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Evaluating the Operational Performance in Cairo's Public Administrative Buildings: Stock Characterisation and Typical Energy Use☆

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ABSTRACT

As Egypt relocates its government to the New Administrative Capital, significant investments will be directed towards the renovation and adaptive reuse for Cairo's existing public administrative buildings. Maximising the outcomes from these investments through energy efficiency measures offers a valuable opportunity, yet limited knowledge of building stock characteristics and operational energy performance can potentially hinder the formulation of informed and effective retrofit decisions. This study identifies and examines the stock subject to relocation, providing insights on building age, area, and common architectural characteristics. Applying K-Means clustering by age bands, the analysis identified three primary building groups within this stock: pre-1930 (Khedivial), 1960 s (modernist), and post-1980 (contemporary).

Given that 1960 s buildings were found to represent the largest proportion of the stock, metered energy consumption data for nine buildings as such were collected and analysed. Annual energy data indicate that most buildings consume, on average, approximately half of a World Bank-adopted benchmark, offering novel projections of potentially diminished retrofit savings. Monthly energy consumption analysis highlighted seasonal energy profiles: a fixed low winter monthly energy use of about 5 % of the annual EUI, contrasting with peak summer monthly energy use of about 13 % of the annual EUI. These typical seasonal profiles helped with evaluating a typical energy end-use breakdown: about 40 % for cooling, and 60 % for lighting and electric equipment combined. Supporting effective retrofit decision-making, this study presented the first known characterisation of Cairo's public administrative building stock, proposed a methodology for analysing metered energy consumption that counteracted data availability limitations, and provided preliminary estimates for energy breakdown by end-use that disentangled the aggregated metering for the fully electrified consumption in Cairo's public administrative buildings.

1. Introduction

The Egyptian government is relocating its headquarters to The New Administrative Capital (NAC) currently under construction east of Cairo. This relocation will leave behind a vacant stock of ∼ 45 public administrative buildings across several urban centres of Cairo. It is planned that these buildings will be refurbished and go through adaptive reuse to as part of visions for revitalizing Cairo [1,2,3]. Aligned with the country's declared climate actions to lower emissions from the built environment[4], integrating energy efficiency measures into the planned refurbishment and repurposing initiatives can offer an opportunity to maximise the benefits from these investments. However, realising these benefits depends on a thorough understanding of the existing operational conditions, which remains largely unknown due to the lack of available evidence.

Critical information gaps persist as there is no comprehensive inventory of the buildings to go through adaptive re-use, as some authorities occupy multiple premises or share buildings with others [5]. Additionally, few case studies have evaluated retrofit savings in public administrative building [6, 7], but it is unclear how representative these cases are of the entire stock. Most baseline benchmarks used in previous studies lacked sufficient validation against empirical evidence, further

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limiting the reliability of retrofit outcomes. These knowledge gaps can pose significant challenges to decision-makers, who are required to assess the suitability and the impact of implementing energy efficiency measures without having sufficient knowledge about baseline conditions.

To examine the knowledge gaps, the literature review will explore the significance and the challenges of characterising Cairo's public administrative buildings and analysing their energy performance, suggesting the importance of validated benchmarks and context-specific empirical evidence. This study aims to bridge these knowledge gaps by achieving the following objectives:

1. Developing an inventory for the public administrative buildings subject to relocation.
2. Characterising the buildings based on their age, gross floor area (GFA), and architectural form/style.
3. Analysing the operational metered energy consumption to understand the seasonal energy variations and evaluate end-use breakdowns.

2. Review of The current Status of Cairo's public administrative buildings

2.1. Building inventory and stock significance

Although the Egyptian government announced the relocation of 34 ministerial buildings, the parliament, the presidential headquarters, the general state authorities, and foreign embassies to the new administrative capital [8,5,9], the exact number of buildings subject to relocation, along with their basic information, could not be obtained from any known inventory available. As undertaking adaptive reuse projects in the existing stock in partnership with private investors is planned[10], estimating the size of the building inventory and analysing its characteristics can be essential for formulating suitable stock-level retrofit plans.

This absence of building data does not reflect the significance of these buildings. Many of the buildings that are planned to be vacated date to the late 19th and mid-20th centuries, holding significant heritage value [11,12,13]. Owing to their relatively large sizes and key locations, these buildings are perceived as landmarks that contribute to the city's identity, presenting both opportunities and challenges for retrofitting [14,15,16].

Moreover, many of the vacated buildings, such as Al-Tahrir, played significant roles in the city's urban fabric as they used to act as hubs that receive hundreds of daily visitors[17,16,18]. These hubs used to attract services such as markets, transportation networks, and accommodation [19,18]. The relocation of the government will affect the surrounding areas, necessitating that the incorporation of building adaptive reuse into a larger urban revitalisation scheme that looks at a district-level master plan[13,3].

2.2. Buildings' operational energy performance

Egypt's public administrative buildings were largely considered by the government to be "energy intensive", reportedly consuming approximately 6 % of the country's total final electricity while constituting only 0.5 % of the number of grid subscribers [20]. With a lack of data available in Egypt on the buildings' operational performance benchmarks, The World Bank & ESMAP [21] estimated that governmental buildings have an annual energy use intensity (EUI) of around 140 kWh/m^2, using this estimated benchmark as a guide for assessing current energy use and identifying potential savings [21]. This estimate was developed using data from local authorities via the *TRACE 2.0* tool, a decision-support system backed by real data collected from local authorities, designed to help policy-makers prioritize energy efficiency interventions at city scale [22].

In Abdelhafez et al. [6], the Petrojet Company's (a public sector office affiliated to the Egyptian Ministry of Petroleum) baseline was estimated to have a total EUI of 134 kWh/m2 per year. However, the models do not seem to have been calibrated against actual meter readings, which could introduce some uncertainty into these figures. Hamada et al. [23] assessed the energy performance of the Central Agency for Public Mobilization and Statistics (CAPMAS) building, establishing a baseline energy consumption of approximately 78 kWh/m2 per year for its current use, with a projected increase to up to 97 kWh/m2 per year if the building's use were repurposed into a private sector office. Similar to the Petrojet study, this model was not validated against metered consumption data.

Yassin et al. [24] developed a theoretical benchmarking framework specifically aimed at improving the energy efficiency of administrative buildings in Egypt. The study emphasised the importance of energy audits and identified critical areas for improvement, including building envelopes, air conditioning systems, and lighting. However, this framework was not found to be inclusive of real-world data, thus not providing estimates of operational building performance benchmarks [24].

Mahmoud et al. [25] conducted a simulation analysis on an administrative building in Cairo where they demonstrated that implementing passive design features—such as courtyards, double-walled envelopes, and window solar heat gain reductions—could reduce annual energy consumption by 11 % compared to conventional designs. However, these findings were based on simulations that were not validated against measured energy performance data [25]. Similarly, Hanna [26] explored incorporating renewable energy sources and retrofit measures in public administrative buildings, but the models do not appear to have been validated against measured data either.

With relevance to public administrative buildings, Elharidi et al. [27,28] provided estimates of energy consumption for 59 office buildings in Alexandria through surveys and energy audits. The findings suggested that naturally ventilated offices without cooling systems had the lowest energy consumption, averaging 23 kWh/m^2 per year, while naturally ventilated offices with cooling systems could consume around 51 kWh/m^2 annually, buildings with mechanical ventilation and split-unit air conditioning were estimated to use about 105 kWh/m^2 per year, and offices with full mechanical ventilation and central HVAC systems were estimated to have the highest consumption, averaging 150 kWh/m^2 per year. In Ibrahim et al. [12], the retrofit of the "La Viennoise" office building in downtown Cairo offered insights demonstrating the potential for energy reductions. Using model calibration against metered data, the building was estimated to have a baseline consumption of 99.7 kWh/m^2 per year.

While these studies provide useful indications of the operational performance of Egypt's public administrative buildings, discrepancies and a lack of empirical validation of public administrative building models suggest that further research is needed to characterise the operational performance of existing public administrative buildings to locate potential areas of performance improvements, and set realistic retrofit targets. This gap is deepened by the lack of knowledge of the building inventory in terms of the number of buildings, their age, areas, and physical characteristics that will be essential to roll out suitable and effective retrofit measures.

3. Methodology

3.1. Data sources

The governmental authorities subject to relocation were initially identified following the government's media announcements [8,5,29,9]. The buildings subject to vacation could be found by looking up and mapping each of the relocated authorities, finding out if these authorities occupy a single or multiple buildings, or are part of a mixed public administrative building. Data such as the buildings' age, area, number of floors, architectural style, and metered energy use were collected for the buildings identified from a number of sources.

Table 1 shows how data sources were used to establish knowledge about each of the building attributes, ordered from most to least important. The following sources were accessed and used, in addition to the data available in the public domain such as the published literature, satellite images, street views, the sources below were used for data collection.

- A two-volume report conducted by the Faculty of Urban and Regional Planning (FURP) in 2006 that studied the governmental/ ministerial district in Downtown Cairo, under direct commission the Ministers' Cabinet in Egypt, hard copies were accessed physically in FURP's library in 2020[30].
- Public administrative building architectural drawing archives accessed in 2021 via Tarek Waly Centre for Architecture and Heritage (TWC).
- Energy bills from Egypt's Electricity Holding Company (EEHC) and Egyptian Gas Company (EGAS) accessed after obtaining relevant official approvals.

3.2. Methods

The study consists of two parts.

Stock characterisation: including stock general data collection and analysis (i.e., building age, area, number of floors, and architectural style) to support stock classification.
Metered energy consumption analysis: including analysing the energy consumption for a sub-stock to understand typical energy use breakdown and evaluate typical patterns of monthly energy use.

3.2.1. Stock characterisation

Buildings constructed in different eras often reflect distinct design standards, materials, technologies, and regulations [31]. This makes age a strong proxy for many critical characteristics that can be more challenging to evaluate, such as construction materials, insulation standards, HVAC systems, building forms, and glazing ratios [31]. Therefore, many databases consider building age as deterministic to building characteristics, such as the US National Renewable Energy Lab's ResStock[32]and the EU Building Stock Observatory [33].

To characterise the stock, data collection was undertaken via the data sources highlighted in 3.1. The stock was classified based on the age-bands using K-means clustering silhouette analysis method, under the condition that each cluster had to comprise at least three buildings – to prevent the formulation of extremely small clusters, given the small number of the sample.

Clarifying how classification can be implemented; silhouette analysis is a method used to specify the optimal number of clusters in a dataset based on the minimising the distances between the datapoints in the same cluster (intra-cluster distance), and maximizing the distances between data points in different clusters (inter-cluster distance), as shown in Fig. 1. Silhouette score will be a value between −1 and 1, where high silhouette scores refer to lower intra-cluster distances and higher inter-cluster distances. Silhouette analysis is a "trial and error" method where a range of different number of clusters is tried, to find out the number of clusters that will return the highest silhouette score, and consider it to be an optimal number of clusters [34]. As illustrated in Fig. 2, three clusters were identified as they obtained the highest silhouette score, as this optimal number of clusters entailed maximising distances between the data points between the different clusters and minimising distances between datapoints inside the same cluster.

Table 1
Data sources.

Attribute	*Sources, ordered from most to least important (left to right)*
Year built	FURP, TWC archives
Location	Authority webpage, google Earth/ Maps, site visits
Floor areas	Satellite images, FURP, TWC archives, Site visits
Number of floors	Google street views, site visits
Metered energy	EEHC- EGAS

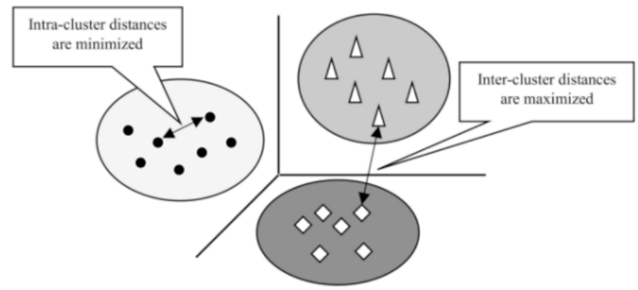

Fig. 1. An illustrative example for forming clusters with minimised intra-cluster distance but maximised inter-cluster distance [35].

Following this classification methodology, building features were analysed qualitatively based on the data collected from the architectural archives and supported by the literature, and quantitively based on the estimated building age, area, number of floors, and nominal depth.

3.2.2. Energy consumption analysis

Following the building characterisation, metered monthly energy consumption data for 11 buildings was collected and analysed. Meter reading dates were found to be slightly inconsistent, changing from one month to another and from one building to another. Reading dates were sometimes undeclared, or taken anytime between 15th and 26th of each calendar month, meaning that monthly readings might not be directly translated into monthly energy consumption. For standardisation, all bill readings were considered to be taken on the 24th, and monthly readings were interpolated according to Equation (1) to reflect the energy consumption for each calendar month, such that:

$$E_i = R_{i+1}*0.80 + R_i*0.20 \quad (1)$$

Where E_i is the estimated energy consumption during month i, R_{i+1} is the recorded meter reading for the following months, and R_i is the recorded reading for the respective months. This assumption means that 80 % of the consumption (~ 24 days) in each monthly bill is attributed to this month, while 20 % (~ 6 days) of the bill is attributed to the month before. To standardise, this "bill to calendar month" conversion approach was implemented to all months, ignoring the caveats mentioned on variable meter reading dates, months' lengths, number of weekends or holidays in a month, etc.

Analysing monthly energy consumption, it was observed that monthly profiles were similar in most buildings such that the energy use annual profile would be almost fixed at low consumption in winter, and peaks in summer between August and September. Given these

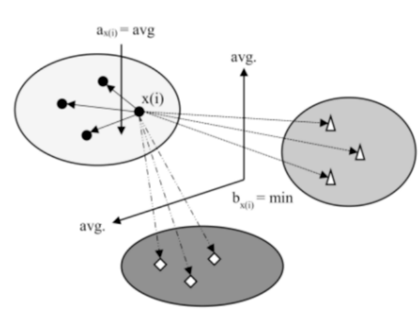

Fig. 2. An illustrative example for Silhouette distance analysis [35].

preliminary observations, a method for predicting a building's monthly energy consumption in terms of its annual consumption, using linear interpolation between winter and summer months, was proposed and tested. Understanding seasonal energy consumption patterns by analysing trends in the monthly consumption aimed at estimating building end-uses, knowing that summer peaks would be attributed to rising cooling loads, while winter troughs would be attributed to lighting and plug-loads.

To test the monthly energy consumption prediction error, the Pearson correlation coefficient (R), the coefficient of determination (R^2), and the coefficient of variance for root mean square error (CVRMSE) were used evaluate the discrepancy between the proposed monthly interpolated values and the metered monthly data to see how reliable this linear interpolation approach can be at predicting monthly consumption. Acceptable thresholds for correlation and R^2 were considered to be higher than or equal to 0.60- based on Priest [36], and below than or equal to 0.15 for CVRMSE[37].

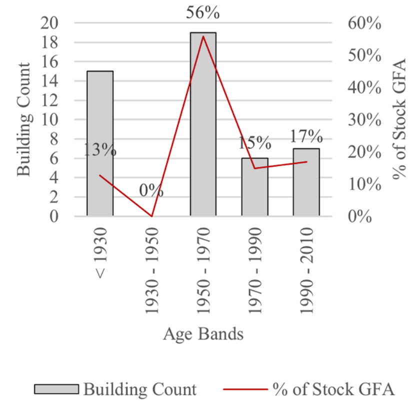

Fig. 4. Building construction dates histogram

4. Results

4.1. Characterising The stock

An inventory that comprised 47 buildings subject to relocation was developed by following the government's spokespeople media declarations and searching their existing locations. The distribution of buildings' ages and gross floor areas was analysed, as shown in the building age/area scatter plot in Fig. 3 – with an area outlier building (Maspero building of GFA ~ 220,000 m^2) presented on top of the graph on a dedicated Y-axis.

The building age-band histogram in Fig. 4 shows that a large number of buildings was built between 1950 and 1970 (19 buildings), and before 1930 (15 buildings). It is observed that buildings built before 1930 were relatively small, as the percentage of their GFA to the overall GFA is disproportionate to the number of buildings. It was observed as well that buildings built between 1950 and 1970 constitute more than half of the stock's GFA.

Fig. 5 shows a building area histogram. It was observed that 19 buildings (40 % of the stock building count and 21 % of the stock GFA) were categorised into the 10,000 – 20,000 m^2 GFA band, followed by buildings of GFA < 5000 m^2 which included 15 buildings (32 % of the stock building count, but only 7 % of the stock GFA). However, the largest buildings in the dataset constituted one third of the stock overall GFA although they formed only 6 % of the stock building count, owing to their large size.

Using the silhouette score method of K-means clustering in Python, and putting a condition for each cluster to incorporate not less than three buildings (to avoid formulating extremely small and non-representative clusters), forming 3 data clusters yielded the highest silhouette score, as shown in Table 2, meaning that the 47 buildings studied could optimally be categorised into three age-bands. Following the bounds of the clusters formed, the three age-bands were labelled as: pre 1930, 1960 s, and post 1980 s buildings. The formed clusters were analysed qualitatively and quantitatively to evaluate the common characteristics found in each.

4.1.1. Descriptive characterisation

1. Pre-1930 buildings.

This group of buildings includes listed buildings located in Cairo Downtown built between 1870 and 1930, which were royal palaces, either gifted from the royal family to the government, or converted by Khedive (Ottoman viceroy) Ismail into public administrative buildings

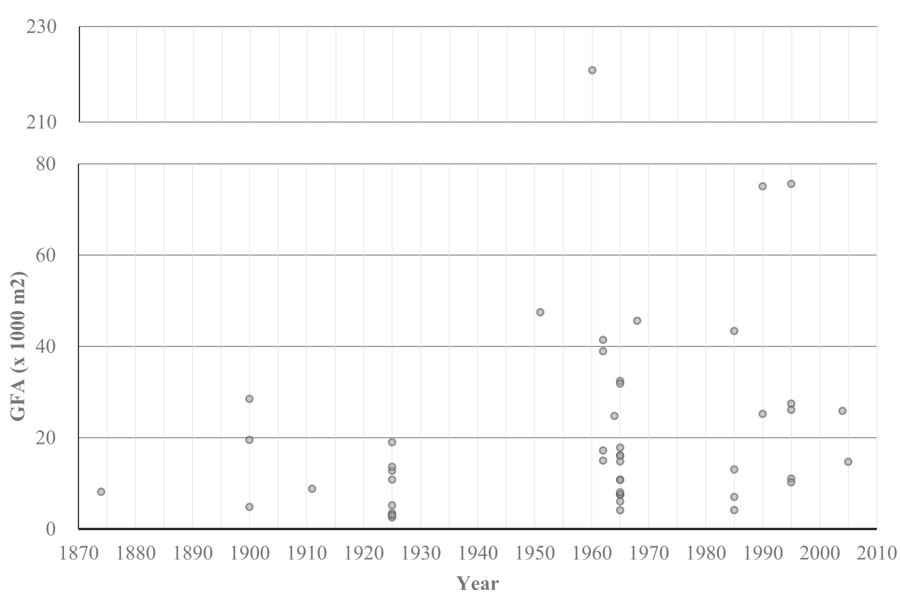

Fig. 3. Building age and gross floor area scatter plot.

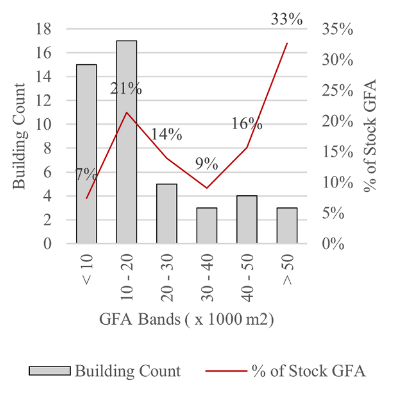

Fig. 5. Building areas histogram.

as detailed in FURP [30]. This group of buildings emerged from radical bureaucratic changes in state governance that resulted from Egypt becoming a kingdom, independent from Ottoman ruling in 1922 [30].

These Khedivial public administrative buildings were mostly load bearing stone/brick constructions with timber floors, but some of them included as well concrete skeletal structures with non-structural brick walls [38,39]. As shown in a few examples in Fig. 6 and Fig. 7, these buildings could be characterised by relatively thick external walls, large clear floor heights, external wooden window louvers/shutters, and distinct ornaments both internally and externally [40,39]. This building group received utmost official and media attention due to their historic value that can be translated into higher investment in asset value that can be attained from private investors [3,[41]].

2. 1960 s Buildings.

This cluster includes several post-war style modernist buildings that are located in Cairo Downtown and Nasr-City – the new at the time district in eastern Cairo. This building group corresponded to a political era following the coup in 1952 when Egypt became a republic after it was a kingdom from 1922 to 1952. Information on the architectural paradigm that underpinned the design of these buildings was documented and discussed in multiple studies [44,11,45].

Although reinforced concrete was introduced in Egypt as early as 1902[38], the wide adoption of concrete in creating larger and taller buildings was triggered worldwide by the post second world war reconstructions. Public administrative buildings started to echo these trends in the 1953, starting with Al Tahrir Complex building[11]. Carrying on with that trend in the 1960 s, public administrative buildings became modular 10–15 floor concrete structures with fired clay or concrete blocks for external wall infill.

As shown in Fig. 8 and Fig. 9, fixed concrete shading devices were installed both horizontally and vertically, depending on the orientation. Most buildings comprised a 2–3 floor podium – that involved public and semi-public spaces such as a library, lecture halls, and the authority's head office (i.e. the minister's main and secretary offices) – and 9–12 typical floors that included the regular employee offices from the different departments. An example for this morphology in the Central Agency for Public Mobilization and Statistics (CAPMAS) building is illustrated in Fig. 10.

It was observed that buildings of this group share several features in common, likely thanks to the following reasons:

- The buildings were constructed over a short time span (a decade).
- Ideas of creating buildings of standardised prototypes that can be mass produced, characteristic of post-war construction, was evident in how Egypt was constructing most public buildings such schools and hospitals in the 1960 s [45].
- All buildings were designed by a few architects like Tawfeek Abdel-Gawad, Sayid Koraym (or Karim), and Mahmoud Riad [11,45].

3. Post-1980 Buildings.

This group of public administrative buildings was not as concentrated (in terms of time and location) as this group of post-modernist (or contemporary) buildings did not correspond to known bureaucratic changes in the state governance. It is observed that these buildings were built to accommodate expanding authorities that acquired new/additional headquarters (such as the Ministry of Foreign Affairs and the Ministry of Finance) and to accommodate emerging/ newly formed authorities (such as the Ministry of Communications and Information Technology and the Ministry of Investment and Internal Trade). The

Fig. 6. The old Ministry of Foreign Affairs (photo credits: Master [42].

Fig. 7. The Ministry of Education (photo credits: Michael [43].

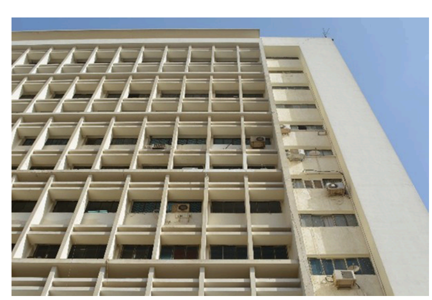

Fig. 8. Central Agency for Public Mobilization and Statistics.

Table 2
Silhouette scores for different number of clusters tested.

Number of Clusters	2	3	4	5	6	7	8	9	10
Silhouette Score	0.74188	**0.8182**	0.79864	0.77021	0.7736	0.7479	0.78749	0.79281	0.76263
Minimum cluster size condition satisfied?	Yes	**Yes**	No	No	No	No	No	No	No

Fig. 9. The Ministry of Supply and Internal Trade (Photo credits: [46].

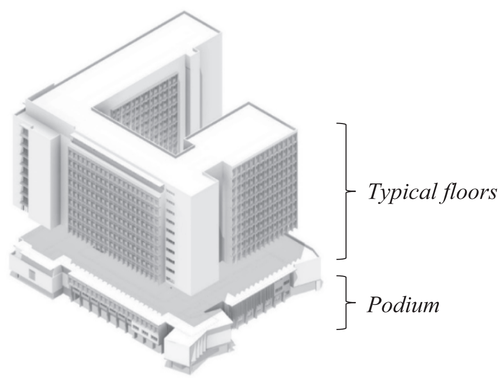

Fig. 10. Typical vs. atypical floors in a public administrative building (CAPMAS)- CGI modelled by the authors.

buildings are not concentrated location-wise as they are located in 5 different districts, and they are not concentrated time-wise either, as they were constructed at different times over two decades, which led to higher variance in building design approach and building GFAs.

Fig. 11, Fig. 12, and Fig. 13 show examples for buildings in this group. Echoing country-wide trends in office and commercial building construction [47], one common feature in these buildings can be the increasing adoption of glazed curtain walls, prefabricated concrete (especially in the ~ 1990 s), and using a myriad of external aluminium cladding (since ~ 2000 s).

4.1.2. Quantitative characterisation

Quantitative analysis of the three building groups was carried out to identify their typical form characteristics and understand how each group is represented in the stock. Fig. 14 shows that 1960 s buildings and post-1980 buildings are relatively larger than pre-1930 ones. Median building GFAs in the three groups (pre 1390, 1960 s, and post 1980) were 8,130 m^2, 16,125 m^2, and 25,200 m^2, respectively, while mean GFAs were 9,579 m^2, 30,221 m^2, and 27,584 m^2, respectively.

Three buildings in were considered as potential GFA outliers: one building from the 1960 s group (Maspero Building with GFA of ~ 220,000 m^2), and two from the post 1980 group, The Ministry of Foreign Affairs and The Ministry of Finance, with GFA of ~ 75,000 m^2 each. It was observed that median building GFA was the highest in the post 1980 buildings, while the mean was the highest in the 1960 s ones – likely biased by the extremely high GFA value attributed to the outlier building (Maspero) that increased the discrepancy between mean and median GFAs for 1960 s buildings.

Fig. 15 shows the number of floors per building across the three age bands. Pre 1930 buildings were found to be relatively low-rise as they would typically include less than 5 floors. 1960 s buildings seem to be the highest with mean and median number of floors of 11 and 12 floors respectively. Post 1980 buildings seem to constitute less floors than

Fig. 11. The Ministry of Finance (Photo credits: [48].

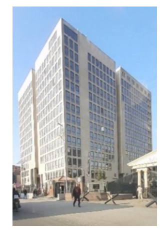

Fig. 12. The Ministry of Electricity and Renewable Energy.

Fig. 13. The Ministry of Investment and International Cooperation (Photo credits: [49].

1960 s, with mean and median number of floors of 9 and 8 floors respectively.Fig. 16.Fig. 17..

Table 3 shows the total GFAs of each age band and the percentages they constitute of the overall stock, with and without the outliers. Total GFAs of the three age bands indicated that 1960 s buildings form a stock majority, both area and count wise. Pre-1930, 1960 s, and post-1980, formed 13 %, 56 %, and 39 % of the total stock GFA (including outliers), and 19 %, 54 %, and 27 % of the total stock GFA (excluding outliers).

To evaluate the spread/variance of building areas from the calculated average, the coefficient of variation in GFA (GFA-CV) for the three building groups was calculated by dividing the standard deviation of GFAs of a certain age band by the average building GFA of that age band. Significant reductions in GFA-CV for the second and third age bands could be observed, showing how representative the average age band

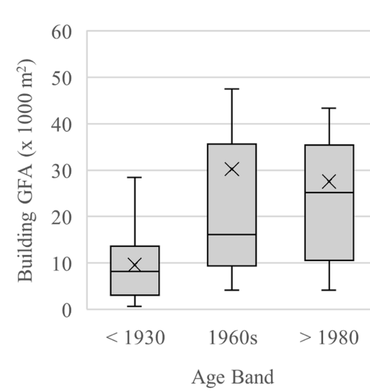

Fig. 14. Gross floor areas of buildings in each age band.

building GFA can be representative of a typical notional building GFA in that age band.

In terms of building compactness, form factors of the buildings in all age bands were evaluated by calculating surface area to volume ratios, and effective (nominal) building floor plan depth was calculated by dividing the typical floor area by the typical floor perimeter to understand how deep the plans of different age bands might differ.

Fig. 18 shows the surface area to volume ratios for the buildings studied, which indicated that the buildings of the post 1980 age band might be slightly more compact than their peers. Fig. 19 shows the effective/nominal floor plan depth, as a ratio between floor plan area and perimeter, which indicated that post 1980 seem to constitute deeper floor plans, justifying their relatively high compactness. 1960 s seemed to have consistently shallower plans, with a relatively small variance/spread of values. aligned with the qualitative observation about these buildings typically comprising office spaces placed on double-loaded corridors.

This rapid assessment of building compactness and depth could provide back of the envelope stock level recommendations about the suitability and effectiveness of certain retrofit measures (i.e., daylight harvesting and cross ventilation can be more suitable for shallow buildings, and fabric measures might be less impactful in compact/deep buildings due to their limited exposure to fabric-attributed heat transfer).

4.2. Analysing energy data

Energy consumption analysis focussed on nine modernist (1960 s) buildings as buildings in this age-band were found to constitute the largest portion of the stock, in addition to the notion that this group of buildings does not comprise historic features or ornaments (unlike pre 1930 buildings) that would complicate the application of retrofit measures.

Energy consumption was found to be electrified as 8 out of the 9 buildings studied did not have gas meters installed, and gas consumption in the only building that had a gas meter was evaluated to constitute only 1.5 % of the building's annual energy use intensity (EUI). Each of the buildings studied had from 2 to 4 electricity meters installed, but none of these submeters could be mapped to certain building end-uses.

Fig. 20 shows an average EUI of 70 kWh/m^2 (and median of 56 kWh/m^2) in the buildings studied, compared to the existing benchmark of 140 kWh/m^2 referred to in World Bank & ESMAP (2017). The findings align more closely with the office building operational performance benchmarks developed in Elharidi et al. [27,28], where uncooled and locally cooled naturally ventilated office buildings were benchmarked at 40 kWh/m^2 and 67 kWh/m^2 respectively.

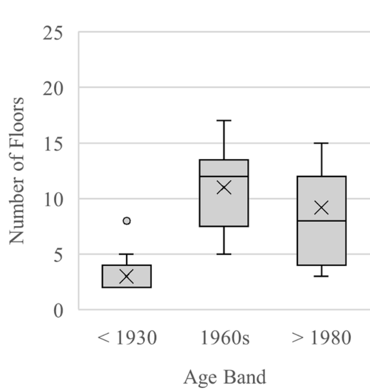

Fig. 15. Number of floors of buildings in each age band.

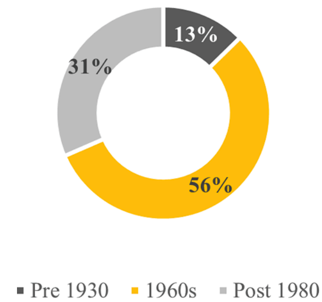

Fig. 16. Stock GFA (including outliers).

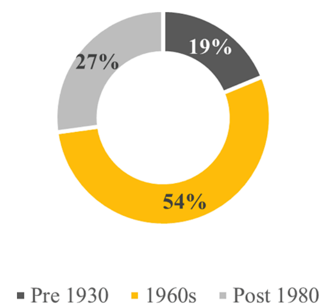

Fig. 17. Stock GFA (excluding outliers).

It is unlikely that the building sample collected belonged to buildings consume significantly lower energy than their peers, but more detailed data via building audits is required to establish a better understanding of the factors leading to this metered energy consumption. The discrepancy from World Bank & ESMAP (2017) could mean that 1960 s buildings are energy efficient (mainly due to the external shading features that signify 1960 s buildings), underoccupied, or under-serviced with sufficient building systems and services (i.e., providing low illuminance levels on insufficient air conditioning). However, none of these characteristics were seen to be obviously particular to the 1960 s buildings studied – in a way that clearly signifies them from their peers. Distinction of buildings' under-occupancy and under-servicing can be hard to observe at stock level, and the impact of distinctive fabric elements in the buildings studied requires further investigation, especially that pre 1930 public administrative buildings have louvered shutter shading while internal blinds are expected to be installed in post 1980 buildings as well. Therefore, further bottom-up investigations of the operational performance are required to find reliable interpretations for this lower-than-expected metered energy consumption.

Examining the metered monthly consumption, Fig. 21 shows the monthly EUI ranges for 9 buildings (average, +/- 1 standard deviation (std), and +/- 2 standard deviation) where the discrepancy of absolute monthly consumption is evident. These discrepancies could be minimised in Fig. 22, which shows that most buildings seem to follow a common monthly profile (monthly EUI percentages of the annual EUI) regardless of their absolute energy consumption. This common average profile featured relatively lower levels of variance, meaning that seasonal energy consumption in most buildings seems to follow consistent patterns, providing leads on how the metered energy consumption in public administrative buildings could be understood.

The average monthly EUI profile was observed to reach a peak value (*max*) in August and September and minimum values (*min*) from December to March, with almost linear gradients in between. Therefore, linear interpolation was proposed to evaluate the monthly consumption for buildings in terms of the annual consumption, thus supporting estimates for seasonal energy end-use evaluations.

If the min and max monthly EUI profile percentages are identified,

Table 3
Area and number sums for the three building groups.

	Including Outliers				*Excluding Outliers*			
	Count	*Total GFA*	*% of Stock GFA*	*GFA-CV*	*Count*	*Total GFA*	*% of Stock GFA*	*GFA-CV*
Pre 1930	15	143,685	13 %	0.80	15	143,685	19 %	0.80
1960 s	19	634,640	56 %	1	18	413,820	54 %	0.59
Post 1980	13	358,596	47 %	0.83	11	207,956	27 %	0.59
Overall	47	1,136,921	100 %	1.37	44	765,461	100 %	0.97

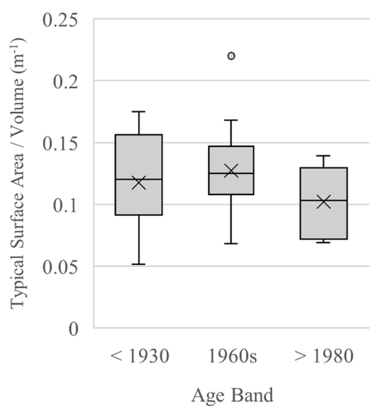

Fig. 18. Typical surface area to volume (form factors) of buildings in each age band.

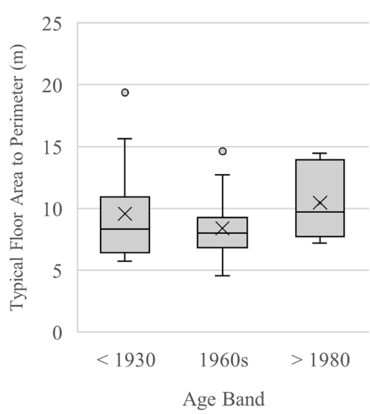

Fig. 19. Typical floor area to perimeter (effective depth) of buildings in each age band.

the sum of an annual EUI profile, where the months between min and max values are linearly interpolated, can be expressed according equation (2), which led to equation (3) – a two variable formula where either the min or the max monthly percentage of annual consumption could be derived in terms of one another.

$$(4^*min) + (2^*max) + \sum_{i=1}^{4}(min + i^*(max - min)/5) + \sum_{j=1}^{2}(min + j^*(max - min)/3) = 100\% \quad (2)$$

$$max = (100\% - 7^*min)/5 \quad (3)$$

Multiple monthly consumption profiles with different min consumption scenarios were tested to see which profile could be most representative of a "typical" consumption pattern in a public administrative building, as shown in Table 4. Monthly min consumption profiles that ranged from 5 % to 6 %, at increments of 0.25 %, were used to evaluate the monthly consumption as per five suggested EUI profiles. The performance of these generated monthly profiles was compared to the known metered consumption in the 9 buildings in Table 5.

It was found that the proposed linear interpolation could yield monthly consumption evaluations with generally acceptable correlations to the metered data, as only two buildings failed to meet the R and R^2 criteria. However, meeting the ASHRAE criteria for energy use calibration was more challenging to meet as at least 4 buildings would exceed the acceptable CVRMSE threshold at 0.15. However, CVRMSE values were still deemed good given that it is a quite ambitious metric that should be used for calibrating models of individual buildings to finetune the model inputs, so the fact that 5 buildings could achieve this target, and that 2 more were close to calibration ($0.15 < \text{CVRMSE} < 0.20$), tells that the actual consumption does not show high discrepancy from this rapid monthly consumption estimate derived via linear interpolation.

It seemed from the results that all profiles had similar a degree of error, but Profile 1 (min = 5 % of the annual consumption), shown in Fig. 23, could be slightly closer to showing minimum discrepancy from real consumption, as the median CVRMSE value in 9 buildings reached a minimum of 0.15. To better visualise the monthly discrepancy between Profile 1 and the actual monthly consumption metered in 9 buildings, a box plot in Fig. 24 shows how the percentage of metered data to the evaluated Profile 1 data, where 100 % indicates a perfect predictions for a monthly reading. It was found that most monthes could be easily predicted with errors ± 20 %.

These findings indicate that min/max linear interpolation might be used to provide preliminary evaluations of the monthly consumption pattern in most public administrative buildings in Cairo if the annual consumption is known. Although this might not be sufficient to calibrate the energy models for individual buildings, but it can provide acceptable preliminary evaluations for monthly consumption and can help with implementing more precise calibration when more detailed data is available at later stages.

Identifying seasonal energy consumption patterns can provide estimates for the energy breakdown by end-use especially when such information can be hard to evaluate empirically at stock-level. This seems the case in Cairo's public administrative buildings where the consumption is fully electrified and building submeters are placed to manage load balancing, rather than to separate end-uses.

The consistent consumption identified in winter months in most buildings could be used to estimate lighting and electric equipment (plug) loads, which are often consistent throughout the year. Accordingly, cooling loads can be the remainder of the monthly consumption during summer, as shown in Fig. 25. Since lighting and plug loads together were estimated to constitute about 60 % of the annual EUI (5 % of monthly EUI multiplied by 12 months), it was estimated that cooling loads could typically constitute about 40 % of the annual EUI given that the monthly profile the linear interpolation proposed.

While equipment loads can be hard to monitor, it can be concluded that accurate lighting audits that capture lighting intensity and control routines can be a recommended step for calibrating most public administrative buildings as lighting loads might be easier to observe and quantify. Accordingly, the harder-to-observe plug loads can be

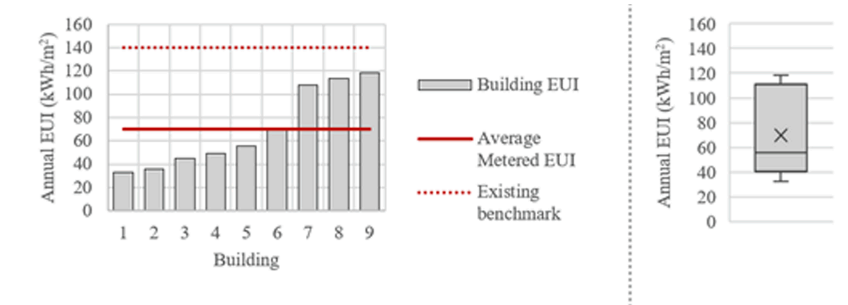

Fig. 20. Annual metered energy use intensity for 9 public administrative buildings.

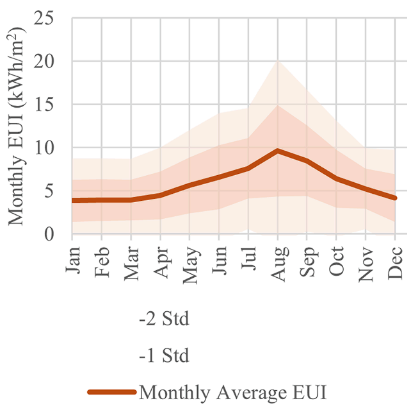

Fig. 21. Absolute average monthly EUI for 9 buildings.

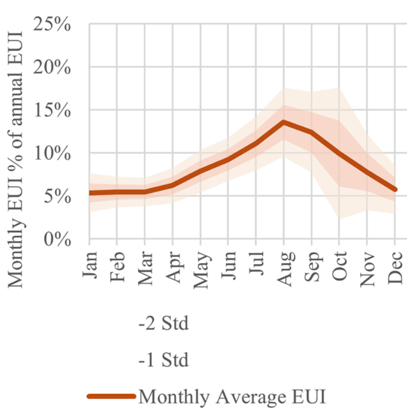

Fig. 22. Monthly EUI profile (percentage of annual EUI) for 9 buildings.

evaluated with more certainty as they would form the remainder energy consumption during winter months.

5. Conclusion

5.1. Summary of findings

This study represents the first analysis of the operational energy performance and stock characteristics of Cairo's 47 public administrative buildings subject to relocation, contributing to the evidence base for informed retrofit strategies. The soon to be reused public administrative building stock in Cairo was identified and characterized. Using K-Means clustering, the stock was classified by age into three major groups: pre 1930, 1960 s, and post 1980.

Pre 1930 buildings are listed khedivial buildings located in Downtown Cairo, formed following Egypt becoming a kingdom in 1922. 1960 s buildings are modernist buildings of distinct value, located in Downtown and Nasr City districts in Cairo, and formed following Egypt becoming a republic in 1952. Post 1980 buildings are contemporary buildings located in scattered locations across Cairo, formed to correspond to expansions in the government bureaucratic body.

The building features in the age bands identified were analysed both qualitatively and quantitatively. The main findings were:

1- 1960 s buildings constituted the largest number of buildings (19 buildings), followed by pre 1930 buildings (15), and post 1980 buildings (13).
2- Gross floor areas (GFAs) of 1960 s buildings also formed the largest portion, representing 56 % of the stock floor areas, followed by post 1980 buildings (47 %), and pre 1930 buildings (13 %).
3- Public administrative buildings are considerably large. Post 1980 buildings were the largest, followed by 1960 s and pre 1930 buildings, with median buildings' GFA of around 25,000, 16,000 and 8,000 respectively.
4- Pre 1930 buildings were the shortest, including typically less than 5 floors. 1960 s buildings were the tallest, with a median number of floors of 12 floors, followed by post 1980 buildings with a median of 9 floors.

Analysing the billed energy consumption in a sub-stock of 9 buildings revealed that the energy use intensity (mean 70 kWh/m^2, median 56 kWh/m^2) is significantly lower than the World Bank benchmark for public administrative buildings (140 kWh/m^2). The findings were more aligned with the office building operational performance benchmarks developed in Elharidi et al. [27,28], where EUI in uncooled and locally cooled naturally ventilated office buildings were benchmarked at 40 kWh/m^2 and 67 kWh/m^2 respectively, though more bottom-up investigation of the metered energy data is required.

Analysing monthly consumption data indicated the presence of typical seasonal pattern: steady low consumption in winter, with peaks in summer. The data suggested the absence of heating loads, meaning that winter consumption is formed primarily by lighting and plug (equipment) loads. Evaluating end-uses can be challenging when metered data is aggregated, but analysing these patterns allowed for auditing lighting loads to reduce uncertainties in end-use evaluations.

To test the hypothesis of steady winter consumption and summer peaks, with gradual changes in between, a methodology for monthly consumption prediction using linear interpolation was proposed and tested. Most buildings were found to follow this seasonal pattern, with acceptable correlations between actual and predicted data. These simplified predictions of monthly consumption were able to meet calibration criteria in many buildings, demonstrating the methodology's potential for broader applications.

The analysis also enabled an approximate evaluation of energy end-uses. Winter consumption, which showed steady low levels, was

Table 4
Monthly profiles for multiple minimum monthly consumption ranges between 5–6%.

Month	*Formula*	*Profile 1*	*Profile 2*	*Profile 3*	*Profile 4*	*Profile 5*
Jan	*min*	5 %	5.25 %	5.5 %	5.75 %	6 %
Feb	*min*	5 %	5.25 %	5.5 %	5.75 %	6 %
Mar	*min*	5 %	5.25 %	5.5 %	5.75 %	6 %
Apr	$min + 1*(max - min)/5$	6.6 %	6.73 %	6.86 %	6.99 %	7.12 %
May	$min + 2*(max - min)/5$	8.2 %.	8.21 %	8.22 %	8.23 %	8.24 %
Jun	$min + 3*(max - min)/5$	9.8 %	9.69 %	9.58 %	9.47 %	9.36 %
Jul	$min + 4*(max - min)/5$	11.4 %	11.17 %	10.94 %	10.71 %	10.48 %
Aug	$max = (100\% - 7*min)/5$	13 %	12.65 %	12.3 %	11.95 %	11.6 %
Sep	$max = (100\% - 7*min)/5$	13 %	12.65 %	12.3 %	11.95 %	11.6 %
Oct	$max - 1*(max - min)/3$	10.33 %	10.18 %	10.03 %	9.88 %	9.73 %
Nov	$max - 2*(max - min)/3$	7.67 %	7.72 %	7.77 %	7.82 %	7.87 %
Dec	*min*	5 %	5.25 %	5.5 %	5.75 %	6 %

Table 5
Evaluation of error in the monthly profiles generated using linear interpolation.

	Profile 1			*Profile 2*			*Profile 3*			*Profile 4*			*Profile 5*		
Min	5 %			5.25 %			5.5 %			5.75 %			6 %		
Max	13 %			12.65 %			12.3 %			11.95 %			11.60 %		
Buildings	*R*	R^2	*CVRMSE*	*R*	R^2	*CVRMSE*	*R*	R^2	*CVRMSE*	*R*	R^2	*CVRMSE*	*R*	R^2	*CVRMSE*
1	0.99	0.98	0.09	0.99	0.98	0.11	0.99	0.98	0.13	0.99	0.98	0.16	0.99	0.98	0.18
2	0.87	0.76	0.18	0.87	0.76	0.16	0.87	0.76	0.15	0.87	0.76	0.15	0.87	0.76	0.15
3	0.91	0.84	0.15	0.91	0.84	0.14	0.91	0.84	0.12	0.91	0.84	0.12	0.91	0.84	0.11
4	0.80	0.64	0.33	0.80	0.64	0.33	0.80	0.64	0.34	0.80	0.64	0.35	0.80	0.64	0.36
5	0.86	0.73	0.20	0.86	0.73	0.20	0.86	0.73	0.20	0.86	0.73	0.20	0.86	0.73	0.21
6	0.96	0.92	0.15	0.96	0.92	0.16	0.96	0.92	0.18	0.96	0.92	0.20	0.96	0.92	0.22
7	0.95	0.90	0.14	0.95	0.90	0.15	0.95	0.90	0.17	0.95	0.90	0.18	0.95	0.90	0.20
8	0.96	0.91	0.11	0.96	0.91	0.10	0.96	0.91	0.09	0.96	0.91	0.10	0.96	0.91	0.11
9	0.37	0.14	0.39	0.37	0.14	0.37	0.37	0.14	0.36	0.37	0.14	0.35	0.37	0.14	0.33
Mean	0.85	0.76	0.19	0.85	0.76	0.19	0.85	0.76	0.19	0.85	0.76	0.20	0.85	0.76	0.21
Median	0.91	0.84	0.15	0.91	0.84	0.16	0.91	0.84	0.17	0.91	0.84	0.18	0.91	0.84	0.2

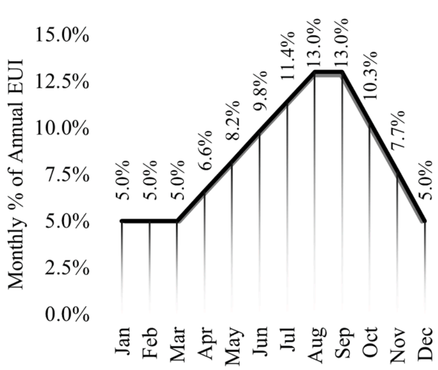

Fig. 23. Monthly consumption profile in Profile 1 (minimum consumption set at 5% of annual consumption).

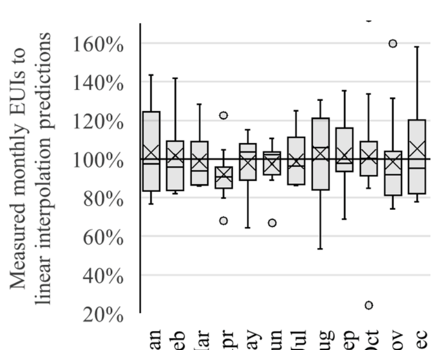

Fig. 24. Percentage of the metered consumption in 9 buildings to the evaluated consumption in Profile 1.

attributed primarily to lighting and plug loads, collectively estimated to form approximately 60 % of the annual energy use intensity (EUI). Summer peak consumption was dominated by cooling loads, estimated at 40 % of the annual EUI.

5.2. *Implications*

This study provided important insights into the potential for retrofitting Cairo's public administrative buildings, with implications for policy, practical applications, and financial sustainability. It emphasised the need for evidence-based approaches to ensure realistic expectations, yet showed how building and energy data could be analysed to counteract limited data availability. The implications can be summarised as follows:

- **Endorsing focus on 1960 s public administrative buildings**

Buildings constructed in the 1960 s can be most suitable for retrofit investigations because they constitute the largest portion of the stock (in terms of both building count and gross floor area), they share many architectural and structural features in common, and they do not feature listed elements or complex ornaments that would make retrofitting particularly challenging. These characteristics allow for retrofitting at scale, presenting a practical and suitable application of energy efficiency measures.

- **Practical implications for energy audits**

The study highlighted the practical use of analysing seasonal energy consumption patterns in fully electrified buildings to disentangle aggregated end-uses and provide rough estimates for cooling loads. Given the absence of any evidence on heating loads, building audits in Cairo's public administrative buildings were recommended to focus on

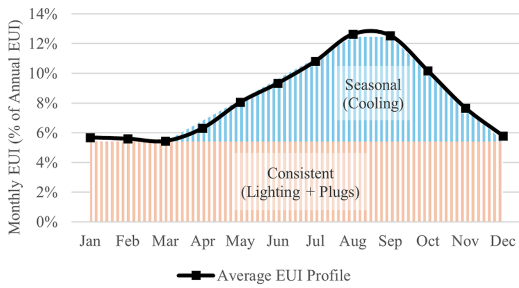

Fig. 25. End-use evaluation for an average EUI profile.

providing accurate assessments of lighting loads as a starting point, as these can be easier to observe and quantify, to minimise the uncertainties regarding plug loads which can be more challenging to evaluate.

- **Risks of overestimated benchmarks and outcomes**

The study shows significant discrepancies between the actual energy consumption and a literature-based energy use benchmark adopted in international guidance. The lack of empirical and context-specific evidence can mislead retrofit practices as providing exaggerated energy use benchmarks would lead to overestimated retrofit outcomes. These inaccuracies can result in unintended consequences, such as halted payback periods, doubts about retrofit effectiveness, and undermining of green funding ecosystems. For developing countries reliant on foreign green funds, the absence of reliable payback evidence could further exacerbate financial challenges.

- **Monetising indirect retrofit benefits**

In case the lower than expected energy consumption is attributed to insufficient thermal and visual comfort in the buildings, making a business case for building retrofit based on the financial feasibility attained from the energy savings achieved will not be effective. In that case, post-retrofit comfort taking can result in an increase in energy consumption which might diminish the savings achieved from retrofit. Therefore, monetising indirect benefits, such as health and productivity benefits attributed to the improved indoor environmental quality, could help develop novel retrofit business models that are better-suited to the buildings' baseline conditions.

5.3. Limitations and Future work

This study represents the first analysis of the operational energy performance of Cairo's public administrative building stock subject to relocation. It identified critical gaps in the literature, including insufficient stock characterisation and the lack of validated benchmarks for operational performance. These gaps hinder decision-makers' ability to evaluate the effectiveness of energy efficiency measures and develop targeted retrofit strategies.

The study tried to counteract data quantity and quality limitations that might not be unique to the Egyptian context. Despite the novel contributions, it is acknowledged that the study could benefit from expanding the evidence collected, by examining metered energy data in a larger number of buildings (quantity) and by getting more detailed data on building characteristics and energy end-uses in each building (quality).

Therefore, the study recommends collecting energy use data for more buildings and undertaking energy audits in case studies to understand the factors leading to the lower-than-expected metered energy consumption. It is important to check whether the average EUI in 1960 s would differ from buildings in other age bands. It is also key to examine how the building spaces are used and controlled, and to check whether the metered energy consumption is attributed to energy efficiency (i.e. efficient building fabric and effective shading), underoccupancy (i.e. the buildings are used less hours or by less people), or substandard indoor environmental quality (i.e. insufficient thermal and visual comfort). Answering all these questions through more building data and detailed building audits can tell policy makers whether integrating energy efficiency measures is required, and – if so – what measures can be deemed effective and suitable for the buildings.

Declaration of generative AI in scientific writing

Generative AI was not used to write or edit the study. However, ChatGPT (models 4o and o1) was used to provide feedback on the clarity and flow of the study.

CRediT authorship contribution statement

Amr Auf Hamada: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sung-Min Hong:** Supervision, Investigation. **Rokia Raslan:** Writing – review & editing, Supervision, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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Glossary

ASHRAE: The American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CAPMAS: Egypt's Central Agency for Public Mobilization and Statistics
CGI: Computer generated imagery
CVRMSE: Coefficient of variance of root mean square error
DHW: Domestic hot water
EEHC: Egypt's Electricity Holding Company
EGAS: The Egyptian Gas Company
ESMAP: Energy Sector Management Assistance Program
EUI: Energy use intensity (measured in kWh/m^2)
FURP: Faculty of Urban and Regional Planning at Cairo University
GFA: Gross floor area
HVAC: Heating, ventilation, and air-conditioning
NAC: The New Administrative Capital in Egypt
R: Pearson correlation coefficient
R^2: Coefficient of determination
Std: Standard deviation
TRACE: Tool for Rapid Assessment of City Energy
TWC: Tarek Waly Center for Architecture and Heritage