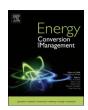
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Decomposing core energy factor structure of U.S. commercial buildings through clustering around latent variables with Random Forest on largescale mixed data



Endong Wang

Construction Management, The University of Tennessee, EMCS 326B, Chattanooga, TN 37403, USA

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ABSTRACT

Accurate selection of explanatory factors is critical for precise quantitative energy analysis (e.g. benchmarking and predicting) to support the sustainability strategy in commercial building sector. Nevertheless, the generic guiding information on factor selection lacks. This paper addresses the research gap to decompose building energy factor structure (i.e. the interaction structure among the factors which affect building energy performance) particularly at a nation level for factor selection. Specifically, an iterative approach is developed by integrating the technical strengths of Variable Clustering and Random Forest to remove collinearity, redundancy and nonrelevance. Based on a comprehensive source database extracted from a multiframe country-wide survey, the core energy factor space is revealed for 2779 commercial buildings in the U.S. In particular, 36 principal factors are identified to reliably explain building energy efficiency variations. These factors are of sufficient independence and heterogeneity which may benefit the development of parsimonious energy modeling frameworks. The robustness of the deciphered factor structure and the representativeness of the recognized critical factors are numerically validated. These acquired results can be useful for informed decision analysis and rational policy design in commercial building sector with a lighter data burden.

1. Introduction

Substantially reducing energy usage in commercial buildings through aimful efficiency initiatives is of paramount significance to the overall success of sustainability strategy in the U.S. given its grand share in the nationwide total building energy consumption. Per the latest report from the U.S. Energy Information Administration (EIA) [1], commercial building sector consumed 4.29 quintillion joules of primary energy, clarifying more than 38% of the aggregated amount attributed to all the extant U.S. buildings. In viewing of this fact, a wide range of conservation ordinances, retrofitting plans, renewable energy incentives at either local or federal level are strategically implemented [2,3]. Regardless of specific objectives and execution procedures, these efficiency programs often commonly require quantitative energy analysis on fault detection, usage projection, etc., to lay solid information bases for decision making or policy design. For instance, robust quantitative benchmarks [4-5] are usually desired for evaluating energy performance to locate the inefficiencies in commercial buildings for drawing sensible decisions during thermal retrofitting.

Statistical models which generate energy performance information essentially by the numerical analysis of available data counting on the

scoped energy variables, appear more attractive in commercial sector over the thermodynamics-based approach [3,6–9]. This turns particularly true for a large-scale building energy investigation which typically occurs in energy efficiency domain, because statistical methods show more capability of accounting for the diverse energy aspects of occupants, structure, environment and geography [3]. From this angle, an extensive number of statistical procedures have been proposed for divergent efficiency upgrading purposes with varying complexities. These procedures typically range from the simple univariate statistical analysis (e.g. energy use intensity (EUI) based single-factor energy benchmarking) [10], to the multi-dimensional machine learning algorithms [9,11] (e.g., neural networks for forecasting) [7]. While these quantitative frameworks often have unequal purposes and complexities, the explanatory variables which characterize relevant factors and potentially affect energy performance are often commonly critical to them.

Nevertheless, the pool of energy factors that have been reported to possibly influence the efficiency of commercial buildings is extremely large due to the complicated interactions (either physical or non-physical) among energy systems and the surrounding built environments. Further, these documented factors are associated with distinct energy perspectives (e.g. the degree days regarding climate conditions,

Abbreviations NWL main cooling replaced NWM main heating replaced NWR number of employees ACW individual room air conditioners OCS occupancy sensors	
NWR number of employees	
AMI advanced smart metering ONE single activity in building	
ANN artificial neutral network OOB out-of-bag	
ATT attic OP4 open 24 h a day	
AWN external overhangs or awnings OPE open on weekend	
BLD building shape OPF open during week	
BOI boilers inside the building OWC owner occupied or leased to tenar	nts
BUL incandescent bulbs OWN building owner	
CAP electricity generation capability OWR owner operate and maintain syste	ms
CEN census division PBA principal building activity	
CFL compact fluorescent bulbs PBS building activity	
CHI central chillers inside the building PCC number of computers category	
COL percent cooled PCM computers used	
COO energy used for cooking PCT number of computers	
COP photocopiers PKG packaged heating units	
DAL percent daylight PKL packaged air conditioning units	
DAY daylight harvesting PKT lighted parking area	
DIM multi-level lighting or dimming PLG plug load control	
DRL demand responsive lighting PRU bottled gas/liquid petroleum/prop	
ELH electricity used for main heating RCA residential type central air conditions and the state of the state	=
ELK electricity for cooking RDC cooling reduced during 24-h period	
ELM electricity for manufacturing RDH heating reduced during 24-h period	ou
ELW electricity for water heating RDL lighting reduced during off hours EMC building automation system REB plumbing system upgrade	
ENR energy management plan REC HVAC equipment upgrade	
EQG equal glass on all sides REE electrical upgrade	
EVA evaporative or swamp coolers REF roof replacement	
FAC of a multibuilding complex REG census region	
FAX FAX machines REL reflective window glass	
FKU fuel oil/diesel/kerosene used REN window replacement	
FLC floor to ceiling height RER structural upgrade	
FLU fluorescent bulbs RES insulation upgrade	
FUR furnaces that heat air directly RET lighting upgrade	
GEN energy for electricity generation REV renovated	
GLS percent of exterior glass REW exterior wall replacement	
GOV government owned RFC number of compact refrigerators	
HAL halogen bulbs RFG count of closed-case refrigeration	units
HEA percent heated RFI number of walk-in units	
HID high intensity discharge bulbs RFN roof material	
HTC heat pumps for cooling RFO cool roof materials	
HTP heat pumps for heating RFP number of open-case refrigeration	units
HTV heating ventilation RFQ refrigeration	_
LAP number of laptops category RFS number of residential refrigerators	S
LAT number of laptops RFT roof tilt	
LED light-emitting diode bulbs RFV count of vending machines	
LNH lit off hours category RGI number of ice makers LOH lit when open category RGS cash registers	
LOH lit when open category RGS cash registers LTE percent of exterior lighted RGT number of cash registers	
LTN percent lit off hours RS random sampling	
LTO percent lit when open SCH light scheduling	
MAI main heating equipment SEN number of servers	
MAL main cooling equipment SER number of servers category	
MAN energy used for manufacturing SKY skylights or atriums	
MAT regular HVAC maintenance SQF building area category	
MLR multiple linear regression SQT building area	
MLT multiple monitors SVM support vector machine	
MON months in use TIN tinted window glass	
NFO number of floors TVV television or video displays	
NGU natural gas used WAT energy used for water heating	
NOA number of businesses category WIN window glass type	
NOC number of businesses WKC weekly hours category	

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