.58	7,200	400	200	1,107	0	1,647
Avg. per Household (68 households)	2.85	75.76	35,402	1,417	706	1,970	301	3,042
Avg. per Resident (194 residents)	—	26.56	12,409	497	247	690	105	1,066
Avg. % of Electricity and Heating Costs with Respect to Household Income (%)	—	—	—	—	2.0	5.6	0.8	8.4

ranged from 1,650 to 5,940 yuan (average: approx. 3,040 yuan). The percentage of electricity and heating costs with respect to total household income is 8.4% on average, ranging from 3 to 30% (see Fig. 4). Among electricity and heating costs, district heating costs were highest (5.6%), followed by electricity costs 2.0% and gas costs 0.8%. This survey found that both electricity and gas costs were lower than heating costs and have no correlation with household income. However, the percentage of electricity and gas costs in terms of total household income is likely to rise in the future.

On the other hand, the district heating rate is fixed at 26 yuan for five months per square meter of floor area: the five-month rate for homes with a floor area of 43 m^2 is 1,118 yuan while it is 4,264 yuan for homes with a floor area of 164 m^2. In other words, heating costs are greatly influenced by floor area.

Like cars and electrical home appliances, a comfortable apartment equipped with district heating is now a status symbol for urban Chinese. District heating rates, which are decided based on floor area, are structured as service charges. With a district heating system, households cannot reduce their heating costs even if they attempt to manage their room temperatures; such a heating system does not encourage users to conserve energy.

The authors also conducted an additional survey of 29 additional households in Fuxin City, in September through October, 2011, and got similar results, concerning the ratios of district heating costs to annual income and the total costs of electricity, gas, and heating.

4. Air Quality and Energy Conservation Measures

4.1 Environmental and Energy Conservation Measures

China's 10th five-year plan, formulated in 2000, classified areas not meeting environmental quality standards into "acid rain control areas" and "sulfur oxide pollution control areas" and set a target of reducing SOx emissions by 20%. However, the Chinese government failed to meet this target; as a result, in the 11th five-year plan formulated in 2005, it set a new, binding target for reducing energy consumption per GDP by 20% and SOx emissions by 10%. Under this plan, a target was set for Liaoning Province of reducing energy consumption per GDP by 20% and SOx emissions by 12%. Designated as a sulfur oxide pollution control area, Fuxin City formed a task force and set a target of reducing SOx emissions by 17.4% by 2010. Since then, the city has been demolishing old burning facilities and small-scale boilers, building large-scale burning facilities, and introducing air pollution control equipment.

Thermal power plants are the largest source of

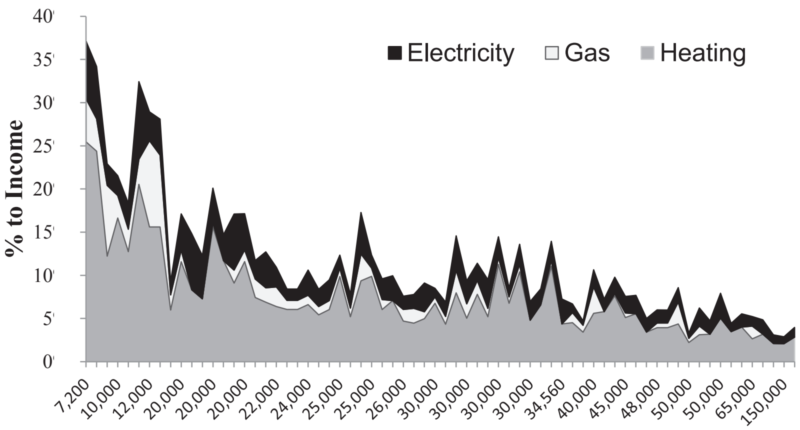

Fig. 4 Ratio of Electricity and Heating Cost to Household Income

air pollution in China. In 2003, SOx emissions from thermal power plants accounted for more than half of gross national SOx emissions (approx. 11 million tons). For Fuxin City, power plants and district heating plants are the largest source of air pollution. In 2006, the city's six major power plants emitted 23,000 tons of SOx (33% of the city's total SOx emissions) as well as 7,602 tons of PM (60% of the city's total PM emissions).

Fuxin has been introducing flue-gas desulfurization equipment (rated SOx removal efficiency: 95%) since 2006. Since 1997, with the support of the central and city governments, work has been being performed on the city's power plants to improve their energy efficiency. Among such work, the third improvement project (the addition of a 350,000-kW unit) was carried out as part of a 2003 provincial project for the 10th five-year plan. In addition, the city built thermal power plants using spoil as a "coal recycling project" in order to promote effective resource usage. In this project, the city installed flue-gas desulfurization equipment and soot collectors in thermal power plants in order to reduce air pollution. Power generation using spoil can both restore the surrounding ecosystem and reduce air pollution by disposing of spoil heaps. Upon the promulgation of a decree on "Administration of Fuxin City's Particulate Matter Control Areas" in 2007, the city replaced buildings equipped with individual coal-based heating systems with building complexes.

The city's other efforts include mandatory installation of desulfurization equipment and soot collectors for coal boilers of a certain size or larger, prohibition of the use of coal consisting of 0.7% or more sulfur in power stations and heat supply boilers, and mandatory measurement of the concentrations of SO_2 and PM (soot) emitted from coal boilers with thermal power of 200,000 t/h or more. SO_2 and PM emissions are subject to monitoring by Fuxin City's Environmental Protection Bureau.

As measures to reduce TSP (Total Suspended Particles), each coal mine operator is now responsible for preparing a waste heap and the Environmental Protection Bureau has specified routes for dump trucks transporting spoil as well as implemented other regulations.

4.2 Introduction of District Heating

In Fuxin City and other northeastern Chinese cities, heating accounts for a large part of nonindustrial energy consumption, which has been increasing rapidly in recent years. Since 1994, Fuxin City has been promoting the rapid adoption of district heating systems (see Fig. 5), which were first introduced in 1981, in order to meet surging demand for heat and energy as well as to achieve higher energy efficiency and better living conditions. Along with promoting energy conservation, increased adoption of district heating systems is one of the most effective means of reducing air pollution.

However, the current policy, which focuses on increasing the coverage of district heating systems, discourages residents from conserving energy because, as stated earlier, end users are unable to adjust the temperature and must pay fixed rates based on their floor area.

In northeastern China, district heating systems that supply both heat and power are generally used. Such systems can achieve a total thermal efficiency

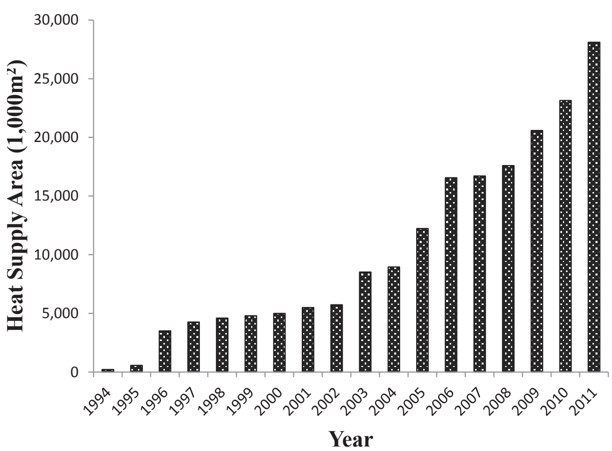

Fig. 5 Heat Supply Area of Fuxin City's District Heating Systems

Source: Fuxin City's statistical yearbooks (1994 to 2011) of 70 to 85% for both power generation and heating. According to official Chinese government statistics, heat supplied from this type accounts for 62.9% of the total heat supply from district heating systems, followed by those using heat-supply boilers (35.75%), and other types (1.35%).

Currently, the district heating operations in Fuxin City use heat from 6 combined heat-and-power plants (cogeneration plants) owned by power companies as well as heat from 13 heat-supply boilers owned by Fuxin City Thermal Power Corporation. The cogeneration plants produce approximately 90% of the heat for Fuxin's district heating systems. In 2007, these systems supplied heat to an area of 20.15 million m^2, including 254,000 households (40% of all households in Fuxin). Thus, many households, particularly those in the city center (heat was supplied to an area of 17.23 million m^2 and 228,000 households) are covered, and such heat is used by two out of every three households. In winter, waste heat from the cogeneration plants can be re-used effectively for district heating, but in summer such heat is discharged into cooling water. For this reason, the cogeneration plants have a low annual thermal efficiency. Two cogeneration plants that were built for spoil disposal and for which intensified measures against air pollution are being implemented combust low-quality coal (heating value: 3,000 kcal/kg) and spoil together; their power generation efficiency is lower than that of similar plants.

In China's cold regions, district heating systems do not supply hot water due to a shortage of water resources. Chemicals are intentionally added to the hot water piped to residences by such systems to give an abnormal odor in order to prevent residents from using the hot water and its heat.

Heat supply operations in China are suffering from surging coal prices. On September 14, 2009, the Price Bureau of Fuxin City officially announced an increase in the heat supply rate. The city government provides subsidies to offset heating costs for low-income households.

4.3 Problems with Fuxin City's District Heating Systems and Possible Solutions

(1) Shift from Fixed to Usage-based Rates

Fuxin City's district heating systems supply a set amount of heat 24 hours a day four months (November to March) a year, enabling users to maintain room temperatures of 16°C or more. As mentioned earlier, district heating systems do not allow for temperature adjustment and users are charged according to the floor area of their residences. A shift from this fixed-rate system to a usage-based system (i.e., one that charges users based on heat loads) has recently been considered nationally to reduce energy consumption. The impetus for this is rising government awareness of the importance of energy conservation. Introduction of a usage-based system requires improving the heat amount adjustment function across district heating systems. Such an improvement will level the total heat load for residences and offices, which have different peak hours, thereby leading to energy conservation. Zhengzhou City in Henan Province, one of the cities considering this shift, estimated that it would initially cost 50 yuan/m^2 to upgrade the distribution networks and 500 to 1,200 yuan per home to add heat meters. As the lifespan of heat meters generally ranges from five to seven years, a usage-based system could raise district heating costs considerably.

To solve this problem, a concerted policy effort is needed to ensure an economically efficient usage-based system through the development of heat-measuring technologies. If a new rate system could be applied to more new residences, mass production of heat meters would result in lower prices. In the end, a metered heat-supply system could create a virtuous circle in which energy conservation increases profits.

To introduce such a usage-based system, users must be able to adjust the temperature when using district heating systems. As the often poor insulation efficiency of Chinese buildings causes great heat loss and limits energy-conservation, perhaps one of the best ways to implement heat-supply systems currently is to install a thermal flowmeter in each apartment building and make the residents split the charges.

Since 2000, heat control has been attempted in China by installing thermal flowmeters in each new apartment building or per each new apartment. Related standards, laws, and regulations are being established and revised. By the end of 2010, 80 out of more than 130 cities in the northern region had made regulations about the price of heating metering and charging. In October 2009, the thermal flowmeters of 392 buildings and 15,539 households in a 1.6 million-m^2 area of the city were upgraded as part of the project; in November, the city government promulgated a decree on "Provisional Management of District Heating Rates for Residents of Dalian as a Heat-flow Model City." The test also revealed that energy consumption of the top-floor, end, and corner residences was approximately three times as much as that of residences in the central part of the building.

Although heating meters have been installed in 700 million square meters, nearly 54% have not started charging. The development and use of advanced temperature adjustment devices similar to those described above can promote energy conservation.

(2) Low Thermal Efficiency of Boilers

Low-quality coal and raw coal, which are commonly used as fuels in Fuxin City, by nature combust incompletely, generating significant heat loss. Thus, the thermal efficiency of the boilers used in the city is only in the range of 60 to 65%, and although the central government has set the target thermal efficiency of boilers at 68% to raise energy efficiency, that target disregards boiler capacity. By contrast, the thermal efficiency of boilers used in Japan and other developed nations is in the range of 80 to 85%. Fuxin City should replace its existing boilers with more efficient models and tighten its fuel regulations.

5. Reducing Air Pollutions and CO_2 Emission Factors

As for Fuxin City's air pollution control policy, it is important to reduce SOx emissions from heat and electric power cogeneration plants and district heating dedicated boilers, which account for 30% of the city's total coal consumption. To verify the effectiveness of the city's air pollution control efforts so far, we analyzed to what degree the introduction of district heating systems has reduced SOx emissions.

First, we estimated the amount of the reduction in SOx emissions due to the introduction of desulfurization equipment in the cogeneration plants as well as the lowering of the sulfur content of coal. Since no official data on the city's coal consumption (C_q) by year (i) is available, we estimated consumption with the formula below using the figures for generated energy (E_q) released by Fuxin's Bureau of Statistics and the figures for average generation efficiency (η) and the coal heating value (H_c) released by China's National Bureau of Statistics. The letter "u" indicates the energy conversion factor (860 kcal/kWh).

$$C_{qi} = \frac{E_{qi}}{\eta_i} \times u \times \frac{1}{H_c} \quad (1)$$

Although there are no available data for generation efficiency (η) specific to the cogeneration plants in Fuxin City, the nationwide averaged values are made public by the central government. According to them, the average generation efficiency (η) was 0.37 from 1990 to 2000; since then, it has gradually been improving: 0.38 in 2001, 0.39 from 2002 to 2004, 0.40 from 2005 to 2007, and 0.41 from 2008 to 2009. For the coal heating value (*Hc*), we adopted 7,143 kcal/kg, the standard value provided by the central government. These values are provisionally used in our calculation.

To estimate SOx emissions from coal consumption (SO_2 equivalent), we used a value of 0.9%, as the averaged sulfur content of coal produced in Fuxin City (S) (based on the statistics by the City), but 0.7% for 2007 and subsequent years (the figure used in the Management of Fuxin City's Particulate Matter Control Areas). We also set the SOx removal efficiency of the desulfurization equipment installed in the cogeneration plants at 95%, according to the City Government's official announcement.

Next, we estimated the improvement in energy efficiency due to the introduction of district heating. Since no data for Fuxin City was available, we adopted the results of measurements in the Shunyi District of the City of Beijing. The results indicate that while coal consumption during the heating supply period (generally from November to March) were about 28.5 kg/m^2 in the case of individual heating using small-scale boilers, consumption decreased by roughly two-thirds (to about 19.4 kg/m^2) in the case of the district heating introduced in 1994. SOx emissions have been reduced in proportion to the decrease in coal consumption.

We calculated the annual (i) SOx emissions from the city's cogeneration plants based on the above findings as well as the implementation of air pollution control measures taken for the city's cogeneration plants and district heating boilers as well as the availability of district heating.

$$Q(d)i = A_{di} \times h_d \times S_i \times \left(\frac{64}{32}\right) \times (1 - R \times \gamma_i) \quad (2)$$

$$Q(o)i = A_{oi} \times h_o \times S_i \times \left(\frac{64}{32}\right) \quad (3)$$

The symbols used in the above formulas are defined as follows:

Q(d): SOx emissions (district heating)
Q(o): SOx emissions (individual heating)
A_d: Floor area for heat supply (district heating)
A_o: Floor area for heat supply (individual heating)
h_d: Coal consumption per unit floor area (district heating)
h_o: Coal consumption per unit floor area (individual heating)
S: Sulfur content of coal
R: SOx removal efficiency of desulfurization equipment
γ: Installation rate of desulfurization equipment in district heating plants (cogeneration plants and district heating boilers)

For the area covered by district heating (A_d), we used data released by Fuxin City's Bureau of Statistics.

Figure 6 shows the estimated SOx emissions from coal used only for supplying heat. Figure 7 shows total SOx emissions from both heating and power generation; in 2010, emissions from cogeneration plants and district heating boilers equipped with desulfurizers (Case B) were some 76,000 tons less than emissions from individual heating (Case A). As mentioned before, cogeneration plants and district heating plants account for more than one-third of the city's total SOx emissions in 2006. And taking account of the effects of flue gas desulfurization equipment and use of lower sulfur coal after 2007, their emission volume of SOx has been reduced to be only 3.9%. Then it can be concluded that the city's total SOx emissions have been reduced by approximately 30%. The introduction of district heating plants has rendered it possible to integrally manage the coal depots and ash storage facilities scattered around the city, as these are also expected to reduce pollution due to particulate matters and waste water.

In fact, the city's air quality has improved significantly since 2007 (see Table 4). The SO_2 concentration in 2011 was only about half that of 2006. The city's PM concentration (as PM10) has also shown remarkable improvement. The reduction target stipulated in the eleventh five-year plan (i.e., reducing SOx emissions by 17.4% from the 2005 level by 2010) was also attained.

We used CO_2 emission factors per heating value for fossil fuels that were provided by the Environmental Agency of Japan to estimate CO_2 emissions per unit of power generation for 2005, when all power plants in Fuxin City were coal-fired (CO_2 emission factor for domestic general coal or low-grade coal: 0.38g-CO_2/kcal), and for 2010, when coal-seam gas power generation (CO_2 emission factor for domestic natural gas: 0.21g-CO_2/kcal) and wind power generation (CO_2 emission factor: 0) were in operation; the CO_2 emissions per unit of power generation improved by 13% from 0.80 to 0.69 kg-CO_2/kWh. However, this is still considerably higher than the

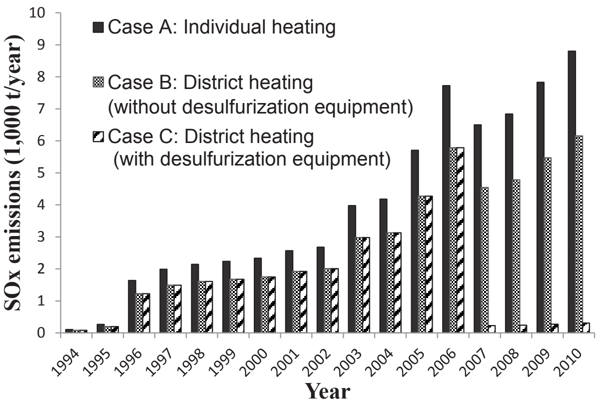

Fig. 6 Reduction of SOx Emissions by Introducing District Heating

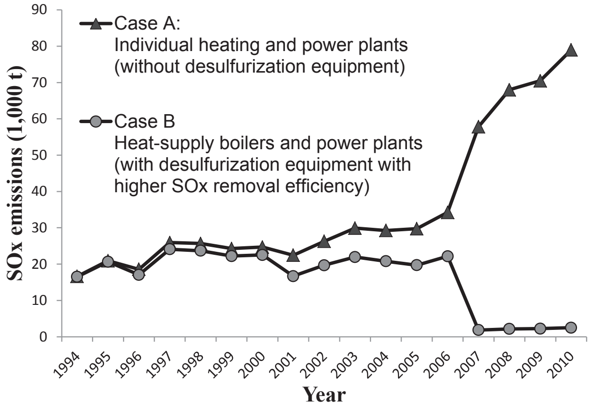

Fig. 7 Reduction of SOx Emissions by Introducing District Heating and Power Plant Modification

CO_2 emissions per unit of thermal power generation for Japanese general electric utilities. To further reduce CO_2 emissions in Fuxin City, the introduction of wind power and other renewable energy sources must be promoted and the use of coal-seam gas must be expanded.

6. Conclusion and Considerations

Based on the results of our study as described above, we evaluated Fuxin City's environmental and energy policies as well as the current district heating systems and their effects on air pollution as well as foreseeable obstacles to reducing air pollution. Our evaluation conclusions and considerations are as follows:

(1) Our questionnaire survey on household energy consumption in Fuxin City revealed that the percentage of electricity and heating costs with respect to household income for 68 apartment-based households were 8.4% on average and over 30% in some cases. District heating costs averaged 5.6% of household income, accounting for two-thirds of electricity and heating costs. Heating costs are a huge burden for low-income households.

(2) The current district heating systems do not have heat measuring systems for each apartment building or each apartment. The fixed-rate billing system, which is based on floor area, does not encourage residents to conserve heat or energy use. In addition, the inability to adjust the temperature of apartments prevents residents from attempting to conserve energy even if they are aware of the importance of energy conservation. To promote energy

Table 4 Annual Changes of Air Pollution in Fuxin City

(unit: mg/m^3)

Item	SO_2	NO_2	CO	PM10
2000	0.095	0.038	-	0.156
	(0.033 ppm)	(0.019 ppm)	-	
2005	0.072	0.029	-	0.115
	(0.025 ppm)	(0.014 ppm)	-	
2006	0.084	-	-	0.118
	(0.029 ppm)	-	-	
2007	0.073	0.043	1.090	0.107
	(0.026ppm)	(0.021 ppm)	(0.872 ppm)	
2008	0.061	0.037	0.670	0.098
	(0.021 ppm)	(0.018 ppm)	(0.536 ppm)	
2009	0.054	0.036	0.740	0.095
	(0.019 ppm)	(0.018 ppm)	(0.592 ppm)	
2010	0.048	0.034	0.650	0.094
	(0.017 ppm)	(0.017 ppm)	(0.520 ppm)	
2011	0.038	0.038	0.620	0.083
	(0.013 ppm)	(0.019 ppm)	(0.496 ppm)	

Source: Fuxin City's statistical yearbooks (2001 to 2012) conservation in the residential sector, it is urgently necessary to make improvements to the district heating systems (e.g., introducing temperature adjustment functions and improving heat efficiency) as well as to change the fixed-rate system to a usage-based system. In order to improve energy efficiency and implement a reasonable fee system, the central government began to install heat meter in new built residence. However, due to the heat meter set and fee systems were not well implemented, it needs the improvement of system to promote the implementation of the policy in the future.

(3) The start of district heating in 1994 and the installation of desulfurization equipment in large sources (cogeneration plants and dedicated boilers) of SOx since 2006 have reduced the total SOx emissions in Fuxin City by approximately 30%. Thanks to this reduction, the city's air pollution due to SO_2 has been showing signs of improvement since 2007.

(4) Although disposal of the city's spoil by incineration is necessary to protect the environment, this forces power plants to use low-quality coal, making it difficult to reduce air pollution and improve heat efficiency. On the other hand, Fuxin, a city with strong winds year-round, could reduce air pollution through introducing large-scale wind power generation. The city must consider reasonable power and heat supply systems from this viewpoint.

(5) Although most power plants in Fuxin City have high CO_2 emissions per unit of electricity produced due to their use of coal, expansion of wind power generation and use of coal-seam gas has reduced CO_2 emissions to 0.69 kg-CO_2/kWh from 0.8 kg-CO_2/kWh over the past five years. It is further necessary to improve the electricity generation efficiency of coal-fired power generation, and to introduce more wind power and other renewable energy sources as well as to expand the use of coal-seam gas.

Postscript

Considering the urgent necessity of reducing air pollution in Fuxin City and the effectiveness of concentrating efforts on large pollutant sources, the introduction of flue-gas treatment equipment is a measure that can be implemented relatively easily and that should produce significant results in terms of environmental protection and energy conservation. The introduction of district heating is also consistent with the direction of the air pollution control policy. However, the city's district heating systems have a number of problems because the city government has emphasized the rate of coverage to the exclusion of other factors. The widespread use of district heating, which should help control air pollution, may instead increase demand for heat because of surging household energy consumption. For this reason, maximum efforts must be made to ensure energy conservation. It is also important to promote energy conservation at home.

As long-term air pollution control measures and enhancement of local energy usage for Fuxin City, promotion of wind power generation by making use of the area's frequent strong winds and expansion of the use of coal-seam gas, which started only recently, are promising. Expanded use of wind power and coal-seam gas should prove very important not only with respect to air pollution control but also in creating a low carbon city.

Footnotes

1) In the western and northern areas of Liaoning Province, new coal-seam gas reserves of 36.5 billion m3 have been discovered.
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University-industry Research Collaboration on Development of Green Mosque Design

環境にやさしいグリーン・モスク開発を通して実証された「産学協同」の有効性。その始まりから、活動、成果を発表。

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Abstract

University-industry (U-I) research collaboration is an important channel for knowledge transfer between academia and the practitioner in a profession. In the architectural profession, many architects or designers have lack of exposure to research-based design process. Meanwhile, the research knowledge among academics requires a platform for application and demonstration to the profession. Since the last decade, there has been an increasing amount of research carried out on green building design in tropical climates within Malaysian universities. This paper presents new insights into the role of a research university in green building knowledge and technology transfer to the building industry. The process, challenges and benefits of the U-I collaborative research project on development of a green mosque design are discoursed. The interactive design review process between the two parties has stimulated innovative design ideas and strategies for a green mosque by considering energy efficiency and renewable energy. Green strategies such as daylighting, solar shading, rainwater harvesting and photovoltaic were explored and applied into the project. This paper concludes that U-I research collaboration is a powerful driver of innovation in architectural profession.

Keywords Green building; Research-based design; Energy efficiency; Renewable energy

Introduction

University-industry (U-I) collaborative research has been increasingly promoted as an important channel for technology and knowledge transfer between the academia and practitioner in a profession. However, many challenges have been identified by previous surveys. One of the major factors contributing to the conflict is dissimilar organizational goals. Universities aim to create new knowledge and to educate; meanwhile industry's primary focus is to capture valuable knowledge that can be leveraged for competitive advantage (Muscio et al., 2012; Motohashi and Muramatsu, 2012).

Bruneel et al. (2010) categorized the challenges in U-I collaboration as 'orientation-related barriers' and 'transaction-related barriers'. The first one refers to the barriers related to differences in the orientations of universities and industry; while the latter refers to those related to conflicts over IP, and dealing with university administration. Nevertheless, the modes and types of collaboration projects determine the intensity of the each barrier. Inter-organizational trust is the strongest mechanism for reducing the barriers to U-I collaboration.

In architecture or building industry in Malaysia, green technology has been one of the most rapidly developing aspects which require more research efforts. Since the 1990s, there has been increasing research projects carried out on green building design in tropical climate among the Malaysian universities. Therefore, the research knowledge within academia requires a platform for application and demonstration to the profession.

Malaysian Standard 1525 was drafted in year 2001 and revised in 2007 for building energy efficiency (Department of Standards Malaysia, 2007). Green Building Index (GBI) was introduced in Malaysia in year 2009 as sustainable building rating system for both non-residential new construction (NRNC) and residential new construction (RNC) buildings (Chen, 2008; GBI, 2009). Thus, there has been more awareness on green building design and technology among the building profession.

Several prominent green buildings were built in Malaysia. For instance, Low Energy Office (LEO) at Putrajaya in year 2004, Green Energy Office (GEO) at Bangi in year 2007 and Energy Commission (EC) Diamond Building at Putrajaya in year 2010. These buildings have become the showcases of energy efficiency and renewable energy in office buildings in tropical climates. These buildings have achieved lower Building Energy Index (BEI) of 65 to 135 kWh/m^2/yr in comparison with the typical Malaysian office buildings BEI of 250 kWh/m^2/yr. (Chan, 2009; Loewen et al., 1992).

The development of some of these green buildings involved U-I collaboration. For instance, Universiti Kebangsaan Malaysia (UKM) and Universiti Teknologi Mara Malaysia (UiTM) collaborated with RKA architect and Malaysian Green Technology Corporation or formally known as PTM (Pusat Tenaga Malaysia) in conducting research on GEO building in Bangi (Mansour et al., 2006). Besides, Universiti Teknologi Malaysia (UTM) collaborated with Public Works Department Malaysia (JKR) to study daylighting performance in existing Malaysian government office buildings to develop daylighting design guideline (Lim et al., 2012a).

In the past, U-I collaborations in green building sector focused on office buildings. This paper presents a U-I research collaboration on development of a green mosque design, for the first time in Malaysia. Research-based design process of the project is explained. The challenges and benefits of the project are explained.

The Green Mosque at Johor Bahru, Malaysia

The Green Mosque research project is a U-I collaboration between Institute Sultan Iskandar, Universiti Teknologi Malaysia (ISI-UTM) and the developer Mudra Tropika Sdn. Bhd. (MTSB). The building is designed by Rashdan Maahfar Architect (RMA) while the owners are *Majlis Agama Islam Negeri Johor* (Johor State Islamic Religious Council) and *Perbadanan Setiausaha Kerajaan Johor* (Johor Government Secretariat).

It is located at Jalan Kolam Ayer, Johor Bahru, Malaysia (latitude 1.45° N and longitude 103.76° E), which has a tropical climate. The site area is approximately 5018.42 m^2 (1.24 acre). This on-going project consists of several main spaces: 1. Main Prayer Hall, 2. Open Prayer Hall, 3. Sub-basement Car Park, 4. Landscape Deck, and 5. Office. The form and spaces of the mosque are shown in Fig. 1. This building has 2 levels (ground floor and mezzanine floor) and a sub-basement, with total built-up area of 2239.02 m^2.

Building Performance Simulation

In the initial stage, the original building design as proposed by the architect was modeled in computer simulation software for building performance simulations. Shadow casting and surface solar insolation were simulated using Autodesk Ecotect Analysis to determine the area exposed critically to direct sunlight radiation. Daylighting simulation was performed in IES (Integrated Environment Solution) Radiance to study the daylighting levels in Main Prayer Hall, Open Prayer Hall and Sub-basement

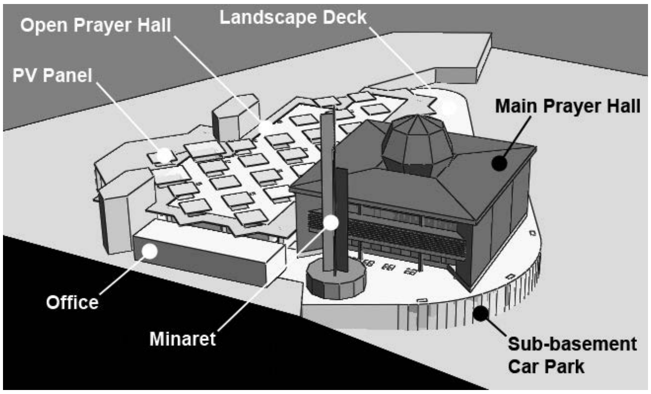

Fig. 1 Green Mosque 3D Modeling in IES <VE> computer simulation software.

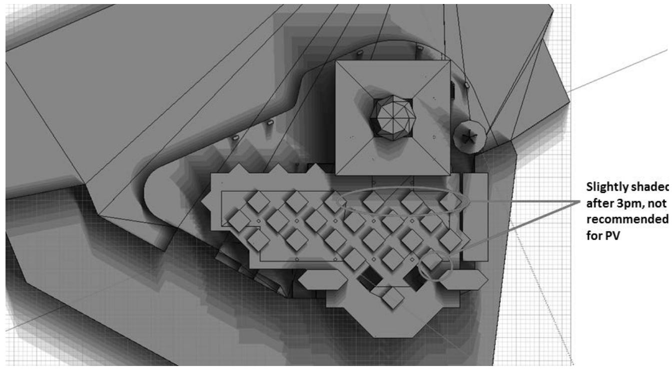

Fig. 2 Shadow analysis of 10am to 4pm on 22 June.

Car Park. Furthermore, CFD (computational fluid dynamic) simulation was conducted using IES MicroFlo to investigate natural ventilation air flow in the building, especially in the Main Prayer Hall. From the simulation results, review of the design was made by the team and finalized by the architect in order to improve the building performance for energy efficiency.

Shadow Analysis

In order to utilize renewable energy, the design team proposed the installation of photovoltaic (PV) panels on the open prayer hall roof slab. It is essential to assure the PV panels are not shaded by the building. Hence, Autodesk Ecotect Analysis was employed to simulate building shadow casting during various times to determine the suitable locations of PV panels.

The simulations were carried out using Sun path at latitude 1.40° N and longitude 104.00° E (closest to Johor Bahru). The sun is closest to the equator during equinoxes (21st March and 23rd September) and farthest away from the equator during solstices (22nd June and 22nd December). Thus, these dates were employed for the experiment to represent the different locations of the sun throughout the year.

The shadow ranges were casted during the duration of 10am to 4pm, which was the optimum period to receive solar radiation for PV in tropical climate. Figure 2 shows an example of shadow analysis simulation results. The simulation results showed that there were 2 areas shaded during 21 March, 22 June and 23 September whereas only 1 area was shaded during 22 December. Subsequently, these 2 areas were not recommended for PV installation.

Solar Insolation

The building façade should be shaded from direct solar radiation to avoid unwanted heat gain and to achieve energy efficiency. Thus, Autodesk Ecotect Analysis was employed to simulate solar insolation on the building façade. The results were used to determine which building façade was most critically exposed to solar radiation and heat gain. Thus, the identified façade requires more shading. The yearly weather data of location at latitude 1.4° N and longitude 104.0° E was applied to simulate the average daily direct and diffuse solar radiation (as shown in Fig. 3).

The simulation result showed that the roof surfaces received higher solar intensity in comparison with the vertical façade. For instance, the flat roof slab at Open Prayer Hall yielded about 4000 Wh/m^2 daily direct and diffuse radiation; thus was potential for PV installation to harness solar energy. On the other hand, many vertical façades were shaded from direct solar radiation. The openings at the Main

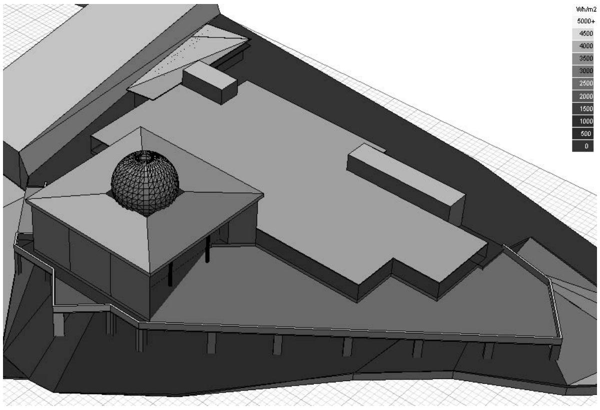

Fig. 3 Average daily direct and diffuse radiation (Range 0 – 5000+ Wh/m²)

Prayer Hall received average daily direct solar radiation lower than 80 Wh/m^2.

Daylighting

One of the important passive design strategies for building energy efficiency was utilizing daylight while avoiding direct sunlight which will cause glare and thermal problems (Lim et al., 2009; Lim et al., 2012b). Thereby, daylighting simulations were conducted for various spaces (Main Prayer Hall, Open Prayer Hall and Sub-basement Car Park) using IES Radiance. Illuminance levels were simulated on a horizontal plane at 300 mm height from the floor. Overcast sky with 10klx external illuminance was employed to represent the worst scenario when the sky was fully covered with clouds and dark. The simulated illuminance level can be converted to daylight factor (DF) using Equation 1. The targeted DF level for the prayer halls was 1.0 to 3.0%.

$$DF = \frac{\text{Internal Illuminance, } E_i}{\text{External Illuminance, } E_e} \times 100\% \qquad (1)$$

The Main Prayer Hall is a double volume space. Daylighting simulation results for various design options for the Main Prayer Hall are illustrated in Fig. 4. Fig. 4a shows that in the initial design, illuminance level was higher than 1000 lx (or DF 10.0%) in the area near the openings. This was because the upper level façade had no glazing or shading screen. According to MS 1525, DF higher than 6.0% will cause glare and thermal problem (Department of Standards Malaysia, 2007). Hence, the majority of the spaces in the initial design will have glare and thermal problems due to extremely high illuminance level. Therefore, the initial design was reviewed by adding a mezzanine floor for female prayer and clear

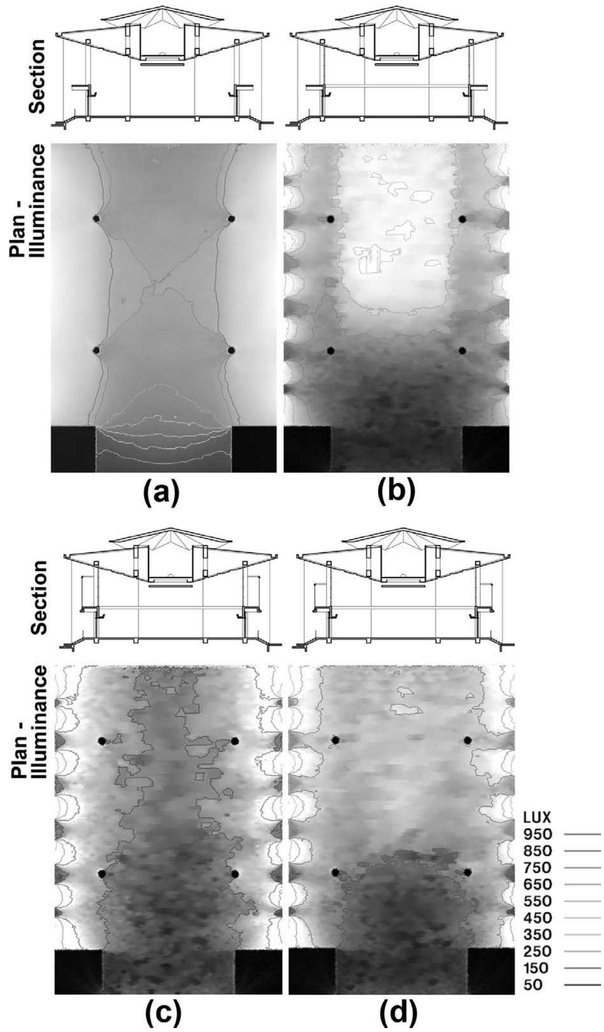

Fig.4 Daylighting illuminance simulation results for Main Prayer Hall under 10klx overcast sky: (a) Initial design without glazing at upper level; (b) With mezzanine floor and glazing; (c) With 3700 mm height decorative screen; (d) With 2800 mm height decorative screen height.

glass glazing at the upper floor façade. Then the DF at the area near to the openings was reduced to about 5.0% (Fig. 4b). Nevertheless, the centre part of the Main Prayer Hall still received high daylight level (DF > 3.0%) due to the double volume openings.

Further enhancement of the daylighting design was proposed by the architect. Decorative screens with 3700 mm height were added at the upper floor side openings to reduce the excessively high daylight level and glare problem. However, the simulation results showed that the DF at the centre part of the prayer hall was reduced to below 0.5% (Fig. 4c). Subsequently, the height of the decorative screen was reduced to 2800 mm in order to allow more daylight penetration and reflection on the ceiling. As showed in Fig. 4d, most of the spaces were able to yield DF of 1.0 – 3.0% which was within the recommended range. As a result, this final design was recommended for daylight utilisation while avoiding glare and thermal problem.

The daylighting design for the Open Prayer Hall was also investigated and improved. Fig. 5 shows the illuminance levels on horizontal plane for the initial design and the reviewed design with side-lighting openings at the concrete roof slab. The side-lighting opening was an integration of daylighting and PV system. The purpose of the side-lighting opening was to allow reflected daylight to penetrate into the Open Prayer Hall while providing spaces for PV panels installations.

The daylighting simulation results of the initial design (Fig. 5a) demonstrated that there was insufficient daylight in the Open Prayer Hall due to the deep planning. DF was even below 0.1% in the middle part of the hall. Thus, modification of the roof slab with side-lighting openings was introduced to increase the daylight availability. From the simulation results shown in Fig. 5b, the reviewed design demonstrated significant improvement. The DF at the middle part was increased to 0.5 – 1.5 %. Therefore, this roof design was recommended for both daylighting and PV installation.

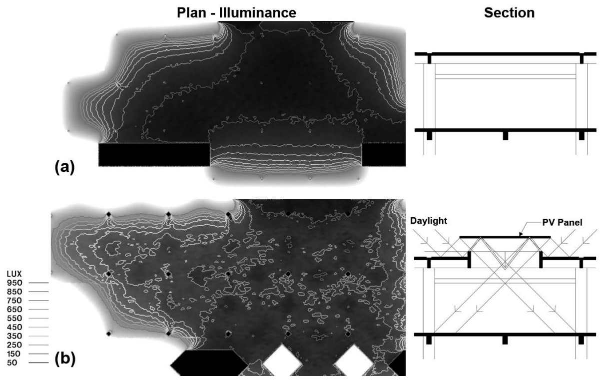

Fig. 5 Daylighting illuminance simulation results for Open Prayer Hall under 10klx overcast sky: (a) Initial design; (b) With side-lighting at roof slab.

Computational Fluid Dynamic

The Green Mosque utilizes natural ventilation as a means of passive energy saving strategy as air-conditioning system consumes high energy for building cooling. One of the most critical spaces for natural ventilation was the Main Prayer Hall because it had huge glazed volume. The air flow and velocity influence the users' thermal comfort. Thereby, CFD simulations were carried out using IES MicroFlo to improve the air flow and velocity in Main Prayer Hall (Fig. 6). Prior to the CFD simulation, the boundary conditions were simulated using IES Apache and IES MacroFlo to determine the outdoor and indoor air temperature, surface temperatures, glazing temperatures and air flow volume. Then, these boundary conditions were imported to IES MicroFlo for CFD simulation.

Without any mechanical ventilation, the air velocity in the Main Prayer Hall ranged from 0.0 to 0.5 m/s only (as illustrated in Fig. 6a). This was too low to achieve thermal comfort. Hence, exhaust fans were suggested to extract the hot air from the hall while increasing the air velocity. Several exhaust fans were installed at the centre of the ceiling to generate 160,000 CFM air flow as shown in Fig. 6b. The CFD simulation result indicated that the air velocity at the centre of the hall was increased to 0.8 m/s. The maximum air velocity of more than 3.0 m/s was achieved in the area near the exhaust fans. Because

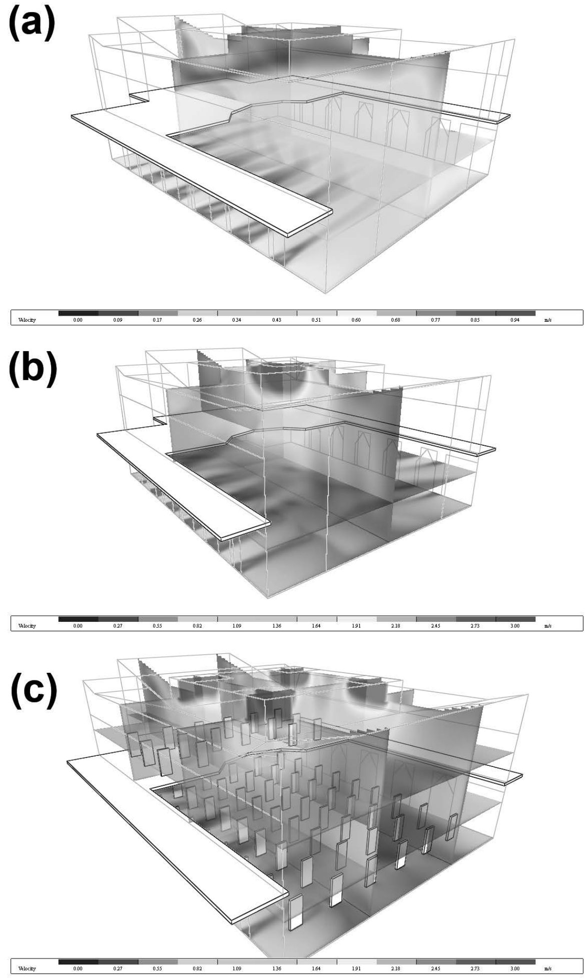

Fig. 6 CFD wind velocity simulation for Main Prayer Hall: (a) Initial design; (b) With exhaust fans of total 160000 CFM airflow at center; (c) With exhaust fans of total 50000 CFM airflow at each of the 4 corners.

the exhaust fans were installed at the centre of the ceiling, the increased air flow was concentrated at the centre of the hall.

Another design alternative was proposed by installing the exhaust fans with a total of 50,000 CFM at the four corners of the ceiling as shown in Fig. 6c. The total generated air flow was 200,000 CFM. The CFD simulation result demonstrated that this design was successful in distributing the increased air velocity within the Main Prayer Hall. Thus, the users could feel the air movement when they are performing their prayers. This design was recommended in order to improve the users' thermal comfort.

Rainwater Harvesting

Rainwater harvesting was employed in this project to collect rainwater for ablution and toilet flushing usage. Apart from that, the grey water will be recycled for landscape irrigation. The rainwater harvesting system had been designed by researchers from ISI-UTM. Throughout the project, the researchers had worked together with the architect and contractor to determine the locations and sizes of the tanks, types of filtration system and use of landscape ponds as water storage. Eventually, the rainwater recycling system included landscape pond as bio-organic filtration system. The schematic design drawings were produced by the researchers and further developed for detail drawings by the M&E engineer.

Photovoltaic

In this project, PV installation was proposed on the roof-top of the Open Prayer Hall. In order to assure that the electricity generated by the PV will be sufficient to cover the daily usage, calculations of PV installation to supply the energy demands of the mosque had been produced by researchers from ISI-UTM. The total surface that can be covered by PV is approximately 300m^2. The calculations showed that the hourly PV electricity power which can be generated is 21 kW/h. Thus, the targeted electricity generation for 5 hours per day is 105 kWh/day. Besides, ISI-UTM also worked together with MTSB, RMA and other consultant teams on the application to SEDA (Sustainable Energy Development Authority of Malaysia) for grid-connection. As a result, the mosque successfully obtained the Feed-in Tariff (FiT) under the category of religious building.

Discussion

This project employed various kinds of computer simulations to study and improve the building performances during design development (detail) stage, whereas previous research (Goulding, 1992; Lim et al., 2008) suggested green building design should begin at the early design stage (pre-design / sketch). The overall building form and orientation had been determined by the architect before the simulation experiment. Thus, it limited the exploration of passive design strategies such as using self-shaded forms, north-south orientation, small volume spaces, etc.

In this project, the architect actually already considered a green design concept in the initial design stage. For example, most of the façades with openings were actually shaded with roof overhangs. Meanwhile, the façades that were facing direct sunlight had no openings, using storage and staircases as buffer zones. However, not all the spaces were given sufficient consideration for green design. For instance, the Main Prayer Hall had a large square volume space which was not recommended for tropical climate (Olgyay, 1963; Yeang, 1994). Besides, the deep planning for the Open Prayer Hall and sub-basement car park was not appropriate for daylight utilization.

Some of the considerations or ideas for green design as proposed by the architect were proven not to be appropriate through the simulation experiment. For example, the architect used openings without glazing in the Main Prayer Hall to allow daylight penetration and natural cross ventilation. The simulation results, however, demonstrated that the excessive use of openings without glazing caused DF above 10.0% which will cause glare and thermal problems (Department of Standards Malaysia, 2007). Subsequently, glazing and decorative screens were proposed to reduce the glare and thermal discomfort.

Due to the proposed building form and massing, some of the passive strategies could not be applied effectively. The use of natural ventilation in the Main Prayer Hall was very constrained due to the large volume space. As shown in Fig. 7, large square volume space has low opening area to space volume ratio in comparison with linear or clustered space planning. Apart from that, the outdoor wind velocity in Malaysia is also very low. According to Hui (1998), the range of indoor air velocity in low rise buildings in the country is between 0.04 m/s and 0.47 m/s. Hence, the simulation showed that the indoor wind velocity in the initial Main Prayer Hall design was below 0.5 m/s. As a result, the prayer hall had to rely on mechanical exhaust fans to increase the wind velocity to 0.8 m/s (60% increment) at the center part of the hall.

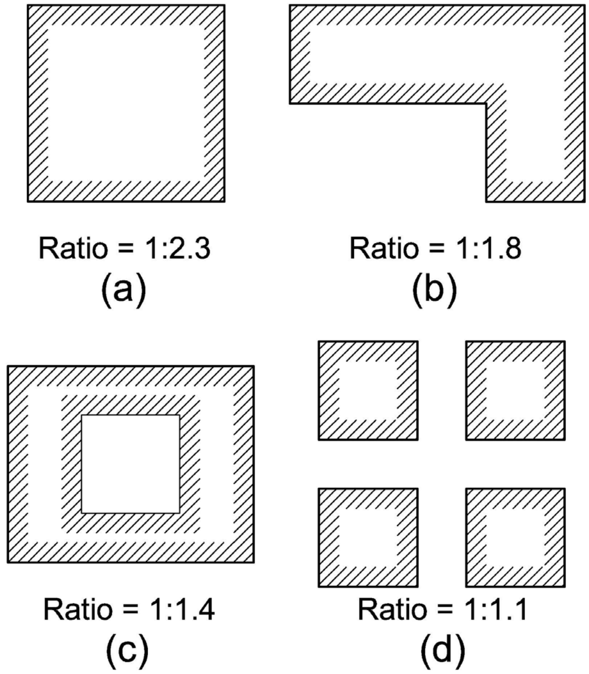

Fig. 7 Opening area to space volume ratios for different building forms: (a) Square; (b) Linear; (c) With center courtyard; (d) Clustered.

The Green Mosque project is a U-I collaborative research project that involved multi-disciplines with varied organizational orientations. Industry demanded immediate results to quicken the construction process while the university researchers took the project as a long-term effort to develop a green mosque design with energy efficiency and renewable energy. The building owner, architect and other consultant teams emphasized solving on-site issues and completion on time. On the contrary, the university researchers looked for potential academic outputs such as scientific publications. 'Orientation-related barriers' as mentioned by Bruneel et al. (2010) were the main challenge in conducting the project. Meanwhile, the 'transaction-related barriers' was not significant in the project.

Building performance study requires time-consuming modeling and simulation processes, with detailed information or data input to assure the accuracy of the results. However, this project was an actual development project under construction. In addition, a lot of detailed information such as the use of materials and finishes was not finalized. This will affect the scientific reliability of the research outputs. The balance between time constrainta and accuracy was vital to meeting the demands of both the U-I. As a result, simplification of the building modeling was needed to reduce the simulation time while still retaining acceptable accuracy.

Despite the 'orientation-related barriers', there were effective knowledge and technology transfer in the U-I collaborative research project. Industry was exposed to a new kind of architectural design process based on empirical research. Besides, various green building technologies were employed in the project such as PV, rainwater harvesting system, light tubing, etc. On the other hand, the university side was given a platform to apply the green design method and strategies on an actual development project.

Throughout the project, there were interactive communications between U-I via various technical meetings. The original mosque design was reviewed several times based on the research results. Integration of the professional and academician resulted innovative green design ideas to achieve energy efficiency and the use of renewable energy. For instance, combination of PV panels and skylight openings on the roof-top of the Open Prayer Hall, integration of rainwater harvesting system with landscape pond and the use of decorative screen to reduce glare problem in the Main Prayer Hall.

Conclusion

The findings indicated that without research basis, some of the initial green design concept determined by the architect were actually not performing as expected. Therefore, U-I collaboration for research-based design process is very important to prove and improve the building performance. Building modeling and simulation is an appropriate methodology which should begin during the early or pre-design stage rather than the design development or detailing stage when the possible design modifications are very limited.

The interactive research-based design review process between the U-I parties had stimulated innovative design ideas and strategies for a green mosque by considering energy efficiency and renewable energy. Green strategies such as daylighting, solar shading, rainwater harvesting and photovoltaic were explored and applied in the project. Thus, U-I research collaboration is a powerful driver of innovation in architectural profession.

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The Association of Transportation and Land Use Planning towards Sustainable Urban Energy Planning

バンコクのような大都市では急速な拡大により都市機能が悪化している。土地利用と新しい交通インフラの統合で都市の活性化を目指す。

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Abstract Recently, global warming has affected paradigm design and restoration of the city with urban infrastructure and energy planning and development. It has received attention from government agencies and related organizations to search for methods of problem solving to sustain the situation of climate change effect, especially in metropolises like Bangkok. Due to complicated structure of land use and overpopulation, Bangkok has inefficient infrastructure and development has focused on expanding road infrastructure to cover the transportation demands. This phenomenon inevitably affects the lifestyle of people in the city, thus this study presents as a potential solution an integrated approach to sustaining urban land use and transportation planning in order to reinvigorate the city through the promotion of integrated land use within the district. The analysis shows that the composition of urban form impacts choices of Bangkok residents which has resulted in residential allocation in the suburban areas and longer commutes. Finally, the increase in energy consumption in the transportation sector will remain unless there is an alternative urban planning with renewable energy sources or vehicle technology choices to replace the outdated version.

Keywords Transportation planning; Land-use planning; Sustainable development; Energy planning

1. Introduction

Rapid urbanization has had both negative and positive impacts on urban residents, especially in uncontrolled urban expansion coupled with inefficient transportation. The negative impact of automobiles on the physical environment and quality of life have become concerns due to the current trend of the global environmental problem of climate change. Not only has pollution from vehicle congestion had a significant impact on urban population, the overconsumption of fuel and energy-consuming automobiles for daily commuters in Bangkok has become a problem for experts and concern authorities of energy planning. Hyper-urbanization has occurred when there is a migration of the population and relocation in urban areas. These changes also influence urban density, which is increasing in growth rate in several dimensions (Litman, 2010). Especially, when consideration is given to developing countries, the rapid growth of urban areas involves the use of private automobiles, energy consumption and deterioration of the urban environment. In Thailand, as a rapidly developing country, the transportation sector comprised of motor vehicles plays a significant role crucial to the economy and urban development. Especially, the growth of the city with the scattering of density and settlement in peripheral zones influences long-distance travel patterns which require more energy consumption (Newman & Kenworthy, 1989). When considering the urban development pattern of the central city of Thailand, Bangkok represented its highest development area during the period from the 1980s to the 2000s as demonstrated in Fig. 1.

It is obvious that Bangkok has become greatly dispersed with the heavy migration, particularly the settlement outside of the urban core, also known as greater Bangkok. This growth of the urban area beyond the boundary of its surrounding has renamed the original Bangkok Metropolitan area to Bangkok Metropolitan Region (BMR) which includes 5 adjacent provinces: Nonthaburi, Samut Prakan, Pathumthani, Samut Sakhon and Nakhon Pathom. With the position of urban core, the present of institutions, employment areas and several activity centers located in this area induced high intensification in these areas with a mix of land uses, including public, commercial, employment and housing activities. However, this intensity demonstrates different degrees of mix in different degree of development in the peripheral or suburban areas.

The wide range of intensity has direct relationship with the density of population and migration which can be noticeably seen in Table 1. The variety rate of population together with the density represent a good indicator to characterize the level of attractiveness for human settlement which would be reflected in the number of households and the immigration and migration numbers. In order to understand this linkage, a basic understanding of transportation infrastructure along with the modal usage is required to encompass the commuting pattern and life style of people in this region. Furthermore, suburbanization allowing the city to spread would also increase the necessity of owning an automobile (Newman, Kenworthy & Vintila, 1995). Based on the World Bank Report (2007), in 2003, Bangkok's in-use national motor vehicle fleet was about 2.9 million. This accounted for about 22% of the nation's registered motor vehicles including 57% of the private car fleet, 12% of national motorcycles and 42% of the combined truck and bus registrations. The majority of commuters were relying on private vehicle rather than transit usage. Considering the transition of urbanization while the congestion spreads outward geographically, BMA, which is the main organization to manage land use and infrastructure development in Bangkok and its vicinities, launched the first transit line. MRT line was completed in 1999 and operated as the Bangkok Transit System (BTS) or

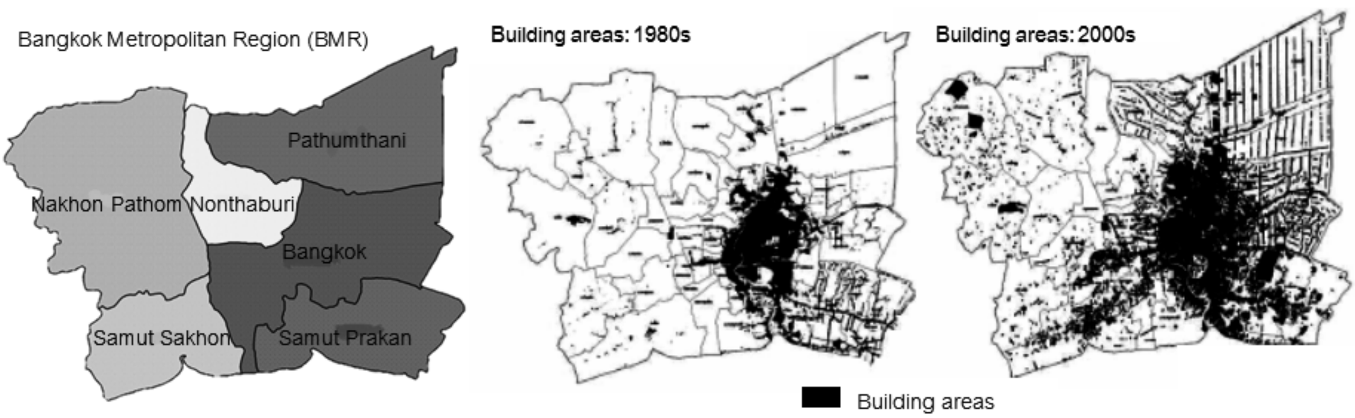

Fig. 1 The growth of built-up areas in Bangkok Metropolitan Region (BMR) Source: Department of City Planning, Bangkok Metropolitan Administration, 2005

Sky Train (Green Line) with a total length of 22.9 km. (IMAC, 2005). However, given the limited service of transit line compared with the road and expressway development, Bangkok and its vicinities have continued to be dominated by roads-oriented development with the unsolved traffic congestion crisis (Rujopaharn, 2003).

However, the other driving force of this pattern may be influenced by not only the transportation infrastructure development but also policy-making for the development plan in this area (Iamtrakul and Hokao, 2011). With the consideration of the development plans at national, regional, sub-regional, provincial and municipality level, Pathumthani was positioned as the prevalent satellite town of educational institutions and industrial area. To accommodate the huge attraction of urbanization in this area including population and commercial development among others, it has been recognized that one of the most effective ways to facilitate urban restructuring is to move towards a polycentric system from the current mono-centric system in Bangkok. Furthermore, this approach can be successfully planned to deliberately utilize the urban rail transit systems. Additionally, to reduce the demands on automobile while most people are now highly dependent on car travel is presented as a new challenge to the planners, the operators, the public, and other stakeholders (Beirão and Cabral, 2007). However, as previously mentioned, the limited mass transit service provided only in the urban core could not accommodate the demand for providing maximum access and connectivity between the central core area and the surrounding areas. It is crystal clear that urban sprawl has become the main influence on settlement along the network expansion. The greater use of private cars raises challenges to sustainable development.

2. Methodology

To investigate urban land development patterns in the study area, the travel behavior approach plays an important role as powerful tool for reflecting the interaction between land use and mobility patterns. This approach has been widely used by several researchers through quantitative and qualitative interviews (Dieleman et al., 2002; Krizek, 2003; Næss, 2006). This study aims to explore the particular dimensions of the built environment in terms of land use and transportation linkage which aim to enhance the attractiveness and accessibility of suburbanized area. The attractiveness could be assessed based on the land-use analysis since most of the development plan induced the new development type to form the new activity center, especially in the outlying area. The form of activity centers should be reviewed from both secondary data and primary analysis of its spatial distribution. The physical characteristics could be geographically analyzed by using the geographic information system (GIS). It was employed to graphically demonstrate the detail of spatial site distinctiveness and allow for more understandable manner about the compatibility of existing land use and living environment.

To assess the spatial configuration of the study area and the employment distribution influence the mobility pattern of the residents in the study area, several studies pointed out that the impact of urban structure may change commuters' choices (Ewing and Cervero, 2001; Meyer and Miller, 2001). The opportunities offer flexibility for certain activities such as shopping, banking and other services and affect destination choices. To graphically differentiate the activities in different sub-centers, this study employed the GIS tool to analyze the site characteristics and to ensure the structures of the site which will be placed in a manner to induce major trips to their locations. To provide a more objective way and to exhibit more about mobility patterns, a questionnaire survey was then conducted to categorize the behavior of people regarding private automobile and public transportation usage. However, integrated analysis of both approaches (physical analysis and behavior analysis) provides interesting results regarding the occurrences of mobility limitations for some parts of the study area.

The sampling method was followed Taro Yamane's population sampling table with ±7% error in order to cover the area sampling. The samples of respondents from this sampling method were a total of 200. Face-to-face interviews were carried out in the survey as well as self-answering by each respondent. Based on this data collection, descriptive statistical analysis and linear discriminant analysis (LDA) was adopted as the methodology to differentiate the travel behavior response to different sub-centers. The findings of this study would be beneficial in terms of incorporating a number of factors other than the land-use environment that can also encompass a profound impact on commuting behavior. Finding the correct combination of land use and non-land use initiatives for achieving various mobility and environmental objectives remains a significant public policy challenge. Moreover, an implication of this study could help as a guideline for an integrating of land use and transportation system development. In particular, it would not only help for promoting ridership of public transport systems in terms of an enhancement of its urban environment while reducing the need for and use of private vehicles, but it would also drive policies for sustainable urban development.

3. Study area: Pathumthani Province

Pathumthani is located in the central region, at approximately 14° North latitude and 100° East longitude approximately 2.30 meters above sea level. The area covers 1,520.856 square kilometers or 950,535 rai, and is situated at the north of Bangkok along the highway No. 1 (Phahon Yothin Road) with a distance of approximately 27.8 kilometers. It has been developed from canal side areas, particularly in Sam Khok District, lateral canal in Klong Luang and Lam Lukka District. It includes a dense residential area along Phaholyothin Road, which is a mixed-use area of residential and commercial buildings. These areas are covered by a dense mix of residential units that are mainly comprised of large commercial buildings and condominium. In addition, the areas also consist of high-density housing in the Navanakorn Industrial Zone where the housing project is certificated by the National Housing Authority to provide for Navanakorn workers for leasing and hire purchase. The project comprises several housing types such as single-detached houses and townhouses. The growth trends are expected in the areas along Chiang Rak–Klong Luang, Phahonyothin–Lumlukka and the lateral canal areas close to other transportation projects. Commercial land is always located along roadsides, particular in easy access areas, turning point areas or dense community such as Rangsit Market Area, Si Mum Muang Market Area and Bangkhan Market Area. Most of such areas were established in the Pahonyothin Road Corridor and were used for commercial purposes including retail stores, sale offices, shopping malls, markets and entertainment areas. Furthermore, due to the increasing price of land, the expansion of industrial sectors is only possible for industrial estate. For warehouses, it also is expected to show growth up because of truck terminal providing in the north of pit stop and transshipment into Bangkok that the growth of warehouse is expected in the areas near Klong Luang Road. In the part, agriculture land plays a key role in this area. But now, agriculture land has decreased because of urban development. Such land is also expected to continually decrease in the future due to the increase of land values. So, land owners will turn to other opportunities that make a higher yield such as selling land to investors for launching land business. Currently, agriculture land remains in some areas including Sam Kok, Klong Luang and Lumlukka District.

4. Land Use Pattern of Pathumthani

4.1 Transition of Land Use

When considering the settlement of housing and transformation of land use in the study area, it was found that there is major change along the highway (Phaholyothin Highway). This is due to the variety of infrastructure services provided to support job and housing development outside CBD under the geographic constraints of the area. Moreover, due to the expanding population of suburban communities according to the polycentric plan, it is required that the government in the surrounding area of Bangkok use the scarce land resources effectively in support of the economic development and housing of the increasing population. Thus, it was found that the employment areas in term of institutions and industrial sectors are growth increasingly in this area. Furthermore, when considering the commercial center, it becomes more concentrated in this zone as well. Thus, the land-use planning also needs to be effectively linked with the transportation plan which could sustain high population density over the years. However, it was found that most of the settlements occur along the highway in the form of ribbon development, which represent the unique mobility pattern of the study area .

4.2 Land Use Distribution

The continuous expansion of cities and the emergence of new concentration nodes at the urban periphery of Bangkok to Pathumthani province is obvious. Due to the rapid rate of the urbanization of Bangkok, the suburban area of its vicinities, especially Pathumthani province, has naturally become the sub-center. This formulation has also been driven by the regional and sub-regional policy to support the land extensive demand with the lower price of housing and other opportunities for business. It can be seen that the reduction in the agriculture land from 1990–2008 (15.18%) was replaced by the building for several purposes to accommodate the growth of the city. The major transition is in commercial (2.4 times), industrial (1.4 times) and residential areas (12%), respectively.

4.3 Urbanization of Bangkok and its Vicinities

When considering the spatial pattern in the study area, urban structure formulation comes into question. This is due to the fact that the population and employment areas settle away from the sub-center which serves as a node of concentration. The scattering of housing, commercial and residential locations form along the road alignment to facilitate accessibility. This is consistent with the detonation of urban sprawl by Ewing (1997). The phenomenon of sprawl was demonstrated to be scattered development as a strip development along the road network. As previously mentioned about the majority building use, the presence of vast residential land use of 50.8% in the study area is followed by industrial (31.5%) and academic institutions (6.3%). Among the abundant proportion of residential use, most of the housing type in the study area is single housing that is about 96.9%.

4.4 Urban Form and Transportation Network

According to the polycentric plan of the study area, the pattern of several centers could be sorted into three sub-categories (economic, industrial and community centers) . Although, its spatial structure could be seen in multiple urban centers with the high level of economic interaction, there is nothing clear about the linkage among these suburban centers. This is due to the definition of Parr (2004) concerning polycentric urban regions should consist of multiple urban centers separated from each other by tracts of open land, in which the maximum travel time between urban centers is one hour. The mobility pattern of people in this study area plays a key role in confirming the interaction of people to the different attractions of the centers. Different urban centers have their own spatial specialization to shape level of mobility of people which will be useful information to confirm the characteristics of study areas of polycentric urban structure. Furthermore, the finding will be utilized for future plan of transit development in the study area which would diminish the current problem while provide an effective link with existing service of transportation and land utilization promotion.

5. Exploring Land Use and Transportation Interaction of Study Area

A total of 200 effective questionnaires on the basis of face-to-face interviews were applied to investigate the interaction of land use and transport in the study area. This relationship could be determined by assessing the travel behavior of people to reflect their mobility pattern. The major destinations of working areas were selected to include into the interview process that are around residential areas, employment area (commercial and industrial zones) and other zones as depicted in Fig. 2. When considering the physical structure of the study area among these three sub-centers, it can be seen that the development of employment centers are situated along the major highway network (Paholyothin No.1). One is the shopping center which is represented as the regional commercial center in this area.

The other employment center is the industrial park which induces massive public investment for low-income housing to create job-housing balance which also helps to promote the new residential construction and massive high-density apartments of this employment area. To obtain the mobility data, the other zones have to be included as the last group for analysis. Accordingly, the actual mobility of citizens could be explored among all means of transportation system available in the network. This travel behavior data will be used to identify the relationship between land use and the transportation system due to the fact that the destinations of trips represent their attraction to accomplish individual trip purpose and travel from housing location (Van Wee, 2002).

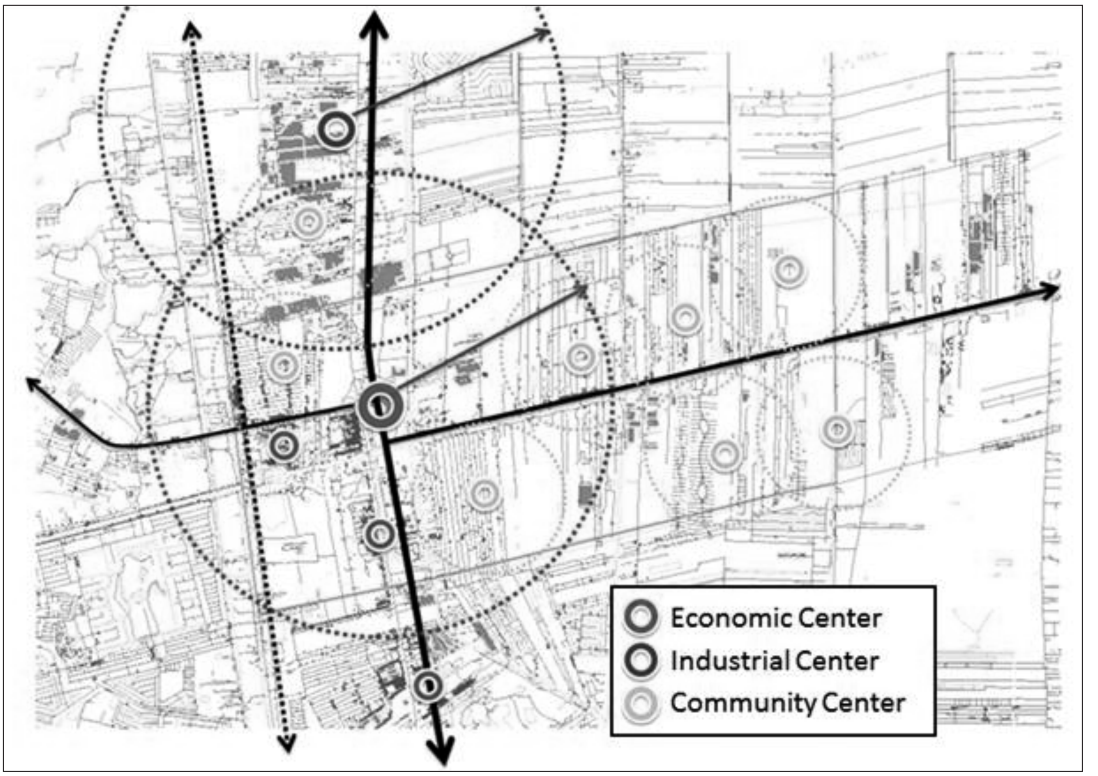

Fig. 2 Pattern of Sub-centers in the Study Area

Table 1 Summarization of Commuters' Mobility Characteristics

Variable		Destination			Total	Percentage	Asymp. Sig. (2 sided)/ Pearson Chi-square
		Residential Area	Employment Area	Outer area			
Mode of Transportation	Private	17	8	34	59	29.50	0.000
	Public	72	29	40	141	70.50	
No. of Connections	0	17	9	34	60	30.00	0.000
	1	10	0	1	11	5.50	
	2	48	21	16	85	42.50	
	3	14	7	23	44	22.00	
Weekday							
Frequency of Trip	1 Roundtrip	84	29	62	175	87.50	0.022
	More than 1	5	8	12	25	12.50	
Distance (kilometers)	6-10	13	1	0	14	7.00	0.000
	11-15	33	12	0	45	22.50	
	16-20	30	21	0	51	25.50	
	21-25	13	3	9	25	12.50	
	26-30	0	0	21	21	10.50	
	>30	0	0	44	44	22.00	
Time (minutes)	16-30	36	11	0	47	23.50	0.000
	31-45	46	23	3	72	36.00	
	45-60	7	3	27	37	18.50	
	>60	0	0	44	44	22.00	
Expenditure (Baht)	30-40	6	3	0	9	4.50	0.000
	40-50	40	18	0	58	29.00	
	50-100	43	16	49	108	54.00	
	100-200	0	0	25	25	12.50	
Weekend							
Activity on Weekend	Shopping	63	19	43	125	62.50	0.004
	Personal Business	6	1	13	20	10.00	
	Social Activity	20	17	16	53	26.50	
	Leisure/Recreation	0	0	2	2	1.00	
Frequency of Trip	1 Roundtrip	71	36	70	177	88.50	0.002
	More than 1	18	1	4	23	11.50	
Distance (kilometers)	6-10	18	5	1	24	12.00	0.000
	11-15	44	14	9	67	33.50	
	16-20	21	7	32	60	30.00	
	21-25	5	11	17	33	16.50	
	26-30	0	0	7	7	3.50	
	>30	1	0	8	9	4.50	
Time (minutes)	<15	6	5	1	12	6.00	0.005
	16-30	28	16	24	68	34.00	
	31-45	46	16	32	94	47.00	
	45-60	8	0	10	18	9.00	
	>60	1	0	7	8	4.00	
Expenditure (Baht)	<20	1	0	0	1	0.50	0.000
	20-30	1	0	0	1	0.50	
	30-40	11	6	0	17	8.50	
	40-50	35	7	26	68	34.00	
	50-100	40	24	32	96	48.00	
	100-200	1	0	14	15	7.50	
	>200	0	0	2	2	1.00	
Total		89	37	74	200	100.00	

5.1 Travel Behavior

Travel behavior between three sub-centers plays an important role in identification of the level of coordination between land use and transport planning, since the location of sub-centers has a significant effect on daily mobility in terms of mode usage and number of connections. Among different modes, commuters travel to their destinations by two major methods, e.g. public transportation (n=141, 70.5%) and private transportation (n=59, 29.50%) as shown in Table 1. The majority of people travel by public transportation (n=141, 70.5%), which also includes paratransit service, e.g. sky train, subway, bus, van, two-row bus, motorcycle taxi. A variety of mode choices enable travelers to work in different areas. One interesting point is most of respondents who are working in the outer area (45.9%) travel without any connection. This means almost half of this group needs to drive to this destination (56.67%). Furthermore, this mode allows flexibility of both space and time to destination.

5.2 Weekday and Weekend Trip Comparison

A comparison of travel behavior of people during weekday and weekend reflects the level of accessibility to reach their destinations and their attractiveness. This consequently results in different expenditures of money and time to travel to their destinations. It is clearly seen that most of the people enjoy shopping trips (n=125, 62.5%) much more than other activities (personal business, social activity and leisure or recreation). Among several destinations of shopping trips, they choose to spend their weekend to travel nearby their residential areas.

Frequency of trip: When considering the frequency of trips on both weekday and weekend among all destinations, it can be seen that there is slightly more frequency of trip in the employment area (24.1% from n=29) and outer area (12.9% from n=62), respectively for 1 round-trip case. This might be due to the variety of shopping malls and other type of services available in the proximity of commercial and industrial area as well as more attractions of activity areas in the urban core of Bangkok.

- Travel Distance: For the distance of travel, most of the people travel in the moderate level of distance, which is about 16–20 kilometers (n=51, 25.5%), followed by 11–15 kilometer (n=45, 22.50), more than 30 kilometer (n=44, 22.0%), respectively. However, people who work nearby their residential area would not face with the problem of long-distance travel. On the opposing dimension, workers who work in the outer zones need to travel very long distances.
- Travel Time: The data on travel time distribution for different sub-centers represents almost the same trend with the travel distance. Most of the commuters travel a moderate duration of travel time, which is about 31-45 minutes (n=72, 36.0%). As expected, people who work in the outer zones need to travel more than 1 hour, which represents about 22.0%. This evidence revealed the urban sprawl situation which shows the excessive time for travel, especially for working trip. This might result in the lack of clear sub-centers with the inadequate or ineffective linkage of transportation network in the study area. Also, there is insufficient active development policy to control this urbanization condition and to concentrate job growth inside the limited number of peripheral centers under the mobility consideration. In the case of weekends, most people prefer moderate duration of travel time (31–45 minutes) to outer zones, especially for the group of people who work in the employment area (from 72, 30.6%).
- Travel Expenditure: As shown in Table 2, the most people spend money to travel for working and for weekend is about 50–100 baht, which could be estimated about 23.9% of their income (based on the previously mentioned average income). This expenditure increases for people who enjoy working and spending

weekends in outer zones. It is seen that of the 100% of the people who are workers in outer zones and approximately 94.1 for weekend trip spend the highest amount of money for their trip (>100 baht). If it is compared to their average income, it would be a major proportion of total spending for transportation cost (31.9%). It can be clearly seen that there is an urgent need to provide the solutions to cope with this inefficient distribution of location of the employment and service and efficient transport system.

5.3 Exploring Land Use Transportation Interaction

5.3.1 Exploring Technique of Linear Discriminant Analysis (LDA)

Based on the descriptive statistics explained in the previous section, the basic figure of the spatial pattern influence on mobility pattern was explained. However, further exploration of the explanatory variables to discriminate the functional of different center is required to clarify the effectiveness of this spatial structure. This study employed the simple statistical technique of Linear Discriminant Analysis (LDA) to identify its deficiency in the relationship for further recommendations. LDA is a well-known statistical method to classify individuals or objects into mutually exclusive and exhaustive groups based on a set of independent variables (Iamtrakul et al., 2005). To confirm the usefulness of this techniques, there are a number of studies which have applied this method of analysis to land-use planning, especially in terms of spatial analysis of urban planning and development field (Mendes and Themido, 2004; Borzacchiello et al., 2010). Due to its excellent group classification performance, this study employed this technique to explain the travel behavior of respondents in working trips with their different mode choice selection. Based on this approach, the variables discriminated between three type of sub-centers could be found in the group of variables to discriminate among them. The independent variables (x), mentioned above, could be input into the analysis to explain the dissimilar sub-centers (S) of the study area. By using the data collection in Table 2, the functions to discriminate three sub-centers in each modal usage could be calibrated. This collected data on different users' socioeconomic and various daily mobility characteristics could then be used to determine which variables are best for classifying the interaction of different sub-centers' location and commuters' choice to travel to them.

Based on the LDA, various combinations of several variables were investigated to determine the most suitable classification model that allows the best discrimination among three sub-centers with a mixture of mode choice characteristics. Thus, this study divided the relationship between the sub-center location and travel behavior of people into two categories of mode selections: private and public transport. Based on the analysis of variance (ANOVA) results shown in Table 2, the F test revealed that all independent variables were important to the discriminant function and could be accepted for calibrating the model shown to be significant at confident level of 0.05. By using the SPSS statistic package, the Wilks' Lambda could be used to demonstrate the result of this analysis. The result of the test in Table 3 appears to be significant, which means that a linear combination of the selected variables can discriminate between the three groups of sub-centers. Furthermore, Box's M test revealed that all activity cases significantly met the assumption of homogeneity of covariance matrices due to the assumption and agreement under an obligation to utilize this statistically method.

This investigation was conducted through a combination of more than 20 variables, but only variables found to be the optimal combination of variables could be used to classify the travel behavior to different sub-center destinations. Table 3 provides information on each of the discriminate functions (equations) produced which also demonstrate that canonical correlation is the multiple correlations between the predictors and the discriminant func-

Table 2 Test of Equality of Group Means

Variables	Wilks' Lambda	F	df1	df2	Sig.
Age (year)	.704	11.758	2	56	.000
Income (baht/ month)	.716	11.103	2	56	.000
Travel time of Working Trip (minutes)	.252	83.247	2	56	.000
Age (year)	.850	12.155	2	138	.000
Income (baht/ month)	.928	5.346	2	138	.006
Travel distance of Working Trip (minutes)	.211	258.087	2	138	.000
No. of Connections	.878	9.591	2	138	.000

Table 3 Eigenvalues

Mode	Function	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation
Private	1	3.522a	81.9	81.9	.883
	2	.778a	18.1	100.0	.662
Public	1	3.973a	95.3	95.3	.894
	2	.197a	4.7	100.0	.406

a. First 2 canonical discriminant functions were used in the analysis.

tions with an index of overall model fit. The result of a canonical correlation of private mode for function 1 and function 2 are 0.883 and 0.662, respectively; accordingly, the model explains 77.97% and 43.82% of the variation in the grouping variable. On the other hand, for the public transport, function 1 and function 2 are 0.894 and 0.406, respectively. This means the model can explain 79.92% and 16.48% of the variation in the grouping variable.

5.3.2 Land Use Transportation Interaction Function

There were three classification functions of each sub-center to classify travel behavior by different mode of transport. By applying the methodology explained in the previous section, the generalized discriminant function in Eq. (1) could be used to obtain the most suitable case. The classification scores for each case of different groups can be computed by applying Eq. (1):

$$S_i = c_i + w_{i1}x_1 + w_{i2}x_2 + ... + w_{im}x_m \quad (1)$$

In Eq. (1), the subscript i denotes the respective group; the subscripts 1, 2, ..., m denote the m variables; ci is a constant for the ith group; wij is the weight for the jth variable in the computation of the classification score for the ith group; xj is the observed value for the respective case for the jth variable; Si is the resultant classification score. Consequently, the successive functions could be determined as shown in Table 4.

These unstandardized coefficients are used to create the discriminant functions which contribute similar ways of regression function. Table 4 demonstrated that function 1 tends to separate group 1 (lowest value) and group 3 (highest value). Function 2 separates group 2 (lowest value) from groups 1 and 3 (highest value). The results reveal that func-

Table 4 Canonical Discriminant Function Coefficients

Mode of Transport	Variables	Function 1	Function 2
Private	Age (year)	0.071	-0.155
	Income (baht/ month)	0.590	1.805
	Travel time of Working Trip (minutes)	2.220	0.449
	(Constant)	-11.375	1.097
Public	Age (year)	-0.029	0.127
	Income (baht/ month)	0.286	0.489
	Travel distance of Working Trip (minutes)	1.325	-0.217
	No. of Connections	0.069	0.684
	(Constant)	-5.496	-5.301

tion 1 is positively associated with all variables of age, income and travel time, whereas function 2 is negatively associated with the age variable. When considering the income variable, a more significant impact can be seen in income effect for travelers who choose private transport rather than public transport to all sub-centers, especially the outer sub-center. Furthermore, travel time will have more influence on this group, which might suggest they value the time spent in vehicles more than the group who take public transport.

For public transport mode, Function 1 is positively influenced by the variables of income, travel distance and number of connections; however, it is negatively influenced by the variable of age. Function 2 has opposite trend of function 1 since the travel distance has negative relationships among all positive relationship of other variables. This might represent the reverse relationship of inconvenient mode of travel of public transportation. However, there would be no problem with the more connections due to the positive sign of the coefficients in both functions. The graphically demonstration of the separation among three groups clearly provide the evidence to confirm the influence of outer zone among all sub-centers. This finding reveals the strong characteristics of the travel behavior to the sub-center of outer areas among both private and public transport clusters.

6. Concluding Remarks

The main challenge of rapid urbanization has been the negative effect of automobiles usage which recently has deteriorated the quality of the people's life. Especially, when it occurs in the area of enormous number of migration of the population distribution changes, this suburbanization induces the necessity of owning an automobile. Moreover, with the limited service of transit availability, the majority of commuters need to rely on their private vehicle with longer travel time and distance rather than transit usage. Due to the high growth rate of Bangkok Metropolitan Region (BMR), Pathumthani province was selected as a case study to confirm the evidence of sprawling effect though an exploration of the land use and transportation interaction. The results of analysis indicate the poor accessibility level and the connectivity of all selected sub-centers due to the high proportion of travel expenditure and some of them need to travel to outer areas not only on weekends but also in their daily work. Thus, the availability of destinations together with an interconnected street network makes sufficiency mode of transport either public transport or nonmotorization a more competitive and attractive mode of travel than other options. Accessibility should also be taken into consideration as the sub-centers are located far from trip generation point, the number of commuters would be expected to decline in accordance with the longer distance. Finally, the results of this study also demonstrate a number of factors other than land-use environment have a profound impact on commuting behavior. Thus, considering the enhancing of connecting sub-centers to the housing, commercial and employment area and infrastructure might be an initiative for achieving mobility policy challenges. Furthermore, a more compact and intermixed urban environment is preferable to shorten the distances between destinations. If the sub-centers or destinations for work and leisure trip are located far from the community, the numbers of person who ride both public transport modes will definitely shift to their private vehicles to avoid congestion of vehicles. Thus, the provision of sustainable development should be raised to encourage the suitable development of suburban plan.

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Dynamic Simulation of Land Use Change Based on CA Model: A Case Study of Saga in Japan

アジア各国では急速な経済発展により、水陸の生態系に大きな負荷がかかっている。それを改善する土地利用の方法をさぐる。

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Abstract

This study demonstrates a combined Markov-Cellular Automata model to analyze temporal change and spatial distribution of land use stressed by natural and socioeconomic factors in Saga, Japan. Firstly, area change and spatial distribution of land use are calculated using GIS technology, and then the transition among different land use types is analyzed to obtain the transformation matrices during a period 1976–2006. Meanwhile, an integration evaluation procedure with natural and socioeconomic data is used to generate the transition potential maps. Secondly, using the transition potential maps and transition matrices, a Markov-Cellular Automata model is established to simulate spatial distribution of land use in 2006. Finally, we use this Markov-Cellular Automata model to forecast future land use changes during the period 2015–2042. As a consequence, area change simulation predicts a continuing downward trend in agricultural land and forestland areas, as well as an upward trend in built-up areas; spatial distribution simulation indicates that built-up land will expand toward suburban regions, and land use at the urban center is in the decline stage. Hence, if the current trends keep constant without holistic sustainable development measures, severe land use decline will ensue.

Keywords Land use change; GIS; Markov model; Cellular automata model; Saga in Japan

Introduction

Land use models are core subjects of Land Use/Cover Change (LUCC). In recent years, the LUCC community has produced a large set of operational models that can be used to predict or explore possible land use change trajectories. Models not only support the exploration of future land use changes under different scenario conditions. Scenario analysis with land use models can also support land use planning and policy. Until now, all these models were divided into three classes: empirical and statistical models, such as Markov chains and the Regression model; dynamic models, such as the Cellular Automata (CA) model, the Agent-based model and the System dynamic model; and integrated models, such as CLUE (Conversion of Land Use and its Effects) model. Empirical and statistical models can complement dynamic simulation models. Dynamic models appear to be better suited to predict land use changes in the future than empirical and statistical models. An integrated model that is based on multidisciplinary and combining elements of different modeling techniques will probably best serve the objective of improving and understanding land use change processes.

The objective of this study is to simulate future land use changes based on the Markov-CA model with natural and socioeconomic data in Saga, Japan. First, transition matrix is computed from the land use maps (1976, 1987, 1997 and 2006) using the Markov model to forecast area change of land use. Secondly, an integration evaluation procedure is used to generate transition potential maps based on natural and socioeconomic indicators. Finally, transition matrix and transition potential map are implemented in the Markov-CA model to simulate spatial distribution of land use from 2015 to 2042.

Material and Methods

Study area

Saga is the capital of Saga Prefecture, located on the island of Kyushu, Japan. After a merger in 2005, the city became very long in the direction of north-south, as shown in Fig. 1. It borders the Ariake Sea to the south and Fukuoka Prefecture to the southeast and north. Its total area is 431.42 km^2, population is 238,934 as of February 1, 2009, and population density is 554 per km2. For a long time, the region has been chiefly aiming at urban expansion and ignoring reasonable adjustments of the land use structure. So, potential disadvantages are threatening its sustainable development of urban land use. In this paper, land use types are divided into 6 classes (agricultural land, forestland, water, built-up land, roads and other lands) according to national classification standard of land use. Other lands include barren land and beaches.

Methods

This study employs a coupled Markov-CA model that integrates GIS software to simulate land use changes and spatial distribution in the future. The detailed steps are shown in Fig. 2. First, we obtained land use maps from 1976 to 2006 with GIS technology. Then, transition matrixes were established using Markov chain analysis. Secondly, seven assessment

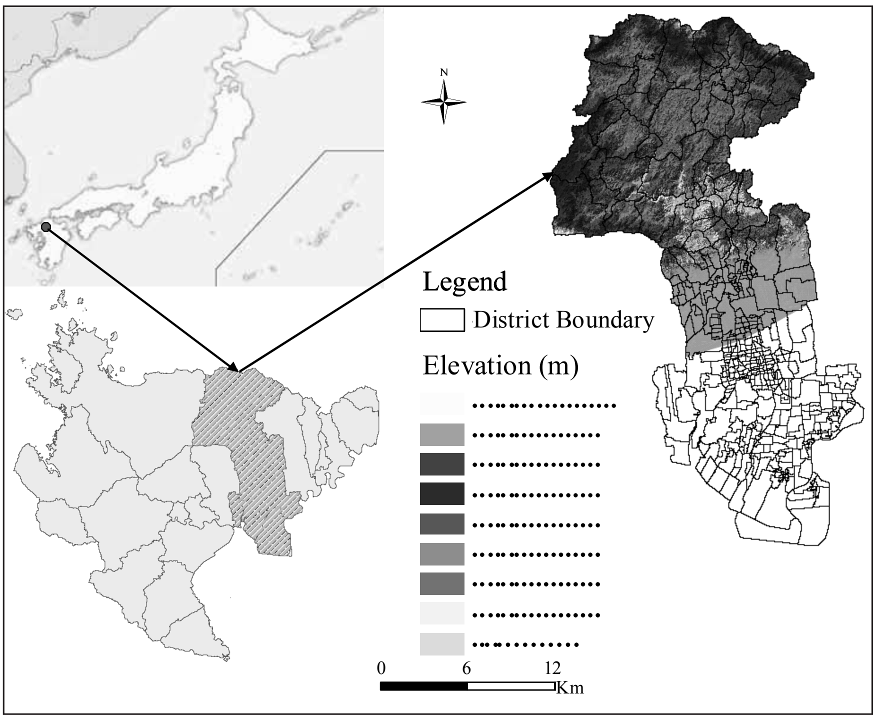

Fig. 1 Location of study area

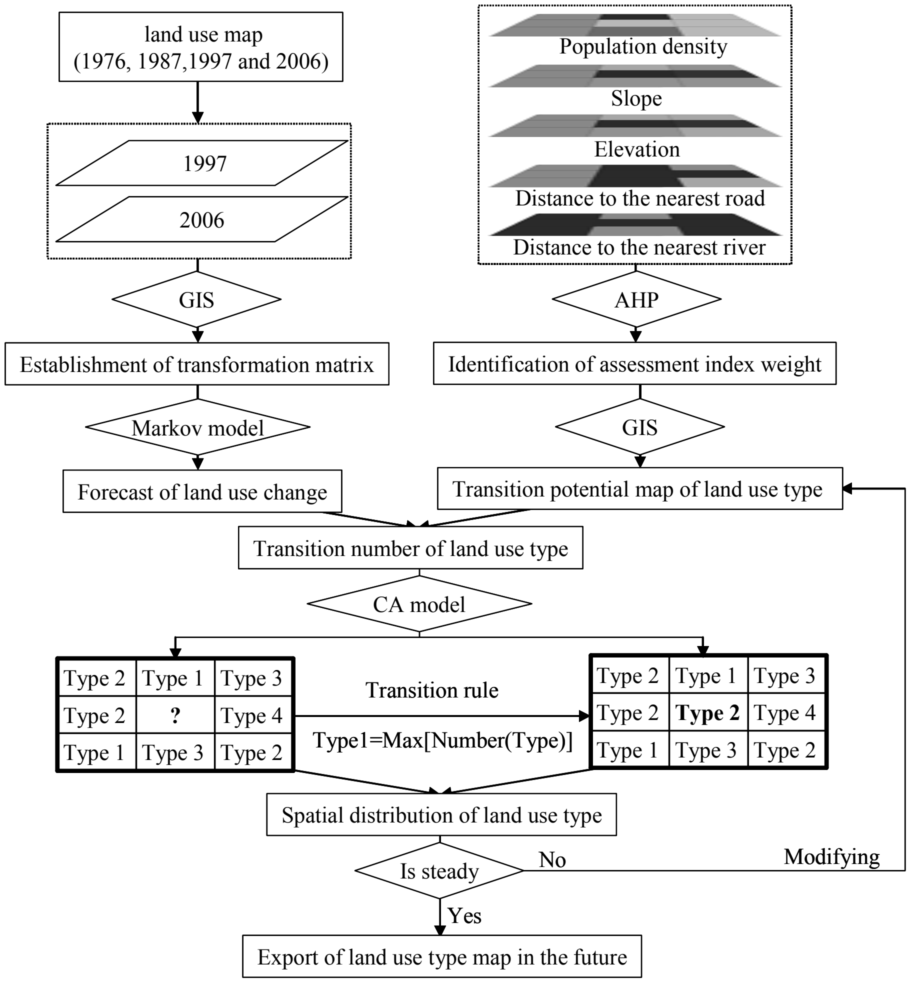

Fig. 2 Research flow chart

indicators were selected to compute transition potential maps of land use. Finally, we used the transition matrixes and transition potential maps to simulate spatial distribution of land use on the basis of the transition rule of CA model.

Results

Analysis of transition matrix

Analysis of land use area changes in Fig. 3 indicates that agriculture, forestland and built-up land were the dominant types of changed land use in the studied area. From 1976 to 2006, forestland areas decreased from 43.33% to 43.03%, while in 1987 they slightly

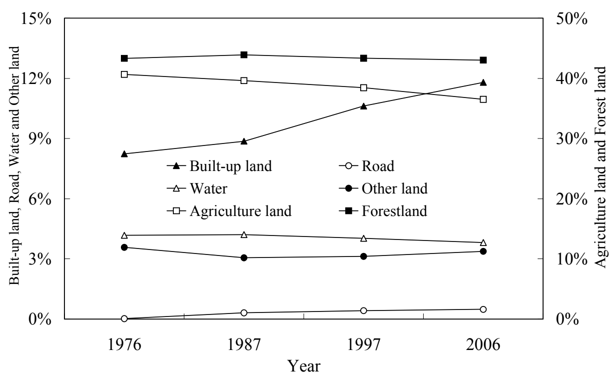

Fig. 3 Area change of land use from 1976 to 2006 in Saga

increased to 43.93%. However, agriculture areas decreased significantly from 40.67% to 36.51% during 1976–2006. During this period, the built-up area increased from 8.24% to 11.80%. Other land area reduced by 3.05% from 1976 to 1987, and then dramatically increased by 3.38% from 1987 to 2006. The area of water and road increased slightly.

Spatial distribution of land use types in Saga city at the four year nodes were also obtained by virtue of GIS spatial technology. From Fig. 4, we can see that the spatial pattern of land use in the four periods was mainly characterized as changes of patch distribution. First, agricultural land, built-up land, and unused land patch showed continual fragmentation and dispersion, indicating that the extent of human expansion and utilization intensity became larger and larger. Secondly, patch numbers and patch areas of built-up land continued to increase and showed the diffused distribution patterns from urban center to suburban region. This is because urban construction of Saga city accelerated urban development and 1ed to rapid expansion of urban land use. Thirdly, urban centers appeared in more patches of other land type from 1987 to 2006, suggesting that land use extent of Saga city had entered a declining stage.

As a result, the total region transformation tendency of land use types from 1976 to 2006 appeared as an unbalanced tendency of unidirectional-transformation. The built-up land continuously increased, and the agriculture land continuously decreased. The increasing source of built-up land was changed from the previous agriculture land and other land, to the present forestland and agricultural land.

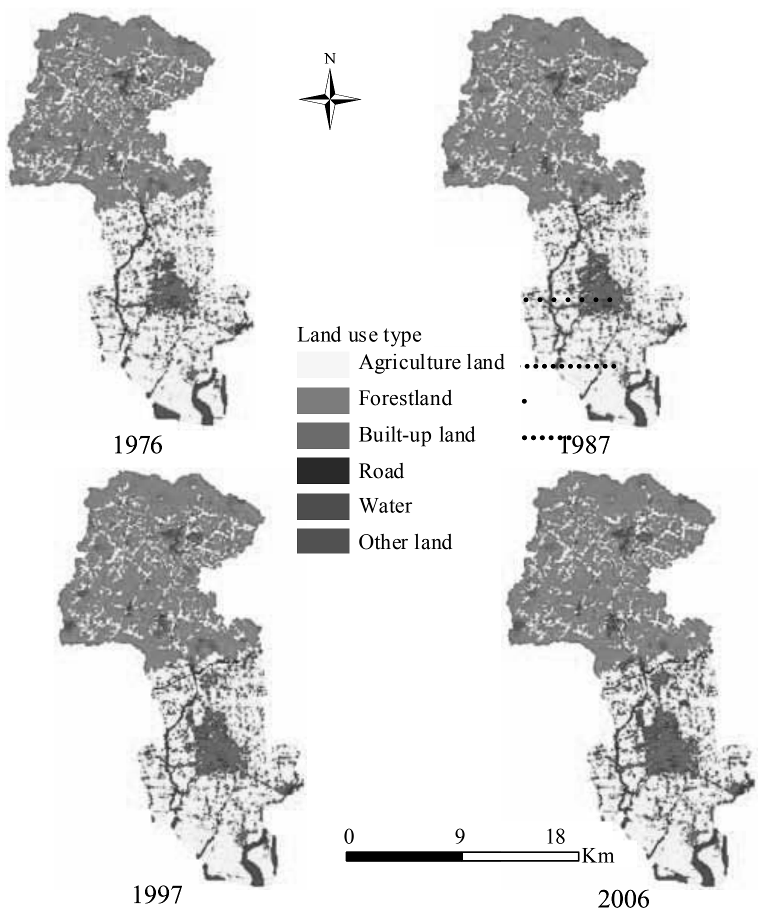

Fig. 4 Space distribution of land use from 1976 to 2006

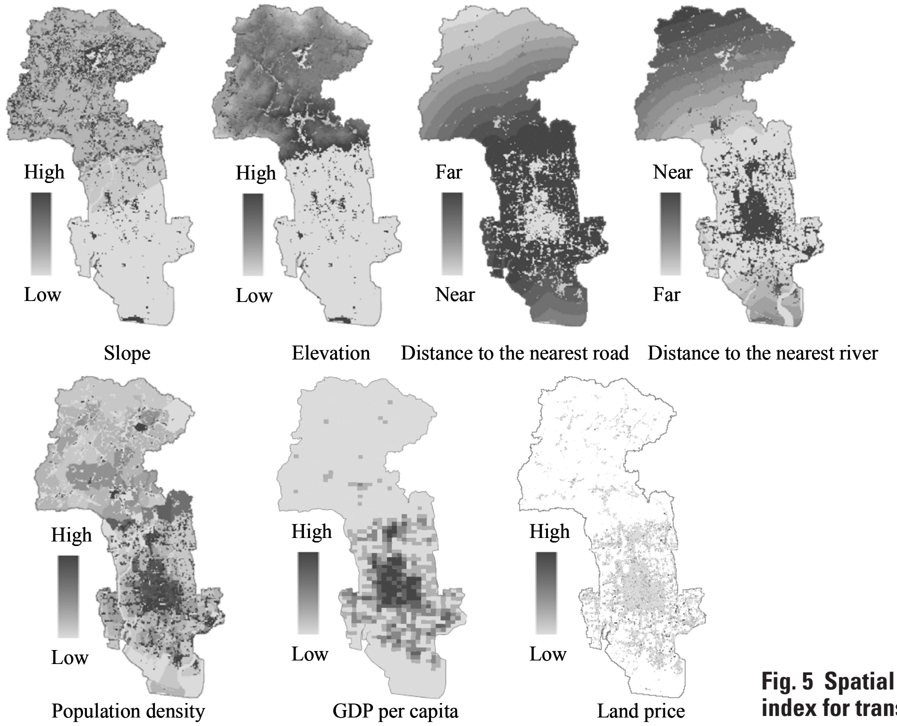

Fig. 5 Spatial distribution of assessment index for transition potential map

Analysis of transition potential

Seen from Fig. 5, the south region is the urban center of Saga city, where population density, GDP per capita, and land prices are high, and distance to river and road is short; slope and elevation are high in the north region. Transition potential of each land use type is obtained by combining spatial distribution, standard and weight of assessment index. Fig.6 represents the transition potential from one land use type to all other land use types. For example, transition potential of agricultural land indicates the transition potential of agricultural land to all other land use types (forest, built-up, water, road, and other land). Also seen from Fig. 6, the transition potential of agriculture land and forestland are high; transition potential of built-up land and other land are low.

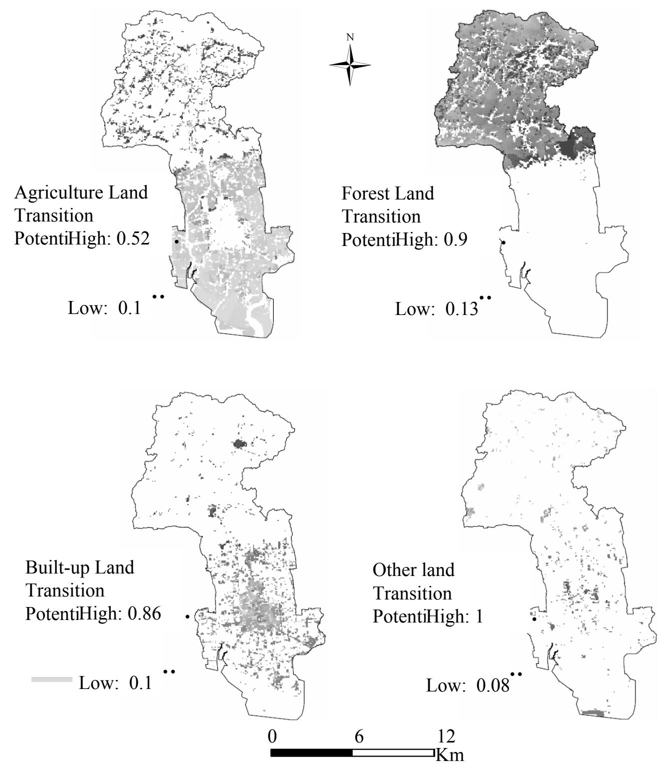

Fig. 6 Transition potential maps of land use type in 2006

Analysis of simulation results

Because the accuracy of forecasts cannot be guaranteed if different potentials are used we therefore only used the transition probability matrix of the latest 1997–2006 period to forecast land use change in the future 30 years. First, 2006 is set as the starting year; transition probability matrix of 1997–2006 periods is used to forecast 2015 year land use change; then, 2015 year is set as the starting year; transition probability matrix of 1997–2006 periods is used to forecast 2024 land use change; thirdly, 2024 is set as the starting year; transition probability matrix of 1997–2006 periods is used to forecast 2033 land use change; finally, 2033 year is set as the starting year; transition probability matrix of 1997–2006 periods is used to forecast 2042 land use change. Based on the successful simulation of area change and spatial distribution in 2006, we forecast the area change of future land use and land use maps from 2015 to 2042 as shown in Fig. 7 and Fig. 8, by using land use base map in 2006, transition probability matrix of 1997–2006 period, and transition potential maps in 2006. Seen from Fig.7, area change results show that agriculture land areas would decrease from 36% to 28% in the study area, while built-up land would increase slightly from 12% to 16%. Other land areas would also increase from 3.3% to 3.7%. Conversely, forestland areas would slightly decrease from 44% to 41%. As shown in Fig. 8, spatial distribution results indicate that all land use type would exhibit the concentrated spatial distribution patterns; urban built-up land would expand to suburban, because agriculture land in the suburban areas would rapidly convert into built-up land. Meanwhile, the transformation tendencies for forestland and built-up land into other land would be enhanced. In the view of total study area, we can see very strong transformation tendencies of all land types into built-up land.

Discussion and Conclusions

In this study, using land use maps (1976, 1987, 1997 and 2006 year), and natural and socioeconomic data, we combine Markov-CA model with GIS technology to successfully simulate the land use changes in Saga, Japan. Our model is validated with the actual data of 2006 and shows very high reliability. Based on the validation, the Markov-CA model is used to simulate the future land use changes up to 2042. The area change results show the decrease in agricultural land and forestland, and the increase in built-up land. From the aspect of spatial pattern change of land use from 2015 to 2042, urban built-up land would expand to suburban, because a certain proportion of agricultural land would be transformed into

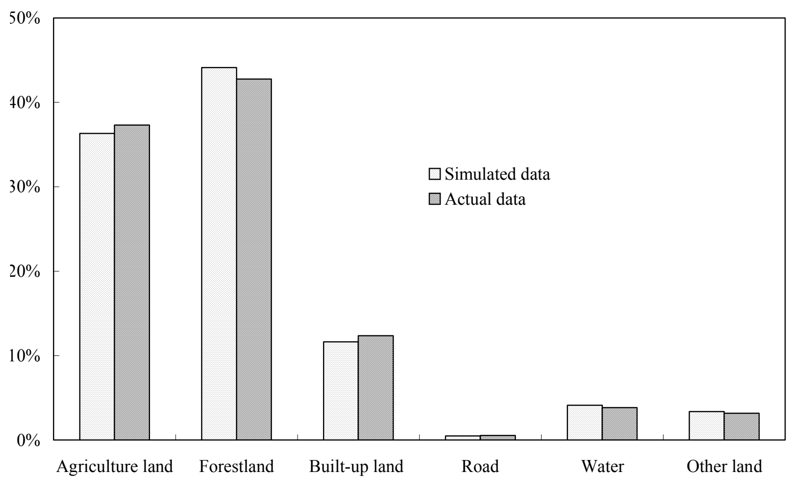

Fig. 7 Area change of land use from 2015 to 2042 in Saga