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A COMBINED APPROACH FOR ANALYZING THE IMPACT OF SPATIAL CLUSTERING ON LARGE-SCALE URBAN ENERGY SYSTEM OPTIMIZATION

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ABSTRACT

Modelling and optimization of a large-scale urban energy system with sufficient spatial resolution is a complex challenge. By proper clustering technique, a large-scale problem could possibly be divided into small ones with high spatial resolution and accuracy. Existing literature tends to lower the complexity of large-scale urban energy system problem by accumulating demand profiles on the spatial dimension. This study proposed a new combined clustering approach which considers not only the spatial dimensions, but also the load characteristic of all buildings to solve a large-scale urban energy-water nexus optimization problem. The load complementarity can level off the total demand profile, which is helpful to obtain more economic benefit. The approach can divide district with a large number of buildings into small clusters including fewer buildings. By using complementarity indexes, the load heterogeneity of each cluster can be assessed. And the density of each cluster is used to investigate the distance among buildings within the same cluster. The combined clustering approach consists of two different routes: one is to lower down complementarity index with density as constraints; the other one is evaluating both two criteria simultaneously as a single objective. Through a case study, the proposed combined clustering approach can generate a new clustering map and finally save 4.4% total cost compared to density-based clustering approach.

Keywords: urban energy system, combined clustering, large scale, OPTICS, energy-water nexus, demand complementarity

NONMENCLATURE

Abbreviations	
AE	alkaline electrolyser
ATC	annualized total cost
CAPEX	capital expenditure
CHP	combined heating and power
OPEX	operating expense
PEME	proton exchange membrane electrolyser
STDEV	standard deviation
PAR	peak to average ratio
Symbols	
E^{dem}	electrical demand
E^{im}	electricity imported from main grid
E^{CHP}	CHP electricity generation
E^{ex}	electricity fed into main grid
E^{ec}	electricity consumed by electrical chiller
E^{hp}	electricity consumed by heat pump
E^{AE}	electricity consumed by AE
E^{PEME}	electricity consumed by PEME
E^{comp}	electricity consumed by hydrogen compressor
E^{bcomp}	electricity consumed by booster compressor
E^{pv}	PV electricity generation

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1. INTRODUCTION

Sustainable urban energy system (UES) has already become a more environmental-friendly option to fulfill the energy demand of buildings by combining local renewable energy sources [1]. It can be built as decentralized mode to solve large scale system optimal problems with significant economic benefits compared to conventional ones [2]. Besides, such problems of dealing with design or operation plan for decentralized urban energy system are usually formulated as Mix Integer Linear Programming (MILP) by researchers [3], [4]. In addition, the inter-relation of production and consumption between energy and water are increasingly important, which will influence the city planning and management [5]. It is essential to consider the urban energy-water nexus system problem from economic or other objective aspects.

Moreover, solving large scale energy system problems through MILP can be computationally time-consuming. This is caused by the large number of integer variables and model constraints. Spatial clustering approach for neighborhood or larger area is a commonly used techniques to reduce problem scale so as to save solving time and increase solution accuracy [6], [7]. Meanwhile, recent study [8] shows that demand complementarity is also a factor to lower down the final system cost by leveling off the total demand profile. So, it is valuable to consider both spatial and load characteristics while dividing buildings into different clusters.

2. COMBINED CLUSTERING APPROACH

The proposed combined clustering approach considers not only the spatial characteristics of each building but also the load complementarity in every cluster. For the density-based clustering method (OPTICS), it divides all buildings into several clusters by evaluating the distance between each building while the buildings those are too far away from their neighbors, where the distance among them are larger than the assigned threshold, will be regarded as outliers [9]. This decomposition process can reduce the computational time and improve the accuracy of solution. The cluster with the lowest density indicates the shortest mean distance of each building within it. As for the load-based clustering process, two complementarity indexes are utilized, i.e., STDEV and PAR, to explore three types of loads' characteristics. The lower the complementarity index, the more heterogeneous the total load profile is.

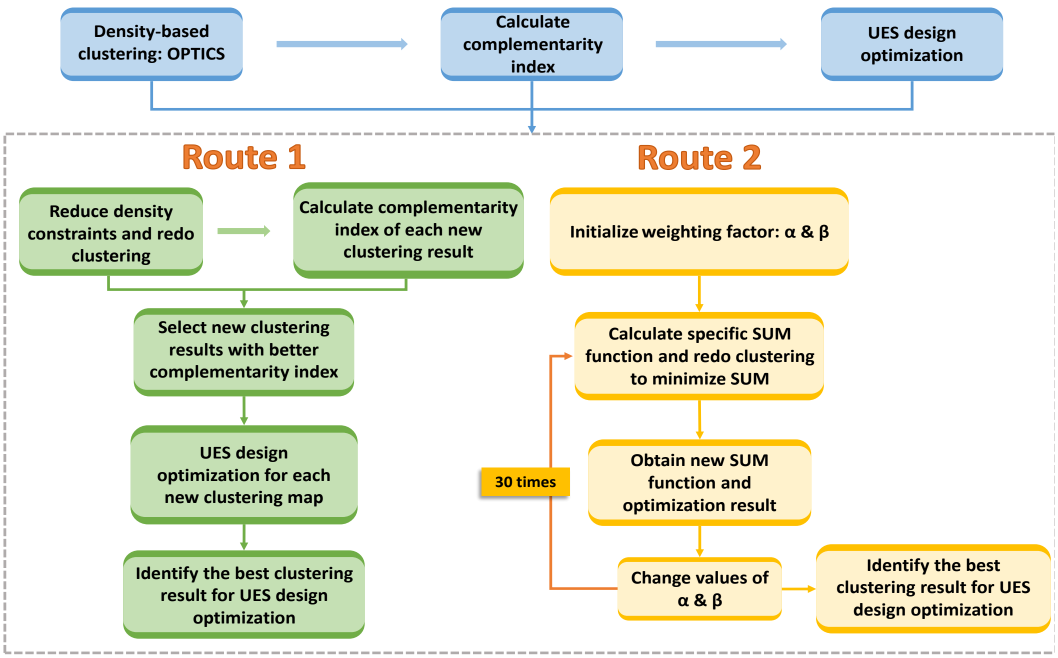

Fig 1 The structure of the proposed combined clustering approach.

The approach can be further divided into two routes, where the order of dealing with two criteria are distinguished. The first one evaluates the load criterion with the density as a constraint, while the second one explores two criteria simultaneously.

2.1 Route 1

Based on the basic clustering results, the density of each cluster will be increased by 10% to obtain new clustering maps. The new maps forming process consists of two strategies: combining two basic clusters as one or adding one outlier building in a basic cluster. Then, complementarity index of each new cluster, with higher density than before, is calculated each time and the results showing lower index value will be selected. In addition, new clustering maps are generated and the system design optimization module can be further applied for each new clustering result. At last, the new clustering map with the lowest system cost result will be regarded as the final option.

2.2 Route 2

Similar with the former route, Route 2 is based on basic density clustering results as well. A SUM function is formulated to evaluate two criteria simultaneously, as shown in Eq. 1.

$$SUM = \alpha \times DT + \beta \times \mathrm{CI} \quad (1)$$

where α and β are weighting factors. *DT* is DENSITY and *CI* denotes Complementarity Index. The basic SUM function will be calculated with the initialized weighting factor values. Then, the similar process as stated in Route 1 can generate a new clustering map with the lowest SUM function value. Based on the updated clustering results, the energy system design can be further optimized. Furthermore, a tuning loop of changing values of α and β will be conducted for a sufficient number of times (e.g. 30 times in this case) in the interval [0-1], a specific clustering map with corresponding objective optimization results will be generated each time. At last, the clustering map with the best objective results will be selected.

3. MODEL DESCRIPTION

The proposed structure of future urban energy-water nexus system is illustrated by Fig 2. An energy hub model is formulated with five types of energy balances, namely, heating, cooling, electricity, water and hydrogen. The water from the city grid or rainwater collection system will fulfill the water demand of energy supply techniques, such as boiler, fuel cell and chiller. Meanwhile, two available hydrogen production technologies, i.e., AE and PEME, will satisfy the needs of fuel cell vehicles. A brief description of the mathematical equation is as follows. Eq. 2 displays the energy balance.

$$\begin{aligned} &E_{s,h}^{\mathrm{dem}} + E_{s,h}^{\mathrm{ec}} + E_{s,h}^{\mathrm{ex}} + E_{s,h}^{\mathrm{hp}} + E_{s,h}^{AE} + E_{s,h}^{PEME} + E_{s,h}^{comp} + E_{s,h}^{bcomp} \\ &= E_{s,h}^{\mathrm{pv}} + E_{s,h}^{\mathrm{im}} + E_{s,h}^{\mathrm{CHP}} \qquad \forall s,h \end{aligned} \quad (2)$$

where E^{dem}, E^{ec}, E^{hp}, E^{AE}, E^{PEME}, E^{comp}, E^{bcomp}, and E^{ex} are electricity demand and power consumed by electrical chiller, heat pump, AE, PEME, hydrogen compressor, booster compressor and electricity exported, respectively; E^{pv}, E^{CHP} and E^{im} are power generated by PV, CHP and imported from grid, respectively.

The objective function is to minimize the annualized total cost (ATC) for design and operation, including the pipe cost. It consists of the capital expenditure (CAPEX) and the operating expense (OPEX), where OPEX includes the fuel cost, the maintenance cost and the cost of water and electricity imported. All the cost values are counted in US dollars ($) in the present study.

$$CAPEX = \sum_{t} CAP_t \times \mathrm{C}_t^{\mathrm{CAP}} \times \mathrm{CRF} + \mathrm{C}_{\mathrm{pipe}}^{\mathrm{CAP}} \times \mathrm{CRF} \quad \forall t \quad (3)$$

$$OPEX = \sum_{s,h} [FC_{s,h} + MC_{s,h} + WC_{s,h} + GC_{s,h}] \quad \forall s,h \quad (4)$$

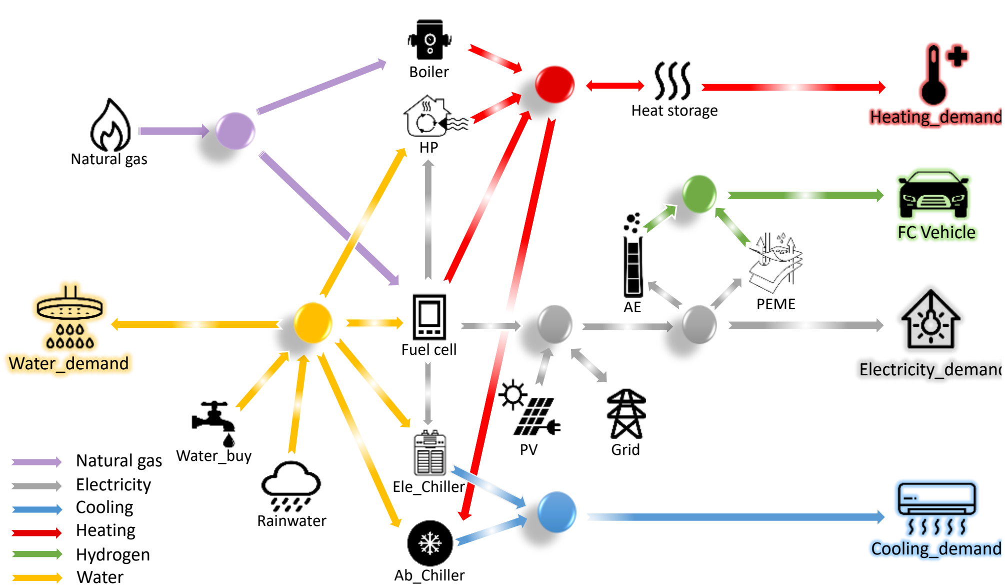

Fig 2 Illustration of a future urban energy-water nexus system.

where CRF is the capital recovery factor, *FC*, *MC*, *WC*, *GC* are fuel cost, maintenance cost, water cost and grid cost, s and h represent seasons and hours, respectively.

energy supply techniques and OPEX lower down by 4.5% and 4.3%, respectively. The total economic objective (ATC) of basic C2 and the outlier, reduce 4.4% (i.e., $304,699).

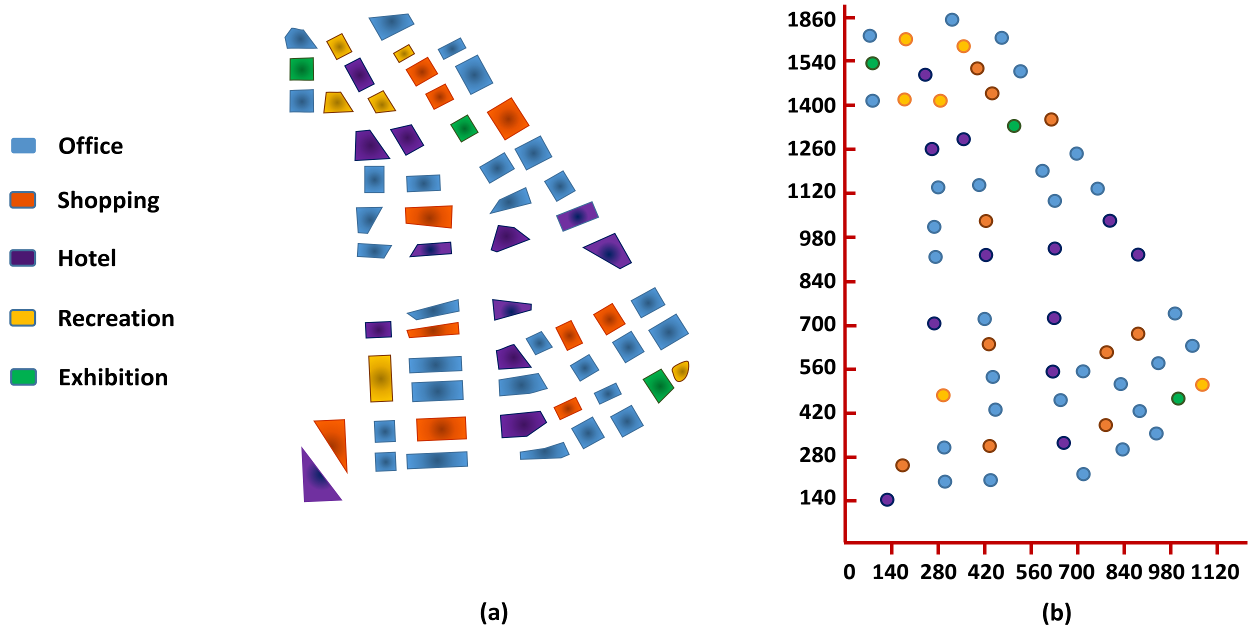

Fig 3 Building categories (a) and location map (b) of the case study.

4. CASE STUDY

To verify the proposed combined clustering approach, a case study at a district with 60 buildings in Shanghai, China is conducted. There are five kinds of buildings with various load characteristics in this area, i.e., office, shopping, hotel, recreation and exhibition. Moreover, each building can connect to others with flexible network connectivity. In addition, the energy hub will be built in the building with the highest energy demand in each cluster, while the outlier buildings will build their own systems.

The system model is built in GAMS calling CPLEX solver on a PC with CPU of Core i7, 8 GB RAM, the CPU time ranges from 35 to 45 seconds for different clusters. The pre-clustering process is conducted in Spyder using Python 3.6.

5. PRELIMINARY RESULTS

Based on the final cost (ATC) results obtained from Route 1, the difference of basic and new clustering map is illustrated by Fig 4.

By considering both density and load characteristics, cluster 2 (C2) adds one more building into the original clustering result with a longer network. In this case, the pipe cost of basic C2 increases from $70,523 to $82,763. Nevertheless, as indicated by Fig 5, both capital cost of

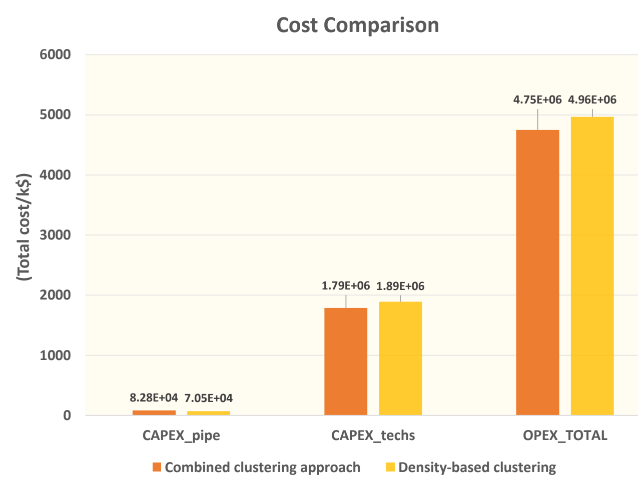

Fig 5 Cost results comparison.

Compared to the existing method, which either aggregates all buildings as one cluster with less resolution or models for individual building with long computational time (up to days), the proposed method achieves a compromise with sufficient efficiency and accuracy. Moreover, as a large-scale district development tends to be phased in stages in practice, the proposed method can be an effective decision-supportive tool for the design of district-level urban energy systems.

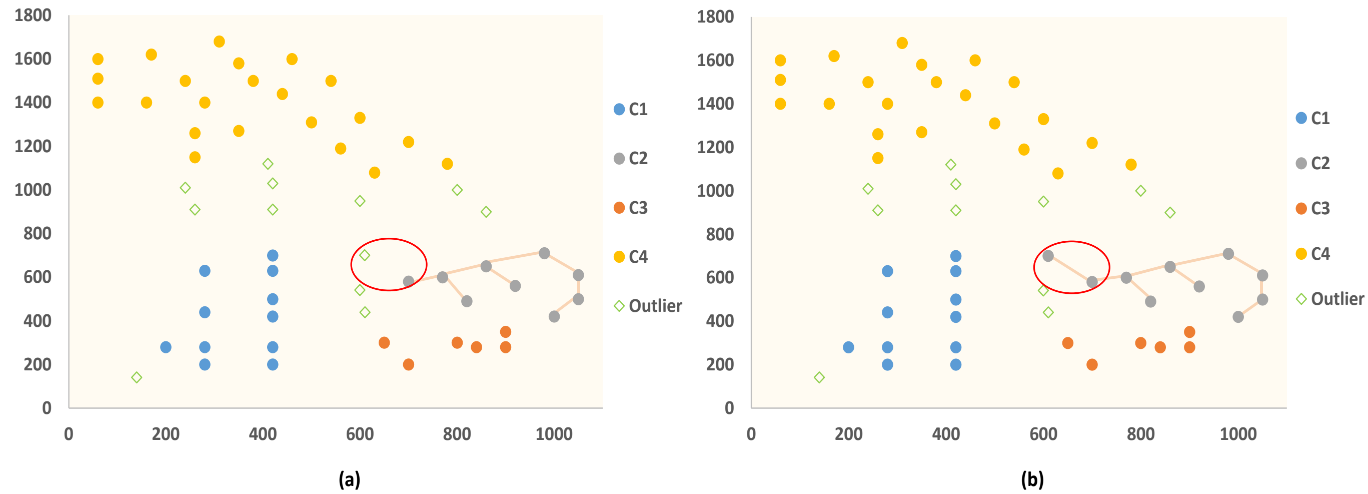

Fig 4 Comparison of clustering results (a) basic clustering map through density-based approach (b) new clustering map through combined clustering approach.

6. CONCLUSION AND FUTURE WORK

The proposed combined clustering approach divides larger scale problems into smaller ones by taking buildings' load characteristics into consideration. It can be an efficient solution for solving the optimization problem of future urban nexus systems. The results indicate that building types can affect the heterogeneity of total demand profile in each cluster and further influence the CAPEX and OPEX of the nexus system. In addition, a cluster with lower heterogeneous index may reduce final economic results.

In future work, Route 2 of the combined clustering approach will be further explored to solve the optimization problem. Comparisons between two routes will be conducted in-depth. Moreover, the impacts of two criteria on the final cost results will be investigated. Besides, the applicability of different physical clustering method, e.g., K-means and OPTICS, will be also studied to explore the effect to districts with various spatial characteristics.

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