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Office building cooling load reduction using thermal analysis method – A case study

Wan Iman Wan Mohd Nazi *, Mohammad Royapoor, Yaodong Wang, Anthony Paul Roskilly

Sir Joseph Swan Centre for Energy Research, Stephenson Building, Newcastle University, Newcastle NE1 7RU, United Kingdom

HIGHLIGHTS

- Proposed a retrofit methods centered on a simulation based thermal analysis.
- An office building in tropical condition was used as a case study.
- Actual energy and indoor environmental measurements were analyzed.
- Retrofit strategies were derived from 3 stages of thermal analysis.
- Simulation and actual implementation results are presented.

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ABSTRACT

Buildings worldwide consume approximately 45% of primary energy sources, making it the single largest energy consumption sector. The importance of improving a building's energy performance was emphasized by the government with the enforcement of sustainable building policies. Article 9 of the Directive 2010/31/EU of the European Parliament and the Council (19th May 2010) on the energy performance of buildings states the importance of stimulating refurbishment of existing buildings into near zero-energy buildings. However, the effectiveness of the process depends on the basic building structure and the refurbishment designs. Hence, methods to find the effective strategies for retrofitting and modelling to predict energy reduction is vital. Unlike the previous studies, this paper presents a method for a deep building retrofit based on the whole building's thermal analysis specifically for cooling demand countries. This work set against recommended best practice office building energy benchmarks in Malaysia, and following a comprehensive building audit, a retrofit strategy was proposed based on target building's thermal analysis with cooling demand reduction in particular focus. It was found that 71% of the building's heat gain emanated from its lighting system and solar heat gain through windows. A 40.2% reduction in the building's cooling load is estimated to reduce 47% of the total energy consumption. A comparison of the actual and simulated energy results suggested that the simulation made under predicted the energy reduction by 4.3%.

1. Introduction

Buildings account for a large share in global energy demand. They consumed 30% of the primary energy in South East Asia [1], 40% in International Energy Agency (IEA) countries [2], Europe [3,4] and 50% globally [5]. The figure is expected to increase in the future due to the growth in population, development, increasing demand for improved building's services and comfort levels and the rise in time spent in buildings [6]. This statement is supported by the building energy demand annual growth rate in several countries (Table 1) extracted from Perez-Lombard et al. [6] and South East Asia Energy Outlook report by IEA [1].

The call for improvement in building energy efficiency was highlighted by changes in sustainable building policies, legislation and incentives. Due to high numbers of unsustainable existing buildings, great interest was paid on building refurbishment to increase energy efficiency [7]. In many cases this process is more economical and has a less environmental impact compared to a complete demolition and rebuild [7–9]. However, the effectiveness of the process depends on the basic building structure and the

* Corresponding author at: Sir Joseph Swan Centre for Energy Research, 2nd Floor, Stephenson Building, Newcastle University, Newcastle Upon Tyne NE17RU, United Kingdom. Tel.: +44 7719757554; fax: +44 (0)191 208 6920.

E-mail addresses: w.i.b.wan-mohd-nazi@ncl.ac.uk (W.I. Wan Mohd Nazi), mohammad.royapoor@ncl.ac.uk (M. Royapoor), yaodong.wang@ncl.ac.uk (Y. Wang), tony.roskilly@ncl.ac.uk (A.P. Roskilly).

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Nomenclature

ACC	annual cooling system's energy consumption
AEC	annual energy consumption
AELC	annual electricity consumption
AHU	air handling unit
BEI	building energy index
BMS	building monitoring system
COP	coefficient of performance
$COP_{chiller}$	coefficient of performance for the GDP's chiller
CO_2	carbon dioxide
C_p	the ratio of cooling system's electricity usage per total building's electricity usage
CV(RMSE)	coefficient of variation of the root mean square error
$CW_{(RTH)}$	chilled water consumption in RTH
DOSH	Malaysia's Department of Safety and Health
EEMs	energy efficiency measurements
$El_{building(kWh)}$	building's electricity consumption
$El_{CS(kWh)}$	electricity consumption for the cooling system's equipment inside the building
$E_{CW(kWh)}$	energy consumption by GDP's chiller in kW h
FA	conditioned building's floor area
G	solar irradiance
GEO	green energy office
GF	ground floor
GDP	gas district cooling plant
HVAC	heating, ventilation and air conditioning
kW h	kilowatt hour
LEO	low energy office
LOR	light output ratio
M	meter
MBE	mean bias error
MF	maintenance factor
M_i	measured data at instantaneous i
N_i	the count of the number of values used in the calculation
PL-C	Philips lamp (compact type)
PL-L	Philips lamp (L type)
P_{sys}	power consumption by lighting system
Q_i	instantaneous room's heat gain
RH	relative humidity
RTH	refrigeration tonne per hour
SHGC	solar heat gain coefficient
SHGW	solar heat gain through windows
S_i	stimulated data at instantaneous i
T	temperature
Ta	outside ambient temperature
Tr	room temperature
U	lamp's utilization factor
U_g	U-value (thermal transmittance) for glazing
VLT	visible light transmission
η_{LS}	lighting system's efficiency
η_L	lamp efficiency
η_g	lamp's gear efficiency
ϕ	luminious flux at task area

refurbishment designs [8,10]. Hence, methods to find effective strategies for retrofitting and modelling to predict energy reduction are vital [9,10]. General energy retrofit guides and energy efficient measures (EEMs) were published by various institutions including the US Department of Energy (US DOE) and ASHRAE (in collaboration with other institutes) [11–13] as a response to the increasing demand for building refurbishment. Nonetheless, retrofit measures may have different impacts on different buildings due to the variance in design and sub-systems, making the retrofit selection very complex [9].

In previous studies, buildings were audited to determine the area of concerns before applying EEMs [14–19] selected based on the multi-objective optimization methods [9,10,20–22] or cost-benefit analysis [23,24]. Mainly, the audit process concerns the end-use energy consumption to determine sector that requires retrofitting but not in depth holistic approach to define the building's parameters that contributing toward the large energy share from the sector. Whereas in early design phase, sensitivity analysis is widely adopted to determine parameters which significantly contributes toward the performance of the design solution [25]. Andarini et al. [26] used a sensitivity analysis to obtain parameters that can significantly reduce cooling demand in a shophouse design for Indonesia climate. A sensitivity analysis was also performed by Yildiz and Arsan [27] to define parameters in an apartment's design which greatly contributes toward heating and cooling load. While Heiselberg et al. [25] studied a wider range of input parameters to determine their impact on the total energy performance of an office building design. Normally, heating and cooling load were assigned as the output variables for the sensitivity analysis as it is a significant energy performance indicator and the major building's energy consumer globally [6,25–29]. Whereas, in cooling-dominated countries, air conditioning dominated the building's energy share [15,27,30]. A study by Aun [31] concluded that Malaysia's office buildings used 64% of the total building's energy for air conditioning. Meanwhile other tropical countries such as Indonesia, Thailand and Singapore, spent 51–59% of the building's energy budget on air conditioning [15,26].

Against this background, this study proposed a retrofit methods based on a whole building thermal analysis to determine parameters contributes toward heat gain. It was developed to cater buildings in cooling dominated countries encompassing a building audit, simulation based whole building thermal analysis, devise energy saving options to reduce the heat gains and hence cooling loads while adhering to thermal comfort and stakeholder's requirement. It is hoped that the steps followed could provide assistance to stakeholders involved in building retrofits (focusing on buildings with cooling systems as its highest energy user) within high-density urban areas in climates similar to that of our case study building.

Table 1
Buildings energy demand annual growth rate by country.

Country	Buildings energy demand annual growth rate (%)	Sources
Europe	1.50	[6]
USA	1.90	[6]
UK	0.50	[6]
Malaysia	3.10	[1]
Spain	4.20	[6]
Indonesia	1.00	[1]
Thailand	2.40	[1]
Philippines	2.00	[1]

2. Methods

The proposed method consists of four steps as summarized in Fig. 1. The process is further elaborated in Sections 2.1–2.4.

2.1. Building energy audit

The Building Energy Index (BEI) was used as a benchmark to compare the current building energy performance with the low energy office (LEO) suggested by the Malaysian government