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Energy load superposition and spatial optimization in urban design: A case study

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ABSTRACT

Building energy consumption accounts for a large portion of total energy-use in a city or a regional district. However, energy load spatial distribution has seldom been considered during urban design phase. And energy conservation and energy efficiency measures pay more attention to individual building than buildings in a district or regional space as a whole. If buildings with different functions are mixed together and share same energy system, the savings on system capacity and peak electricity load can be significant. In this paper, a load superposition concept is proposed. The term 'superposition' refers to overlapping of energy demand load curves from different buildings and so that the total peak is smaller than the sum of individual peaks. Three spatial optimization methods of demand side load management and three different schemes of energy systems are proposed in this paper. And economic analysis is recommended to evaluate the different energy systems. The applicability of different approaches and the significance of load superposition was analyzed and elaborated through a case study to offer planners a feasible way for evaluating the potential of load spatial optimization.

1. Introduction

With rapid industrialization and urbanization in developing countries, the consumption of fossil fuel increases perpendicularly (Budzianowski, 2011, 2012; Mohr, Wang, Ellem, et al., 2015; Tsinghua University, 2013). According to the statistical analysis, a large portion of energy in cities of many parts of the world is used for building heating and cooling. However, energy used for building heating and cooling fluctuates drastically throughout a whole year compared with other energy demand in buildings. It is urgent to find out a suitable and effective way to ensure the low peak energy value. Thus, district level or regional level urban planning of energy systems inevitably plays an indispensable role in energy conservation management. The original definition of 'region' refers to social communities that dwell in specific areas of any scale (Smith, 2003). In this paper, 'region' is defined as planning land area and normally it is about 1–10 km^2. Energy system spatial optimization of heating and cooling is taken into greater consideration. Energy systems in this paper refer to energy, such as gas and electricity, used to provide heating and cooling in the planning area. Usually regional energy infrastructures are built with the construction of a city, and the infrastructure cannot be easily modified or rebuilt once finished. Therefore, during the planning phase, an elaborate energy planning is one of the top priorities.

In traditional design, energy supply is designed to meet energy demand one to one basis. Namely, total energy supply is the sum of all peak load of demand. But actually, electricity peak and valley time occur differently in different types of buildings (Li, Zhang, & Chen, 2010; Zhang & Long, 2010). That is to say, the peak loads of demand do not happen simultaneously, so it does not make sense to design a system with a capacity of providing energy that equals to the sum of all peak load of demand. The load discrepancy between different building types at regional level has been regarded as a virtual resource for a long time, but there are still few examples on how to realize them in district planning.

The methods of regional energy planning are divided into two main categories, top-down approach and bottom-up approach (Chingcuanco & Miller, 2012; Kim, Sting, & Loch, 2014). In this paper, bottom-up approach is adopted to in order to reduce the total and peak energy consumption. We calculate cooling and heating load of each building, and then load superposition is done to get the total peak. According to different values of total peak got by different spatial arrangements, we can make sure which way can get the lowest total peak.

One prospective of district energy planning is DSM (Demand Side Management). DSM includes energy efficiency retrofitting and load management and it is normally used for existing buildings. The prime concern of energy efficiency management is to adopt advanced energy-saving technique and high-efficiency appliances, whereas load management lies in shifting peak load (Finn, Fitzpatrick, Connolly, et al., 2011; Nie, 2006; Wilhite, 2007). For new construction, Liang and Long (2010) developed a model of regional energy. In this model, by comparing different scenarios of energy supplying to demand, an optimal solution can be determined and this solution will lead to increased energy-consuming efficiency and the declined peak power grid load. Long and Liang (2011) pointed out that because electric is hard to store, off-peak electric energy should be stored by means of heat/cool

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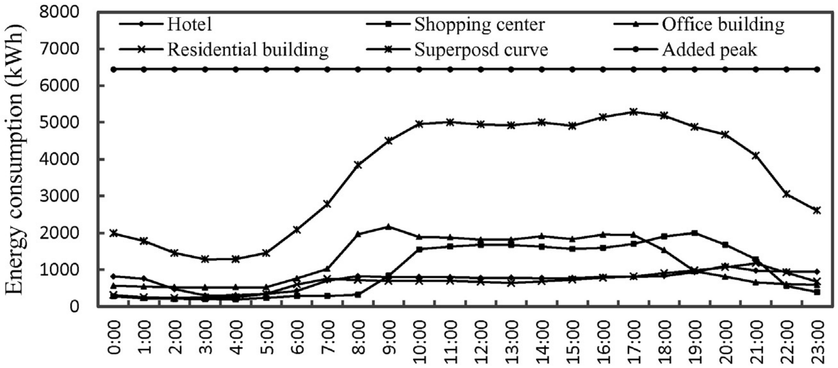
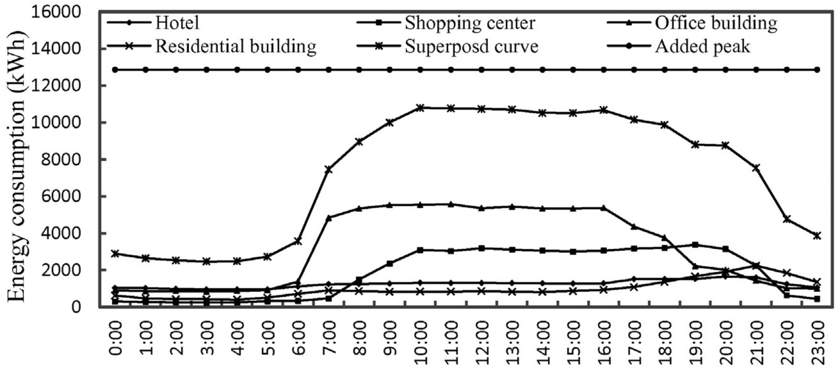


(a) Transition seasons (spring and fall)



(b) Summer

Fig. 1. Energy demand curve of measured data from four buildings.

storage and then released during peak times. In this way load shifting can be attained, while less total energy is used by avoiding two conversion processes in conventional electric storage, the charge and discharge. Nikonowicz and Milewski (2012) addressed that DER (Distributed Energy Resource) system has great development potential. One of the most important reasons is that DER system can compensate load from different buildings at different time, and so the overall total peak load can be shifted. In the paper, different system schemes have been compared, and DER system is taken into consideration.

Energy storage is not always the most effective way to minimize peak load. Instead, it is more important to optimize energy demand, in particular the spatial distribution in district planning phase. Energy load superposition refers to overlapping energy demand curves from different buildings. The superposition can not only reduce the peak demand and installed utility capacity in a region, but also improve the overall grid security and economics with an overall flat energy demand curve. Undoubtedly, this type of load arrangement at regional level can treated as one type of passive demand side management methods. Energy load superposition and load spatial optimization can be utilized to reduce peak energy consumption to some extent in a region with diversified building functions. In addition, previous researchers have found that peak load shifting through demand-side load spatial optimization can not only ease pressures of the grid but also bring considerable economic benefits to energy users (Ashok & Banerjee, 2000; Gang, Wang, Gao, et al., 2015; Kurz, 2002; Middelberg, Zhang, & Xia, 2009; Van Staden, Zhang, & Xia, 2011; Wilhite, Shove, Lutzenhiser, & Kempton, 2000).

Fig. 1 is an example of energy system superposition. Four lines at the bottom are measured energy demand curve of four real buildings, a shopping center (40,000 m^2), an office building (98,830 m^2), a residential building (63,000 m^2), and a hotel (19,991 m^2). The added peak of three buildings is much higher than the superposition load curve. Therefore by mixing buildings of different functions together, the overall installed capacity of energy system can be much lower. Although the concept is simple, it is seldom a practice during urban design, because normally location and function of buildings were set first before engineers start to design energy system.

In this paper, a method of energy load superposition is proposed at the regional level. This paper focuses on the load superposition in the regional energy system planning and three specific spatial load optimization methods of calculation are provided, 1) simultaneity factor method, 2) site survey method and 3) simulation method. An actual regional energy planning case study was performed to illustrate the effect and significance of load spatial optimization and peak shifting.

2. Methodology

2.1. Method of load spatial superposition

2.1.1. Simultaneity factor method

In this method, load intensity index, formulated in national or local codes, refers to the cooling and heating load density of different types

Table 1
Introduction of the three types of energy systems.

No.	System	Description
1	Distributed system	Household air-conditioner or VRV system is used in each building
2	Small-scale central system	A small-scale central system is chosen in each function zone. Chiller and gas boiler are used to supply cooling and heating.
3	Regional central system	Four regional central energy plants are built in the whole region. Chiller and gas boiler are used for space cooling and heating,

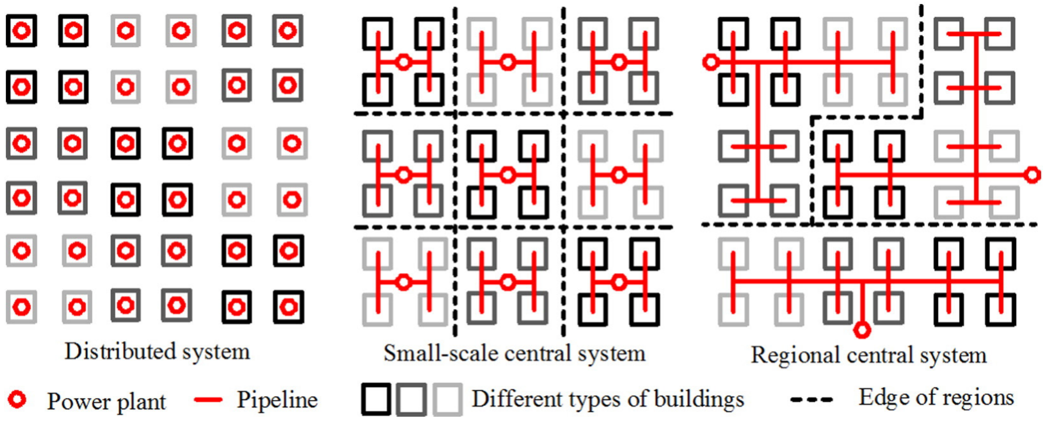


Fig. 2. Schematic diagram of the three schemes.

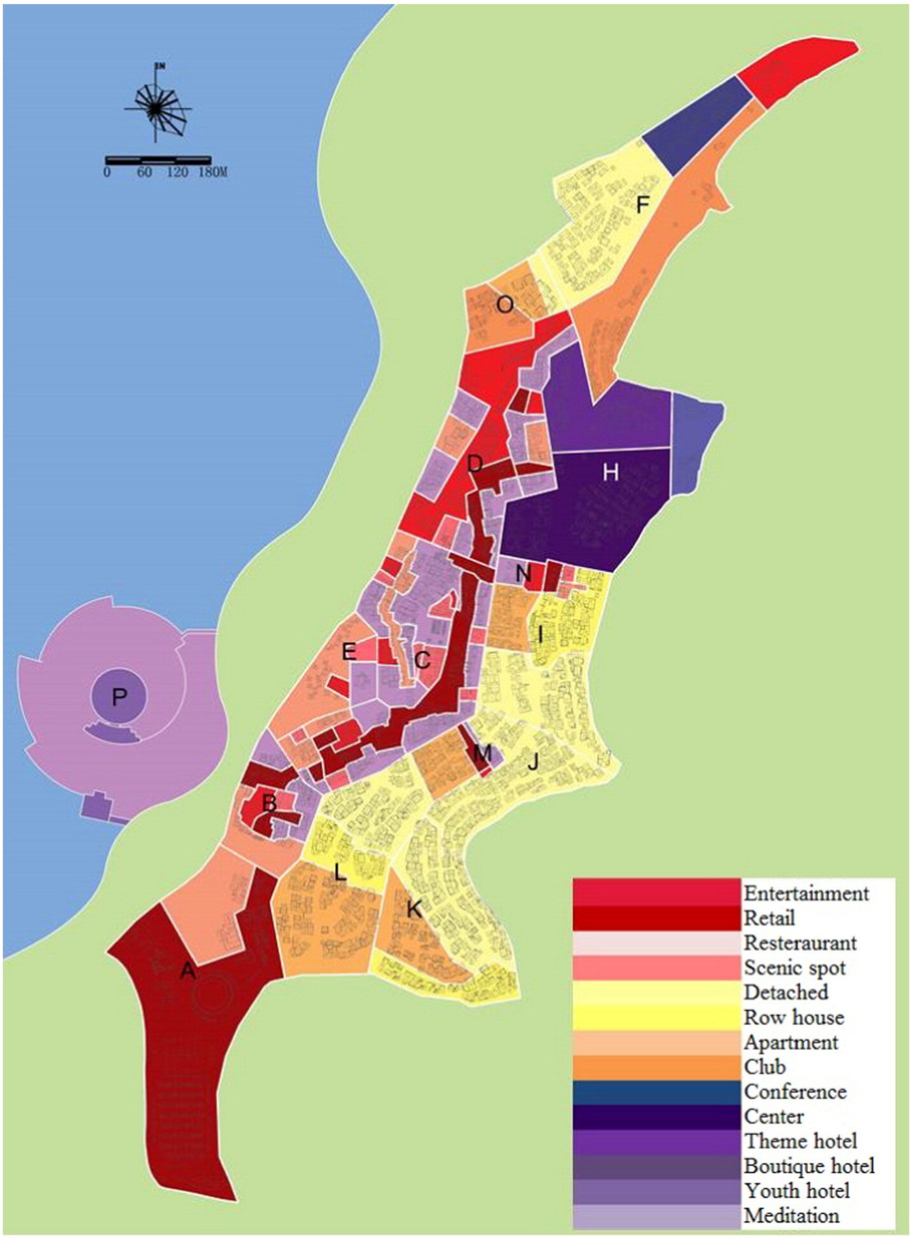


Fig. 3. Distribution of different buildings types in the planning area.

Table 2
Gross area of different buildings types.

Types	Area (m^2) A	B	C	D	E	M&N	Total area by type (m^2)
Entertainment		720	4067	6730	210	1906	13,633
Retail	4900	1376	5251	3920		520	15,967
Catering	1760	2070	9066	4470	1308	370	19,044
Scenic spot		638	2308		108	960	4014
Youth hotel		5563	24,918	17,330	587	2710	51,108
Total area by region (m^2)	6660	10,367	45,610	32,450	2213	6466	

Types	Area (m^2) F	H	I	J	K	L	O	Total area by type (m^2)
Detached	10,310		9850	19,730	13,210	20,260	1700	75,060
Row house			2160	2520	19,800	3190	4169	31,839
Apartment			2300	7110	1950	2280		13,640
Club	3000						5610	8610
Conference hotel		20,000						20,000
Conference center		8000						8000
Theme hotel		10,000						10,000
Boutique hotel	3600							3600
Meditation (P)								22,612
Total area by region (m^2)	16,910	38,000	14,310	29,360	34,960	25,730	11,479	

of buildings in planning areas. Simultaneity factor represents the percentage of operating load of a system from the rated load in the same building at the same time. Simultaneity factor method calculates load through the following two equations. Eq. (1) is to determine hourly superposition load in a planning area and Eq. (2) is to calculate peak load in a planning area.

$$E_t = \sum_{i=1}^{n} (\varepsilon_{it} \times L_i \times A_i), t = 1, 2, \ldots\ldots, 24 \quad (1)$$

where E_t is the cooling or heating load in the superposition area at hour t in the cooling or heating design day, W; n is the total number of different building types in the superposition area; ε_{it} is the simultaneity factor of building type i at hour t; L_i represents the cooling or heating load of building type i, W/m^2; and A_i represents the total air-conditioning areas of building type i, m^2.

Air-conditioning areas means the construction areas where air-conditioning is available. In some places of construction areas such as storage room, corridors and so on, air-conditioning is not available. As to total air-conditioning area, there are two conditions. 1) If the drawing design has been completed, the air-conditioning area can be calculated according to the drawings. 2) Before drawing design stage, since construction area rather than air-conditioning area is known, so the air-conditioning area can be determined by total construction area multiplying by a certain factor, which is generally based on engineering experience.

Table 3
Cooling/heating load of all kinds of buildings.

Types	Building code cooling load index (W/m^2)	Building code heating load index (W/m^2)	Simulated peak cooling load (W/m^2)	Simulated peak heating load (W/m^2)
Entertainment	180	80	120	38
Retail	150	70	80	33
Catering	180	60	97	35
Scenic spot	120	70	67	54
Detached	90	60	88	63
Row house	90	60	75	31
Apartment	90	60	63	35
Club	200	100	123	56
Conference hotel	110	70	78	35
Conference center	120	90	69	59
Theme hotel	110	70	92	44
Boutique hotel	120	80	101	67
Youth hotel	80	60	49	23
Meditation	180	120	143	75

$$E_p = \mathrm{Max}(E_t), t = 1, 2, \ldots\ldots, 24 \quad (2)$$

where E_p represents the peak load of cooling or heating load in the superimposed area, W.

2.1.2. Site survey method

The fundamental equations in survey method is same as simultaneity factor method, except the data are not collected from building codes, but by on-site survey. Parameters from relevant codes or specification can be unreliable because building functions and occupants behavior change over time. Without field survey, engineers tend to assign conservative factors in sizing the energy system. In this method, the demand-side load level and simultaneous usage data of existing buildings in the nearby area are used as the reference for designers. Also, because many new district areas are developed in phases, if the current planning project is not the first-stage, designers can also take measured data in earlier phases as a reference.

2.1.3. Simulation method

Simulation method is to optimize the load spatial distribution using building energy performance simulation such as, EnergyPlus, eQUEST, TRNSYS, IES-VE. With survey data, calibrated simulation method is more accurate than the above two methods. The individual building model grouped together at regional level can reflect the real energy use hour by hour. The simulated data is generated from some well-tested energy models defined in the simulation software, and so the variation of the energy consumption is more accurate. Simulation method can also be incorporated with the method in subsections 2.1.1 and 2.1.2. Overall energy load is calculated by following two equations. Eq. (3) is to calculate hourly superposition load in a planning area and Eq. (4) is to calculate peak load in a planning area.

$$E_t = \sum_{i=1}^{n} (L_{it} \times A_i), t = 1, 2, \ldots\ldots, 8760 \quad (3)$$

where E_t is the cooling or heating load in the superimposed area at hour t in one year, W; n is also the total number of different building types in

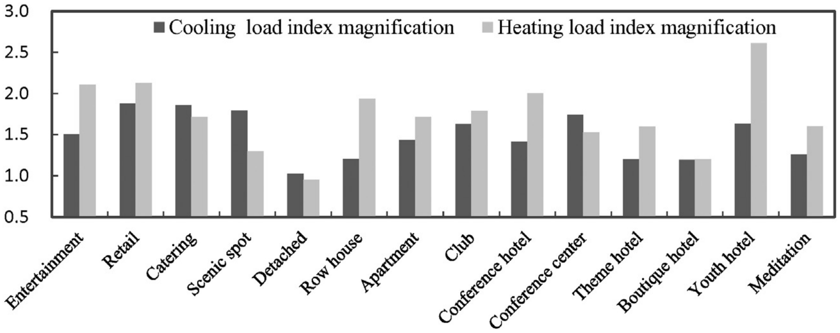


Fig. 4. Magnification of cooling and heating load index.

the superimposed area; L_{it} represents cooling or heating load of building type i at hour t in one year, W/m^2; A_i represents the total air-conditioning area of building type i, m^2.

Same as before, only construction area rather than conditioned area is known at planning stage, so the air-conditioning area can be determined by total construction area multiplying by a certain factor, which is generally 0.7 to 0.8. Unlike the E_t in Section 2.1, in this method whole year is taken into consideration instead of whole day

$$E_p = \text{Max}(E_t), t = 1, 2, \ldots\ldots, 8760 \tag{4}$$

where E_p represents the peak load of cooling or heating load in the superimposed area, W.

These three methods of demand-side load superposition have their pros and cons respectively. As for the simultaneity factor method, the data is obtained based on national or local standards and specifications. It is arguably the easiest and the quickest method. However, this method is too general and data are not specifically targeted on the planning area, resulting in the deviation of results from actual situation. Many times, energy systems are sized too large. Site survey method, if implemented effectively, can generate an accurate outcome matched with practical case. But sometime field investigation is difficult and it is hard to get exact same building type information. For example, survey is impossible if a project kick-off time is not in cooling or heating seasons. In fact, this method can be integrated into other methods as a good supporting means. Simulation method, as the focus of this paper, is unthinkable before when computing power is limited and hard to simulation every building in a region. The simulation method has the merits of accuracy, good data integrity and flexibility in adjusting building functions. In the simultaneity factor method, the method can only get the hourly cooling load and heating load data in the cooling design day and heating design day, so the peak load appears in design days. While in the simulation method the peak load appears in which day is according to the simulation result.

2.2. Comparison of different system schemes

2.2.1. Description of schemes

Considering the terrain of the planning area, the requirements of project investors, and the relative rules regulated by the planning department, three types of HVAC systems are proposed and energy use of three options were analyzed thoroughly in this subsection. The three schemes are listed in Table 1. Fig. 2 illustrates these schemes in detail.

As mentioned above, the three schemes all belong to simulation method. We get the cooling load and heating load around the year by simulation method with simulating software such as EnergyPlus. The energy consumption of HVAC system can be calculated by the year-sum cooling load and heating load, year-round operation condition COP (GBT 17981, 2007) of chiller and the efficiency of boiler.

2.2.2. Cost calculation for schemes

To compare the economy feasibility of different schemes, ‘annual cost’ is selected as evaluation standard. Annual cost consists of two main parts annual initial cost and annual operation and maintenance cost. The calculation method is described in detail as following Eqs. (5)–(7-3).

$$Y_{ac} = Y_{ai} + Y_{aom} \tag{5}$$

where Y_{ac} is annual cost, million \$/year; Y_{ai} is annual initial cost, million \$/year; and Y_{aom} is annual operation and maintenance cost, million \$/year.

$$Y_{ai} = \frac{Y_{ti}}{y} \tag{6}$$

$$Y_{ti} = Y_{te} + Y_{td} + Y_{tc} \tag{6 – 1}$$

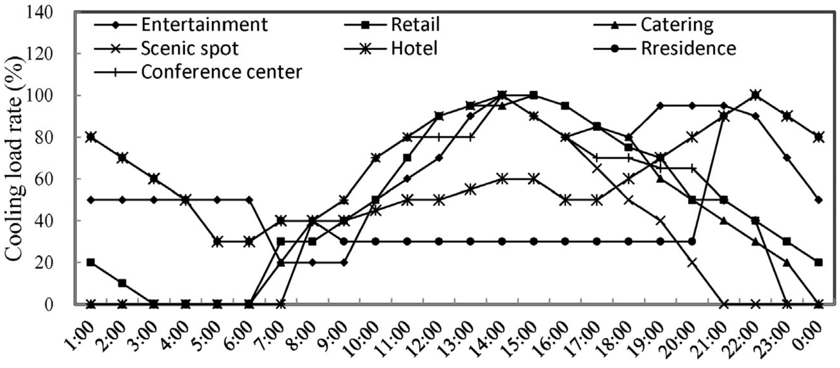


Fig. 5. Simultaneity factors of different functional zones.

Table 4
Simulated peak cooling and heating load of different functional buildings.

Types	Simulation peak cooling load (W/m^2)	Simulation peak heating load (W/m^2)	Area by type (m^2)	Total peak cooling load (MW)	Total peak heating load (MW)
Entertainment	120	38	13,633	1.64	0.52
Retail	80	33	15,967	1.28	0.53
Catering	97	35	19,044	1.85	0.67
Scenic spot	67	54	4014	0.27	0.22
Detached	88	63	75,060	6.61	4.73
Row house	75	31	31,839	2.39	0.99
Apartment	63	35	13,640	0.86	0.48
Club	123	56	8610	1.06	0.48
Conference hotel	78	35	20,000	1.56	0.70
Conference center	69	59	8000	0.55	0.47
Theme hotel	92	44	10,000	0.92	0.44
Boutique hotel	101	67	3600	0.36	0.24
Youth hotel	49	23	51,108	2.50	1.18
Meditation	143	75	22,612	3.23	1.70
Total				25.07	13.33

$$Y_{\mathrm{te}} = \sum_{i=1}^{m} (Y_{\mathrm{cei}} \times C) + \sum_{j=1}^{n} (Y_{\mathrm{hej}} \times H) \qquad (6-2)$$

$$Y_{\mathrm{td}} = \sum_{x=1}^{p} (\mathrm{PR_x} \times \mathrm{L_x}) \qquad (6-3)$$

(Feng, 2007)

$$PR_z = 0.00036 d_z^2 + 2.9471 d_z - 176.971 \qquad (6-4)$$

$$Y_{\mathrm{tc}} = \sum_{z=1}^{q} Y_{\mathrm{tcz}} \times N_z \qquad (6-5)$$

where Y_{ti} is the total initial cost, million \$; y is the service life of each system, year; Y_{te} presents total equipment initial cost, million \$; Y_{td} presents total distribution system initial cost, million \$; Y_{tc} presents total initial cost of plant building construction, million \$; Y_{cei} is the unit cost of the ith cooling equipment, \$/kW cooling load; C is the design cooling load, kW, 'm' is the total number of the kind of cooling equipment, Y_{hej} is the unit cost of the jth heating equipment, \$/kW heating load, H is the design heating load, kW, 'n' is the total number of the kind of heating equipment; $\mathrm{PR_x}$ presents the initial cost of the xth pipe, \$/m; $\mathrm{L_x}$ is the length of the xth pipe, m, d_x is the nominal diameter of the xth pipe, mm; P is the total number of pipes; Y_{tcz} presents the construction cost of the zth kind of plants, million \$/plant, N_z is the total number of the zth kind of plants, and q is the total kinds of plants.

Table 5
Superimposed peak cooling and heating load of every single zone.

Regions	Superimposed peak cooling load (W/m^2)	Superimposed peak heating load (W/m^2)	Area by region (m^2)	Total peak cooling load (MW)	Total peak heating load (MW)
A	83	33	6660	0.55	0.22
B	60	29	10,367	0.62	0.30
C	60	29	45,610	2.74	1.32
D	63	28	32,450	2.04	0.91
E	75	33	2213	0.17	0.07
F	68	43	16,910	1.15	0.73
H	72	30	38,000	2.74	1.14
I	56	36	14,310	0.80	0.52
J	56	36	29,360	1.64	1.06
K	63	34	34,960	2.20	1.19
L	56	37	25,730	1.44	0.95
MN	66	32	6466	0.43	0.21
O	87	43	11,479	1.00	0.49
P	143	75	22,612	3.23	1.70
Total				20.76	10.80

Table 6
Superimposed peak cooling and heating load of multiple zones.

Regions	Peak cooling load (W/m^2)	Peak heating load (W/m^2)	Area by regions (m^2)	Total cooling load (MW)	Total heating load (MW)
ABLK	50	29	77,717	3.89	2.25
CEIJMN	47	29	97,959	4.60	2.84
DH	52	24	70,450	3.66	1.69
FO	71	43	28,389	2.02	1.22
P	143	75	22,612	3.23	1.70
Total				17.40	9.70

$$Y_{\mathrm{aom}} = Y_{\mathrm{acc}} + Y_{\mathrm{ahc}} + Y_{\mathrm{am}} \qquad (7)$$

$$Y_{\mathrm{acc}} = E_{\mathrm{ac}} \times C_c \qquad (7-1)$$

$$Y_{\mathrm{ahc}} = E_{\mathrm{ah}} \times C_h \qquad (7-2)$$

$$Y_{\mathrm{am}} = \frac{Y_{\mathrm{tem}} + Y_{\mathrm{tdm}}}{y} + S \times N_s \qquad (7-3)$$

where Y_{acc} presents annual operation cost of cooling period, million \$/year; Y_{ahc} presents annual operation cost of heating period, million \$/year; Y_{am} presents annual maintenance cost of equipment and systems, million \$/year; E_{ac} is the energy use of cooling period, kWh or m^3; C_c is the unit price of cooling energy use, \$/kWh or \$/m^3; E_{ah} is the energy use of heating period, kWh or m^3, C_h is the unit price of heating energy use, \$/kWh or \$/m^3, Y_{tem} is total equipment maintenance cost, million \$, Y_{tdm} is total distribution system maintenance cost, million \$, S is the salary of each plant staff, million \$/(year·person), and N_s is the total number of staff, person.

3. Case study

The planning area in this case serves as a tourist district of about 3 km^2. The coordinates of the area are 31.42, 120.07. All buildings in this area are two floors or three floors. According to various functions, the whole area can be divided into 15 functional zones, ranging from entertainment, retail, restaurant, scenic spot, detached, row house, apartment, club, conference hotel, conference center, theme hotel, boutique hotel, youth hostel and meditation 14 kinds of building types in all. The distribution and gross area of different formats are shown in Fig. 3

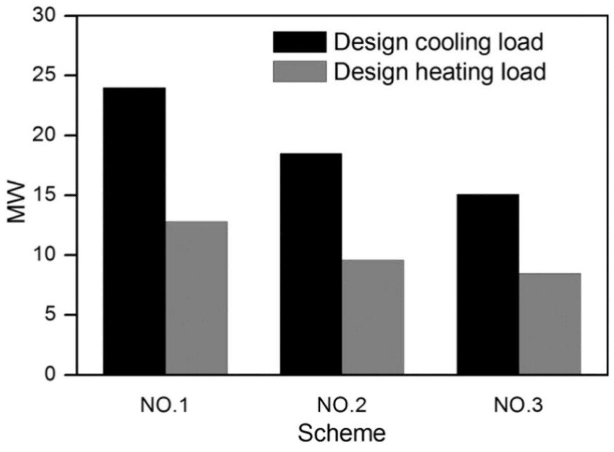


Fig. 6. Design cooling load and heating load of three schemes.

and Table 2. Different kinds of building have their unique characteristics and functions, which directly affect the cooling and heating load. The first step is to analyze and calculate the energy demand side of each kind of individual buildings through simulations.

EnergyPlus is used to model hourly cooling and heating load as well as energy consumption of different building types. The models are established according to the shape and size of actual designed buildings. The materials of roofs, walls and windows in the model are same as what building code in this area is required. In addition, practical test is performed in several sample rooms in this project to obtain heat transfer coefficient of roof, wall and window, transmittance of windows, air tightness of external doors, etc. All models are supposed to be built close to reality as far as possible, and can reflect cooling and heating load as well as energy consumption level of real buildings.

Table 7
Survey data and simulated used for economic calculation.

Scheme No. 1			
Survey data		Simulated data	
Equipment cost (Yuan/kW)	1200	Design cooling load (MW)	24.00
Equipment cost (USD/kW)	187.56		
Service life (year)	10–15	Cooling energy consumption (MWh/year)	8693
Electricity (Yuan/kWh)	1	Heating energy consumption (MWh/year)	4638
Electricity (USD/kWh)	0.16		
Scheme No. 2			
Survey data		Simulated data	
Chiller (Yuan/kW cooling load)	650	Design cooling load (MW)	18.58
Chiller (USD/kW cooling load)	101.60		
End-use (Yuan/kW cooling load)	200	Design heating load (MW)	9.65
End-use (USD/kW cooling load)	31.26		
Cooling tower (Yuan/kW cooling load)	40	Fan/Pump energy consumption (MWh/year)	2890
Cooling tower (USD/kW cooling load)	6.25		
Pump, controller et al. (Yuan/kW cooling load)	200	Chiller energy consumption (MWh/year)	5577
Pump, controller et al. (USD/kW cooling load)	31.26		
Distribution system (Million Yuan)	9.27	Boiler energy consumption (km^3/year)	928
Distribution system (Million USD)	1.45		
Gas boiler (Yuan/kW heating load)	550		
Gas boiler (USD/kW heating load)	85.97		
Total number of basement plants	13		
Cost of each plant (Million Yuan)	0.2		
Cost of each plant (Million USD)	0.03		
Service life (year)	15 ~ 20		
Plant staff salary (Million Yuan)	0.06		
Plant staff salary (Million USD)	0.01		
Staff (person/(plant·year))	1		
Electricity (Yuan/kWh)	1		
Electricity (USD/kWh)	0.16		
Natural gas (Yuan/m^3)	3		
Natural gas (USD/m^3)	0.47		
Scheme No. 3			
Survey data		Simulated data	
Chiller (Yuan/kW cooling load)	650	Design cooling load (MW)	15.02
Chiller (USD/kW cooling load)	101.60		
End-use (Yuan/kW cooling load)	200	Design heating load (MW)	8.48
End-use (USD/kW cooling load)	31.26		
Cooling tower (Yuan/kW cooling load)	40	Fan/Pump energy consumption (MWh/year)	2890
Cooling tower (USD/kW cooling load)	6.25		
Pump, controller et al. (Yuan/kW cooling load)	200	Chiller energy consumption (MWh/year)	5228
Pump, controller et al. (USD/kW cooling load)	31.26		
Distribution system (Million Yuan)	1154	Boiler energy consumption (km^3/year)	928
Distribution system (Million USD)	180.37		
Gas boiler (Yuan/kW heating load)	550		
Gas boiler (USD/kW heating load)	85.97		
Total number of independent plants	4		
	0.63		
Cost of each plant (Million Yuan)	1		
Cost of each plant (Million USD)	0.16		
Service life (year)	15 ~ 20		
Plant staff salary (Million Yuan)	0.06		
Plant staff salary (Million USD)	0.01		
Staff (person/(plant·year))	1		
Electricity (Yuan/kWh)	1		
Electricity (USD/kWh)	0.16		
Natural gas (Yuan/m^3)	3		
Natural gas (USD/m^3)	0.47		

4. Results and discussion

In this case, methods mentioned in subsection 2.1 are elaborated. The site survey method is not illustrated separately but integrated into other methods as supplementary information.

4.1. Load superposition

4.1.1. Load superposition based on load index

Load index, formulated in the national or local standards (In the paper, Lu, 2008 and GB50189, 2005 are used), refer to the cooling and heating load of different building types in the planning area. They are shown in the second and third columns of Table 3. Simulated peak cooling and heating load are shown in columns 4 and 5 of Table 3. Generally, the cooling and heating load based on building code index is relatively large. In this case study, a simple comparison is made. The contrast between index selected from handbook (Tabulated values from the construction code) and simulated result is presented in Fig. 4. It can be easily observed that the index is 1.0–2.6 times larger than the simulated data. Building code requirement is larger than the simulated peak load because load index is used for sizing equipment in each kind of individual buildings, rather than trying to reflect the real operations buildings.

In design the overall energy system, the building code in this region defines air-conditioning system simultaneity factor of different functional zones can be obtained, as illustrated in Fig. 5 (GB50189, 2005; Lu, 2008).

In this region, there is cooling-dominated climate and therefore, energy system for HVAC is sized according to cooling load. Based on simultaneity factor method, peak cooling load is 103 W/m^2 at 2:00 p.m., which is calculated by cooling load index multiplied by simultaneity factor in different building types, referring to Eqs. (1) and (2). However, if calculated by simulation method presented in subsection 2.1.3, see Eqs. (3) and (4), the peak cooling load appears at 5:00 p.m. with the value of 69 W/m^2.

According to the above analysis, following conclusions can be drawn: (1) The value of peak cooling load calculated by simultaneity factor method is normally too conservative at regional level, and the peak load 1.5 times larger than what is computed by simulation method. (2) Simulation results can reflect the reasonable peak cooling load because it can simulate the thermal inertia of building envelope thermal delay effect.

4.1.2. Load superposition based on simulation

Simulated peak cooling and heating load index of different functional buildings is shown in Table 4. Total cooling and heating load of the region are the summations of the loads from all different building types, which is 25.07 MW and 13.33 MW respectively. Superposed peak cooling and heating load index of each single zone is presented in Table 5. Similarly, total cooling and heating load of the region are 20.76 MW and 10.80 MW respectively. Compared with the results in Table 4, total peak cooling and heating load are declined by 17.2% and 19.0%. Superposed peak cooling and heating load index of multiple zones is illustrated in Table 6. Total peak cooling and heating load of the planning area are 17.40 MW and 9.70 MW respectively. Similarly total peak cooling and heating load are reduced by 30.6% and 27.2% compared with the results in Table 4.

The way of zone partition in Table 5 is based on the planning and positioning of the local government. For this reason, the building types of a region are relatively uniform and commercial buildings are separate from residential buildings. And the subdivision approach in Table 6 takes the following 3 factors into full account: (1) Location proximity principle. Adjacent buildings should be divided into a same zone and there is no jumping subdivision. (2) Suitable size. The superimposed area is not the bigger the better. We should seek a balance between the load superposition effect and the cost of pipe network and energy stations. Considering constraining factors of planning terrain, we conclude that the maximum distance of outdoor pipe network should not exceed 1000 m. (3) Diversification principle. The more diversified building types are contained in the same region, the more ideal the load superposition effect will be, and vice versa.

Table 8
Result of economic calculation with the minimum service life of system.

Scheme	No. 1	No. 2	No. 3
Service life (year)	10	15	15
Total initial cost (Million Yuan)	28.80	37.31	36.67
Total initial cost (Million USD)	4.50	5.83	5.73
Annual initial cost (Million Yuan/year)	2.88	2.49	2.44
Annual initial cost (Million USD/year)	0.45	0.39	0.38
Annual operation and maintenance cost (Million Yuan/year)	16.48	14.51	13.83
Annual operation and maintenance cost (Million USD/year)	2.58	2.27	2.16
Annual cost (Million Yuan/year)	19.36	17.00	16.27
Annual cost (Million USD/year)	3.03	2.66	2.54

4.2. Comparison of different system schemes

4.2.1. Analysis of different system schemes

According to the different energy schemes listed in 2.2 and the load superposition results in Section 4.1.2, the approach using the three schemes separately are analyzed in below. Since the meditation hall is isolated from other areas and an independent system is dedicated for that part, it is not taken into consideration in this part.

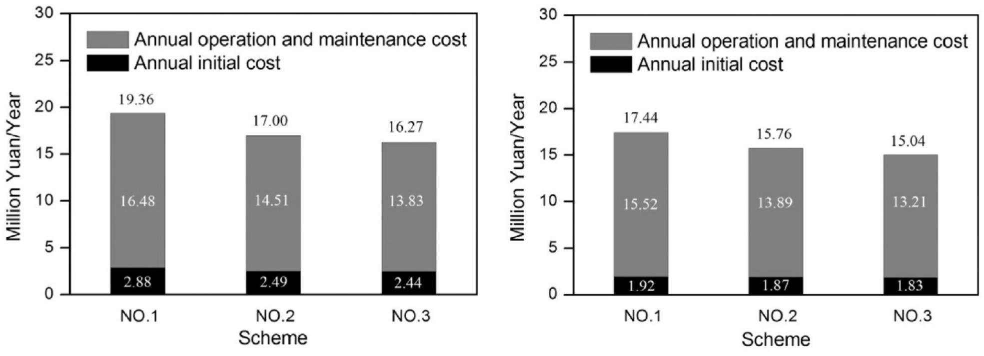
Scheme 1 is a fully distributed system. In this scheme VRV (variable refrigerant volume) system or conventional split household air conditioning is adopted. There is no effect of superposition. Design cooling and heating load is calculated by simulated peak load multiplied by safety factors. According to common engineering practice and local code requirement for HVAC (GB 50736, 2012), except for water-cold-chiller, the sizing factor of the other HVAC systems is 1.1. The VRV system or ordinary household air conditioning is selected according to design cooling load. As listed in Table 4, the total simulated peak cooling load and heating load are 21.84 MW and 11.63 MW, so the design cooling and heating load are 24.00 MW and 12.80 MW respectively.

Scheme 2 is a small-scale central system distributed in the region. The simulated peak cooling and heating loads are 17.53 MW and 9.10 MW respectively (excluding meditation hall), as shown in Table 5. Likewise, there is no need to consider safety coefficient (GB 50736, 2012). However, the energy loss of distribution system should not be controlled within 6% in centralized cooling or heating system (GB 50189, 2005). The ratio of distribution system energy loss is chosen as 6%, so the design cooling load is 18.58 MW and the design heating load is 9.65 MW.

Scheme 3 is a regionally central system. All the regions in this planning area are divided into four larger regions ABLK, CEIJMN, DH and FO, as presented in Table 6. And in each larger region a regional central system is configured. The simulated peak cooling load and heating load are 14.17 MW and 8.00 MW respectively (excluding meditation

Table 9
Result of economic calculation with the maximum service life of system.

Scheme	No. 1	No. 2	No. 3
Service life (year)	15	20	20
Total initial cost (Million Yuan)	28.80	37.31	36.67
Total initial cost (Million USD)	4.50	5.83	5.73
Annual initial cost (Million Yuan/year)	1.92	1.87	1.83
Annual initial cost (Million USD/year)	0.30	0.29	0.29
Annual operation and maintenance cost (Million Yuan/year)	15.52	13.89	13.21
Annual operation and maintenance cost (Million USD/year)	2.43	2.17	2.06
Annual cost (Million Yuan/year)	17.44	15.76	15.04
Annual cost (Million USD/year)	2.73	2.46	2.35



(a) Minimum service life (b) Maximum service life

Fig. 7. Annual cost.

hall), as seen from Table 5. Likewise, the sizing factor is not considered and ratio of distribution system energy loss is also 6%. So the design cooling and heating load in this scheme is 15.02 MW and 8.48 MW, respectively.

Through above analysis, it can be seen that the design cooling and heating load in Scheme 3 are both the lowest, see Fig. 6. After superimposition, the design cooling and heating load are declined to 15.02 MW and 8.48 MW from 24.00 MW and 12.80 MW respectively.

4.2.2. Economic analysis

To estimate initial costs, three top equipment companies are surveyed and the prices from these three suppliers are averaged to calculate system cost. The costs of equipment, distribution system and plant construction contain not only equipment and material cost but also the installation cost and worker cost. To get accurate simulated data, all the models are built completely in accordance with the construction drawings and the performance curves of equipment of HVAC system are entirely based on the sample data from the equipment manufacturers. The data used for economic calculation is listed in Table 7. The calculation results under minimum and maximum service life are presented in Tables 8 and 9, respectively.

According to the calculation in Sections 4.1.2 and 4.2.1, the added peak of every individual building is much higher than the overall load curve by adding those load curves together. In other words, the effect of load superposition and shifting in Scheme 3 is the best. Furthermore, because of the load superposition and peak demand shifting effect, annual cost of Scheme 3 decreases as well, see Tables 8, 9 and Fig. 7. This shows that the load superposition in demand side can not only alleviate the peak load pressure of power grid but also bring economic benefits to users to some extent. Other researchers have reached similar conclusion in these references (Kurz, 2002; Middelberg et al., 2009; Wilhite et al., 2000).

5. Conclusions

Through a case study, several conclusions can be drawn and some suggestions of load superposition are proposed as following.

In urban design, seldom careful consideration has been given to the energy system spatial optimization. Buildings functions areas are determined before calculating the energy impact and energy system pattern. Conventional method of calculating cooling and heating load index, and then determine the utility station sizing is wasteful. Load index method cannot reflect building thermal delay effect and difference in different buildings' peak load time. For example, in the case study, peak cooling load of one building is 69 W/m^2 at 5:00 p.m. and the peak load of the other is 103 W/m^2 at 2:00 p.m. As long as the time and technology are both permitted, it is recommended to utilize simulation method to obtain more reliable and accurate demand side load at regional level.

Preliminary site survey is recommended to perform for investigating actual information of energy use and local weather. Measured data in an established model has a great significance, if possible.

Three principles are observed when performing demand side load superposition. (1) Location proximity principle, avoiding long line in between subdivision. (2) Moderate size principle, keeping energy system moderate small, balancing load superposition effect and initial investment. (3) Diversification principle, the more diversified building types are contained in the same region, the more ideal is the load superposition effect.

The load superposition in demand side can not only alleviate the peak load pressure of power grid but also bring economic benefits to users to some extent. The load superposition and shifting method can be used in single large buildings as well. For the single building with large area and volume, such as commercial buildings more than 50,000m^2, the energy load superposition can be used among different functional parts within itself. This point needs further research and more cases to be illustrated.

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