Finding the optimal operation of air conditioners in Tokyo's office districts focusing on total environmental impacts including labor productivity loss

2022.09 環境システム学専攻　47-206783　薛　雲飛
指導教員：井原　智彦　准教授

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Background

Global climate change and the urban heat island effect have increased the heat load in urban areas, posing threat to health and productivity. With changes in the indoor temperature, the human body reacts in a variety of ways to maintain thermal balance. This reaction may cause office workers to experience fatigue, increase their mental stress, and further reduce their concentration and motivation for work, thereby lowering their work performance[2]. Air conditioner(AC) as a solution to protect labor productivity creates the challenge of increasing electricity consumption and greenhouse gas emissions, exacerbating climate change[3]. In addition, the direct heat rejected from the AC unit, adds to street level heat and therefore the urban heat island effect[4]. The air conditioner also brought benefits like reduction in sleep disturbance[5], which cannot be ignored when assessing AC. The working population of Tokyo is 8.397 million, accounting for 12.2% of the whole country. Among this working population, employees working in the office will account for the majority[6]. The Japanese government launched the Cool-Biz campaign aimed at maintaining indoor temperatures above 28 °C to reduce the cooling energy consumed by AC in summer.

Introduction

Research gap

However, there is a lack of research on the optimal setting temperature of AC in Tokyo office districts. So, the limits of 28 °C lack a rational basis. In addition, there is also a lack of quantitative research which takes reduction of the labor productivity loss as the benefits of AC. Therefore, it is very necessary to conduct a comprehensive assessment of AC based on total environmental impacts.

Research objective

This study aims at assessing the cost-benefit analysis of AC focusing on total environmental impacts in the office districts in Tokyo. In the office, the main benefit of using AC is to reduce the loss of labor productivity. Therefore, the economic value of the reduced labor productivity loss is taken as benefits. The energy fees and the environmental impacts caused by the power generation are taken as costs. Another goal of this study is to find the optimal set-point temperature to address the trade-off problem between the labor productivity enhancing perspective and the energy saving perspective. Based on this, verify whether the temperature limit of 28 °C is reasonable. Eventually, propose the sustainable way of using AC in office buildings districts.

Methodology

CM-BEM

This study uses CM-BEM to calculate the indoor temperature and energy consumption of AC. The model comprises two sub-models: the canopy model (CM) and the building energy model (BEM). The model describes the feedback process, which is composed of the impact on a building's air-conditioning energy demand from the weather inside an urban canopy and the effects of exhaust heat on the external environment[7]. In the simulation, Tokyo's 23 wards are divided into 2457 urban districts according to the 4th mesh. Among them, 429 districts are selected as office-building districts based on the land and building usage.

Work performance

At present, there is no research on the relationship between indoor temperature and work performance in Tokyo, so it is necessary to select appropriate previous research and revise it. Li Lan[8] pointed out that the relationship developed between thermal sensation vote(TSV) and work performance can be a useful tool to predict productivity loss due to thermal discomfort in the cost-benefit calculations about indoor environments.TSV is used to test the sensation of human body to thermal environment from cold to hot. Kim et al[2]showed the highest work performance point temperature to be 25.15 °C and the TSV neutral point temperature to be 25 °C in Seoul, which are highly consistent and thereby confirmed Li Lan's conclusion. Hom B et al[9] showed the TSV neutral point temperature to be 25.4 °C in the office buildings in Tokyo. In the current studies, Kim's TSV results are the closest to Hom B results in Tokyo. Therefore, Kim's conclusion is more suitable for modification and application in Tokyo. In the results of Hom B and Li Lan, the relationships between TSV and temperature is linear. Therefore, the temperature can be linearly transformed on the result of Kim. Since the thermal neutral temperature in Tokyo is 0.4 °C higher than that in Seoul, the amplitude of this linear transformation is 0.4 °C.Therefore in this study, Kim's results are modified as (1).

$$P = (-0.0035 \cdot (T-0.4)^3 + 0.1840 \cdot (T-0.4)^2 - 2.6171 \cdot (T-0.4) + 56.264)/51.8 \quad (1)$$

Where P represents work performance, T represents indoor temperature.

Economic value of labor productivity loss

the Cobb-Douglas production function is used to represent the conversion relationship between work performance decline and economic loss. The Cobb-Douglas production function is shown as (2), which is widely used to represent the technological relationship between the amounts of two inputs (particularly physical capital and labor) and the amount of output that can be produced by those inputs.

$$Y = AK^{\beta k} L^{\beta l} \quad (2)$$

Where Y represents total production, L represents labor input, K represents capital input, and A represents total factor productivity. βk & βl are the output elasticities of capital and labor, respectively.

Due to the decline of work performance caused by high temperature, capital input, and current technical level remain unchanged, so the only reduction in labor input, i.e. L. Regard Y as GDP, takes the value of βl is 0.75[10]. Therefore, the relationship between work performance and economic loss is as (3).

$$EL = \frac{GDP}{Total\ working\ hours} \times n \times h \times (100\% - P^{0.75})$$

(3)

Where EL represents economic loss, P represents work performance, h represents working hours, and n represents the number of workers.

The labor productivity per worker in Tokyo's 23 wards is JPY6,172 per hour.[11]The number of workers in each urban district is from the national investigation of Japan in 2015[12], and the working hours are from the statistical results of the Statistics Division, Bureau of general affairs.[13]

Evaluation of environmental impacts

OpenLCA is used to conduct the inventory analysis of electricity and gas generation. And the economic value is calculated according to the G20 population-weighted factors of Lime 3. So the results are shown in Table.1.

Table.1 Environmental impacts of electricity and gas

unit	Electricity(1kWh)	Gas(1m^3)
2015$US.ppp	0.020	0.055
円	2.525	6.778

Results

Performance and AC power

Fig. 1. shows the relationship between indoor temperature and work performance. When the indoor temperature reaches 25.55 °C, the work performance is the highest.

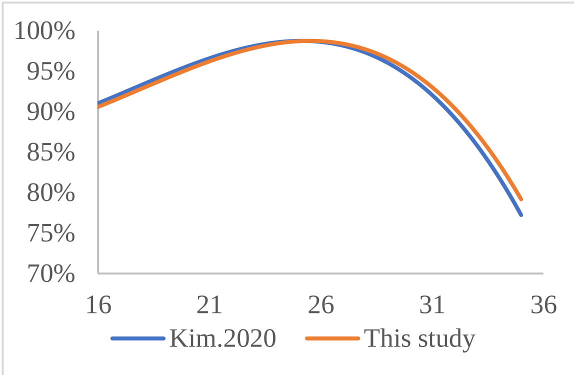

Fig.1 Relationship between indoor temperature and work performance

After getting the Relationship between indoor temperature and work performance, I can calculate the labor productivity protected by the AC. CM-BEM also gives the power of the AC. The district 533945471 on July 29th with a setting temperature of 26 °C is taken as an example. Fig.2 shows the power of the AC and the working performance protected by AC on a working day.

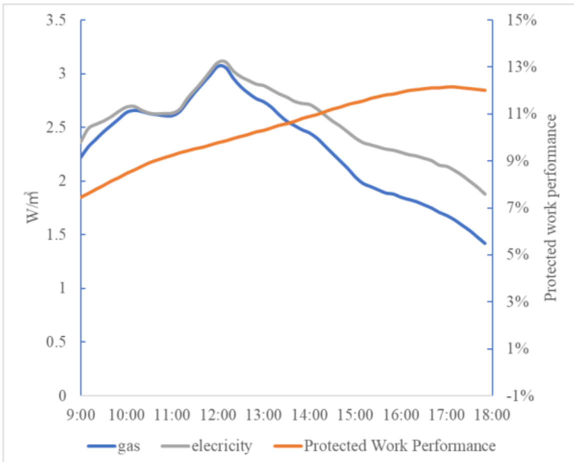

Fig.2 AC power and protected work performance

Protected labor productivity by AC

The results of protected labor productivity are shown in Fig.3. When the AC setting temperature is 26 °C, it reaches the maximum value, about 43 billion yen. At

24 °C, the protected labor productivity reaches the minimum value, about 40 billion yen.

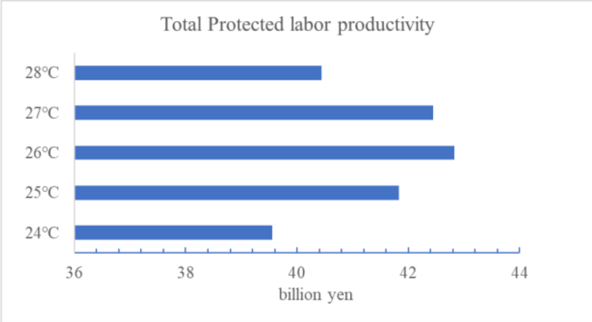

Fig.3 total protected labor productivity

Comparing the per capita protected labor productivity with the GDP of Tokyo in summer, the results are shown in Fig.4.

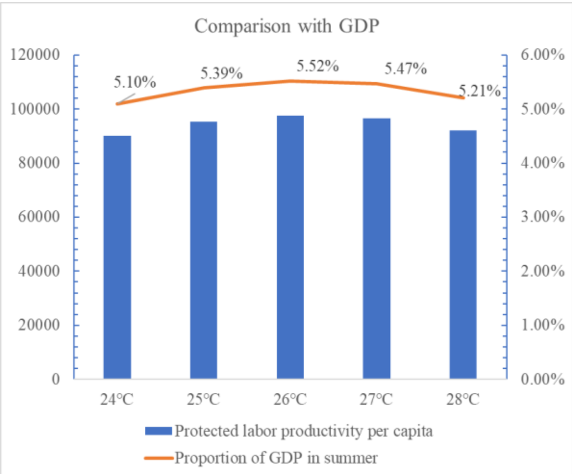

Fig.4 Per capita labor productivity protected by AC

In general, the labor productivity protected by AC exceeded about 5% of GDP in summer and reached a maximum of 5.52% at 26 °C.

Energy fees and environmental impacts

The total cost of all 429 districts is shown in Fig.5.

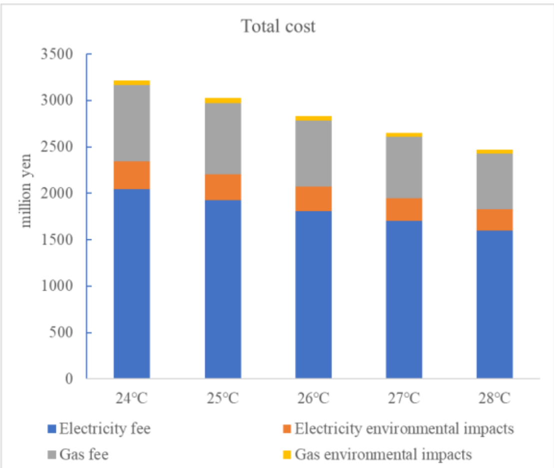

Fig.5 Total cost of each setting temperature

In terms of cost composition, the largest part is the electricity fee, followed by the gas fee, electricity environmental impacts, and gas environmental impacts. With the increase of the setting temperature of the AC, the proportion of the cost of gas in the total cost will be lower, while the proportion of electricity will rise.

Cost & benefit results

The cost-benefit analysis represents the net economic benefits of AC in this district. The AC setting temperature with the highest cost-benefit analysis result is regarded as the optimal setting temperature. As shown in Fig.6, the cost-benefit analysis results are quite huge reaching about 40 billion yen when the setting temperature is 26°C. The cost-benefit analysis results are the net benefits shown as bars below, the costs are shown as upper bars. Two bars together are the protected labor productivity.

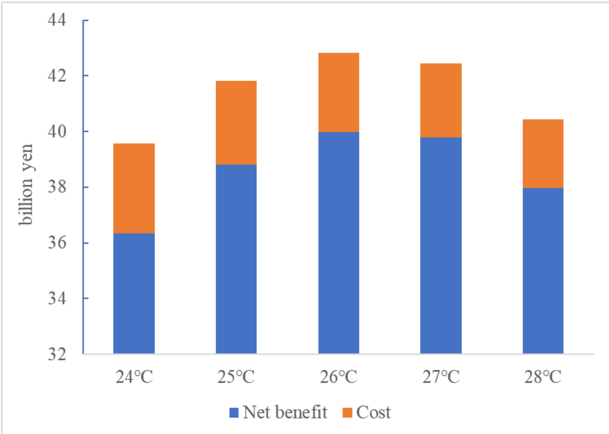

Fig.6 Cost & benefit results of each setting temperature

As shown in Fig.7, the cost-benefit analysis results per capita reached 910,44 yen, accounting for about 5.15% of the per capita GDP in summer when the setting temperature is 26°C. Even when the setting temperature of the AC is 24 °C, the cost-benefit analysis is the smallest, reaching 82739 yen, accounting for about 4.68% of the per capita GDP in summer.

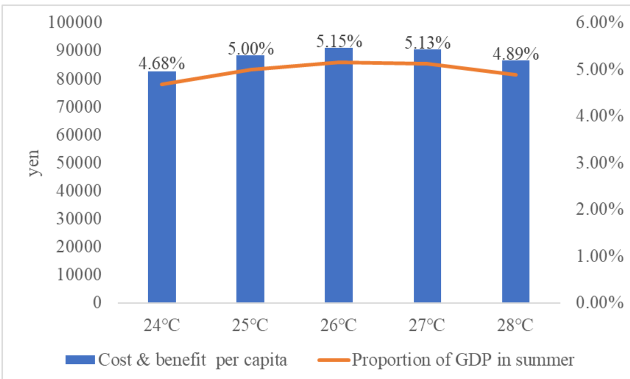

Fig.7 Cost & benefit results per capita of each setting temperature

The optimal setting temperature of AC

The optimal AC setting temperature of each district is shown in Fig.8. The optimal setting temperature of AC in central Tokyo is higher, mostly 27 °C or 28 °C. And slightly away from the center, the optimal setting temperature of the AC is mainly 26 °C and 27 °C. The optimal setting temperature of the AC in the office district further away from the center and distributed with the rail transit lines are 26 °C. Only a few districts have the optimal AC temperature of 25 °C, most of them are located near the water area.

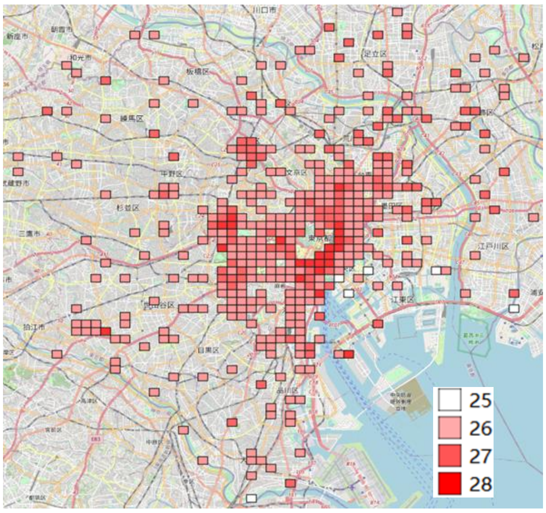

Fig.8 Optimal setting temperature of each district

The statistical results of districts and workers are shown in the table below.

Table.2 Distribution of optimal setting temperature

AC settings	25℃	26℃	27℃	28℃
Districts	6	305	96	22
Proportion	1.4%	71.1%	22.4%	5.1%
Workers	2,912	348,695	85,691	1,969
Proportion	0.7%	79.4%	19.5%	0.4%

For the vast majority of Tokyo office buildings, the optimal setting temperature of AC is 26 °C.

Comparison between 26°C and 28 °C

26 °C is the most common optimal AC setting temperature obtained in this study, which is not consistent with the 28 °C recommended by the government. So, it is necessary to compare the two situations. As shown in Table.3, the protected labor productivity, energy fee, and environmental impacts are all declining by 5.9%, 14.6%, and 13.9% respectively. But the cost-benefit results are also declining by 5.3%.

Table.3 Comparison between 26°C and 28 °C

per capita(yen)	26℃	28℃	Decrease range
Protected labor productivity	97,488	92,053	5.9%
Energy fee	5,737	5,005	14.6%
Environmental impacts	707	621	13.9%
Cost & Benefit	91,044	86,428	5.3%

Conclusion

This study derives the labor productivity protected and the energy consumed by AC by simulating 429 office districts in Tokyo's 23 wards.

(1) The per capita value of labor productivity protected by AC reaches 97,488 yen accounting for 5.52% of Tokyo's per capita GDP in summer when the setting temperature is 26 °C, and 5.15% even after deducting the costs. The total number of workers reached about 439,267, and the total protected labor productivity by AC reached 42.44 billion yen at the setting temperature of 26 °C. The decision of optimal setting temperature is very important. The labor productivity protected by the setting temperature of the air conditioner at 26 °C is almost 3 billion yen higher than that at 24 °C.

(2) From the perspective of the number of workers, 98.89% of the workers have the highest net economic benefits at 26–27 °C. Although the optimal setting temperature may be different in each district, in general, the optimal setting temperature of the AC in the Tokyo office districts is 26 °C.

(3) The 28 °C recommended by the government is indeed effective in saving energy and reducing environmental impacts, but the decline of labor productivity protected by AC is not enough to cover the gap. Therefore, this study concludes that, at least in office districts, a lower AC setting temperature should be adopted.

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