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OPERATIONAL ENERGY AND EMBODIED IMPACTS OF RETROFITTING THE WINDOW FRAMES OF MIXED-MODE OFFICE BUILDINGS

Rafaela Gravia Pimenta, Leticia de Oliveira Neves, Vanessa Gomes*

University of Campinas, School of Civil Engineering and Architecture and Urbanism, Rua Saturnino de Brito, n° 224, Cidade Universitária Zeferino Vaz. CEP: 13083-889 – Campinas – São Paulo, Brazil

* corresponding author: vangomes@unicamp.br

Abstract. Design decisions normally consider the building's operational phase as the main criterion to reduce energy expenses in a building. In less efficient buildings, reducing the operational energy becomes the most important aspect to address in the design, construction and operational phases, for it represents the highest life cycle energy flow. However, energy-efficient solutions often reduce operational energy demand by increasing the building's embodied energy and greenhouse gas emissions, which have been overlooked in energy performance analyses. This work aims at investigating the operational energy and the consequent embodied impacts resulting from the retrofit of the window frame of mixed-mode office buildings located in a hot climate, with a focus on reducing the cooling energy demand. The method consists of an experimental study based on a case study, in which the EnergyPlus and the SimaPro software tools are used to evaluate the operational energy and the environmental impacts. Results showed that reducing the WWR and increasing the window opening factor conveyed operational energy savings but in some retrofit scenarios tested, these retrofit measures were counterproductive from the CED and GWP perspective. The main scientific contribution of this work is understanding the importance of the building analysis from a life-cycle approach. The results obtained can assist companies and designers to make their decisions from a broader environmental perspective.

Keywords: Energy efficiency, operational energy, embodied energy, life-cycle analysis, office building, envelope, retrofit.

1. Retrofit from an operational energy and embodied impacts perspective

In Brazil, reducing building energy consumption has gained attention in recent years. Approximately 47 % from all electricity in the country is consumed by buildings [1]. Of this percentage, about 15 % corresponds to the commercial buildings, with lighting and air-conditioning systems being the most representative end uses [1]. According to the International Energy Agency [2], if energy efficiency strategies in buildings are not addressed currently, energy use for cooling could double by 2040, due to the increased use of air-conditioning.

As operational energy represents the largest energy consumption of a building throughout its life cycle, reducing it should be the most important aspect to be addressed by designers, architects and engineers [3]. The design of energy-efficient buildings is, therefore, focused on reducing their operational energy, which can be achieved through the use of passive and active strategies. Reducing the operational energy, however, often implies an increase in embodied energy through the use of new materials and technologies [3].

Azari [4] shows that, among the publications about energy performance of building envelopes, most are directed to the analysis of operational energy, and few studies investigate the building energy performance from a life cycle perspective. Krstic-Furundzic et al. [5] point out that building envelope is the main architectural element of a building that impacts thermal comfort and energy performance. In terms of its contribution to reducing energy consumption, the authors show that the analysis of various facade scenarios is crucial and necessary for each specific case and climate, from the design point of view. Thibodeau et al. [6], through a comprehensive literature review, indicate that, from a life cycle perspective, it is environmentally advantageous to retrofit a building instead of demolishing and rebuilding it. De Angelis et al. [7] identify that in countries that do not have heating demand, carrying out a retrofit focused on reducing energy consumption is preferable than reconstructing the building, since the reconstruction corresponds to 35 % to 40 % of the life cycle impacts. According to Tokede et al. [8], there are several studies of building retrofit with a focus on the building's envelope that prove possible a reduction in the operational energy consumption and, consequently, a reduction in the carbon dioxide emissions to the atmosphere. Saade et al. [9] present a literature review correlating operational consumption and environmental impacts, with a focus on the impacts of embodied energy and carbon. The authors found a strong correlation between the GWP (Global Warming Potential) and CED (Cumulative Energy Demand) categories, and stated that the advances in buildings operational energy performance led to an increase in their environmental impacts, due to the relative decrease in the operating loads share, and to the resources consumed and emissions generated in materials production.

The building's life cycle analysis depends on the country's energy matrix. In 2018, the Brazilian renewable energy production corresponded to 45.3 % of its total energy production, remaining as one of the highest in the world [10]. Therefore, most research studies concerning operational energy and the consequent embodied impacts of buildings do not apply to Brazil or to tropical climates, where cooling is one of the buildings' main end uses. Thus, the main objective of this paper is to analyse the ratio between operational and embodied energy resulting from the retrofit of the window frame of mixed-mode office buildings, with a focus on reducing the cooling energy demand.

2. Methods

2.1. Reference model and scenarios

A database containing architectural design and envelope information of 153 mixed-mode office buildings (i.e., operating on natural ventilation and air-conditioning modes, alternatively) located in the city of São Paulo, Brazil, was developed by Neves et al. [11] and detailed by Pereira [12]. As it contains a representative sample (about 10 %) of mixed-mode office buildings in São Paulo, this database was used as a basis to define a reference model, as shown in Table 1 and Figure 1.

Table 2 shows the window frame variable parameters used to model the retrofit scenarios, which were chosen based on the literature review [3, 11–15]. The reference model was analysed considering four solar orientations – outdoor facades facing North and East (North-East), East and South (East-South), South and West (South-West) and West and North (West-North), as shown in Figure 1.

2.2. Operational energy calculation

To quantify the operational energy consumption of the retrofit scenarios, computer simulations were performed in the EnergyPlus software. The geometry of the reference model and scenarios were modelled in the Euclid plugin for SketchUp, which interfaces with EnergyPlus. The calculation of the office room's operational energy consumption was performed based on the climate file of the city of São Paulo, based on data from the National Institute of Meteorology (INMet) [16]. The natural ventilation was modelled through the AirflowNetwork module, which performs pressure, airflow, temperature and humidity calculations in the nodes, and sensitive and latent heat exchange calculations [17]. The Energy Management System (EMS) module was used to simulate the mixed-mode system, using as a reference to the indoor operative temperature setpoint the adaptive thermal comfort model from ASHRAE 55 [18]. The window operation was set as opened and the air-conditioning was turned off when the indoor operative temperature within the thermal comfort range and the room was occupied. Otherwise (indoor operative temperature out of range), the window operation was set as closed and the air-conditioning was turned on. When the room was unoccupied, the windows were closed and the air-conditioning system was turned off.

2.3. CED and GWP calculation

The Life Cycle Assessment (LCA) methodology was used to analyse two categories of environmental impacts: Cumulative Energy Demand (CED) and Global Warming Potential (GWP). The guidelines for LCA were based on ISO 14040:2006 [23] and ISO 14044:2006 [24]. The standards were used to define the objective and scope, to set up the life cycle inventory (ICV), to assess the life cycle impacts (LCIA) and to analyse the results (Table 3). Among the life cycle stages indicated by EN 15978-2011 [21], only the construction extraction modules were considered, which are: A1–A4 (considering the distance from the region of demolition to the centre of São Paulo), B2 (maintenance, considering the repainting of the facades); B5 (operational energy consumption) and C2 (disposal of materials after demolition). Modules A5, C1, B1, B3, B4, B6, C3 and C4 were excluded from the analysis.

The SimaPro 8.5 LCA platform was used to model the retrofit scenarios. The Ecoinvent version 3.4 database was used, enabling changes in the energy matrix of the data sets to bring them closer to National production parameters. The reference period considered was 50 years. The Cumulative Energy Demand (CED) method calculates the total primary energy demand in the life cycle of materials and the CML 2001 baseline method addresses several impact categories, including CO_2eq emission. The embodied energy analysis was performed based on the results obtained from the CED method ($MJ/m^2 \cdot year$) and transformed into $kWh/m^2 \cdot year$ to allow a comparison between scenarios. The climate change analysis of the operational and retrofit phases was carried out based on the results of global warming potential (GWP), in $kg\,CO_2eq/m^2 \cdot year$. The quantities of materials used in each scenario were calculated in kg or m^2, and transportation was calculated in ton ∗ kilometre (tkm), as shown in Table 3. The window frames were considered to be made of aluminium and a single pane glazing.

3. Results and discussion

Natural ventilation is known as an assertive passive strategy towards thermal comfort conditions within the humid subtropical climate of the city of São Paulo. Indeed, among the four solar orientations analysed, natural ventilation was used during 60 % of the room's occupancy time for both office rooms facing North

Parameters		Values	Reference
Room geometry	Room area	39.2 m^2	Average value of database [12]
	Floor	6th	Intermediate floor of a 12-storey building (average value of the database) [12]
	Floor-to-ceiling height	2.50 m	Average value of the database [12]
Window frame	Window-to-Wall Ratio (WWR)	25 %	Average value of the database [12]
	Window opening factor	64 %	Average value of the database [12]
Glass	Solar Heat Gain Coefficient (SHGC)	Colored glass (62 %)	Most recurrent case on database [12]
	U-value	Standard glass (5.8 $W/m^2 \cdot K$)	Most recurrent case of the database [12]
Solar shading devices		none	Most recurrent case of the database [12]
Envelope	U-value	2.38 $W/m^2 \cdot K$	Concrete block and mortar (0.28 m) [19]
	Thermal capacity	258.6 $kJ/m^2 \cdot K$	
	Solar absorptance	0.5	Average value of the database [12]
	Emissivity	Opaque material (0.9)	Most recurrent case of the database [12]
Air conditioning	System type	Split	Most recurrent system in office buildings [20]
	Coefficient of Performance (COP)	3.23 W/W	Level A PROCEL [21]
Internal loads	Occupancy (number of occupants and metabolic rate)	0.14 $person/m^2$ 65 W/m^2	[22]
	Lights	9.7 W/m^2	Level A PROCEL [21]
	Equipment	10.7 W/m^2	[22]
Schedule		Weekdays 8 am to 6 pm	[21]
Natural ventilation strategy		Cross-ventilated (adjacent facades)	Most recurrent case of the database [12]

TABLE 1. Reference model's input parameters.

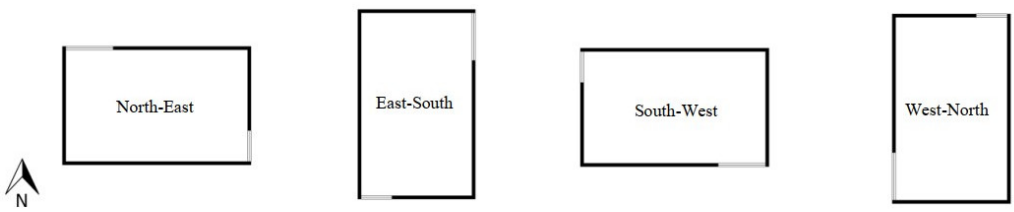

FIGURE 1. Reference model's office room model and investigated solar orientations.

Parameters		Scenarios
Window frame	Window-to-Wall Ratio (WWR)	12.5 %, 25 %*, 37.5 %, 50 %, 62.5 %
	Window opening factor (% of the window frame that is operable for natural ventilation)	35 %, 64 %*, 93 %

* Corresponds to the reference model.

TABLE 2. Variable parameters.

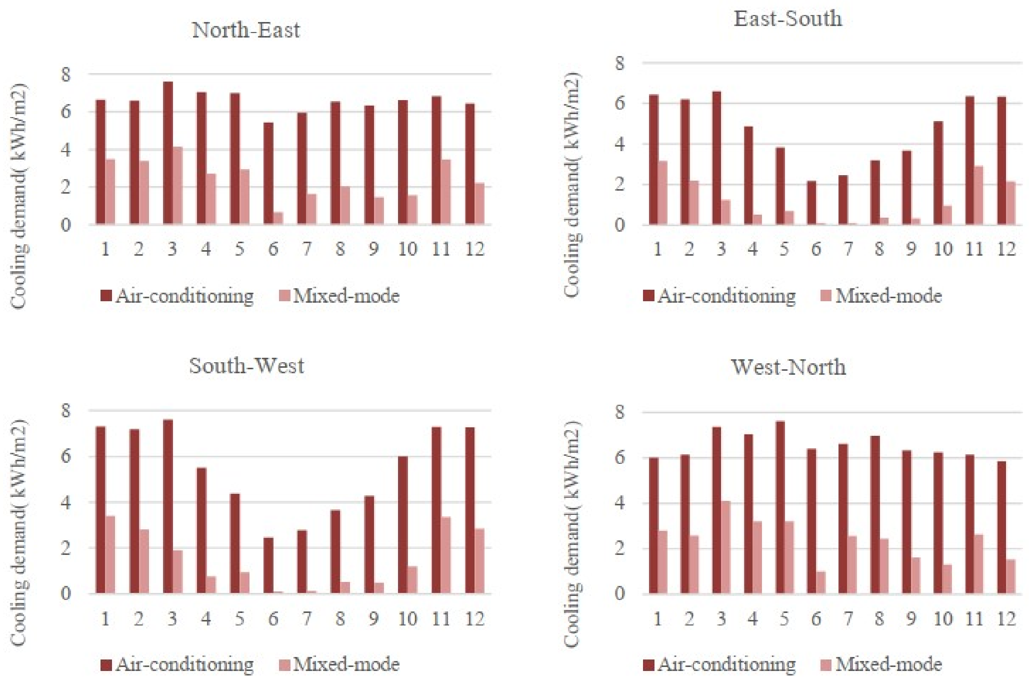

Figure 2. Energy demand for cooling – monthly results.

Parameters			kg	m^2	tkm
		WWR			
Window frame	Aluminium	12.5 %	2.5	-	6.25
		25.0 %	5.0	-	12.5
		37.5 %	7.5	-	18.75
		50.0 %	10.0	-	25.00
		62.5 %	12.5	-	31.25
	Glass	12.5 %	80.0	-	12.50
		25.0 %	160.0	-	24.00
		37.5 %	240.0	-	36.00
		50.0 %	320.0	-	48.00
		62.5 %	400.0	-	60.00
	Window opening factor				
	Aluminium		-	2	12.50
	Glass		160	-	24.00

Table 3. Window parameters and materials used in the life cycle inventory.

(North-East and West-North) and 70 % of the occupancy time for rooms facing South (East-South and South-West). The mixed-mode system was, therefore, responsible for an annual cooling demand reduction of 74 % for the East-South office room and 72 % for the South-West office room, if compared to a fully air-conditioned office room (Figure 2).

An increase in the cooling energy demand during the hot season (October to March) can be observed in the rooms facing South. As to the rooms facing North, the cooling energy demand varies throughout the year and it is not possible to determine the most critical season. The room with the best thermal and energy performance was the East-South room, since it is the room with less direct solar radiation. The office rooms with openings to North-East and West-North had similar performance. The demand for heating had insignificant results so only the cooling demand values were considered in the analysis.

3.1. WWR and window opening factor scenarios

Figure 3 presents the cooling energy demand for the WWR and window opening factor variation. The WWR variation had higher impact over the results, being the lowest percentage of WWR (12.5 %) the scenario with best thermal and energy operational demand performance. Conversely, the highest value of window opening factor (93 %) resulted in the lowest cooling energy demand values for all solar orientations analysed. Low window opening factor values demand more energy for cooling due to its small operable

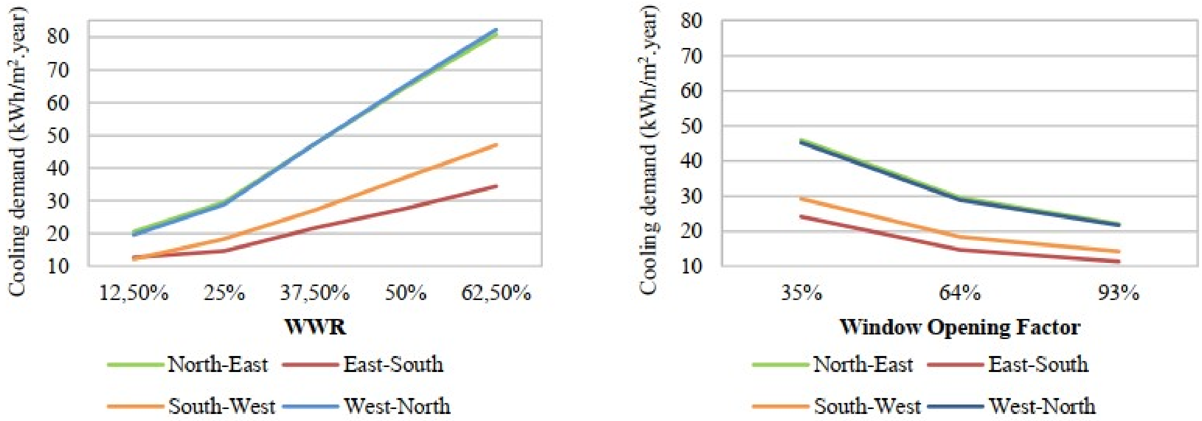

Figure 3. Energy demand for cooling – scenarios for WWR (left) and window opening factor (right).

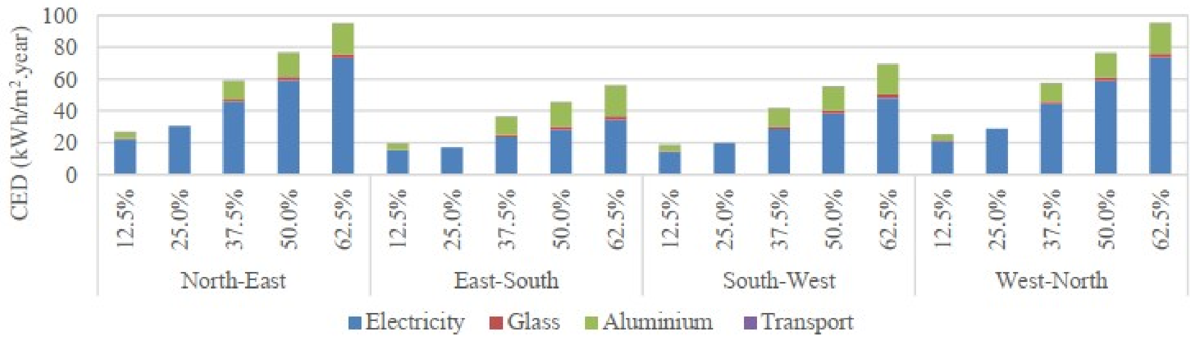

Figure 4. Embodied Energy per $m^2 \cdot$ year – WWR scenarios.

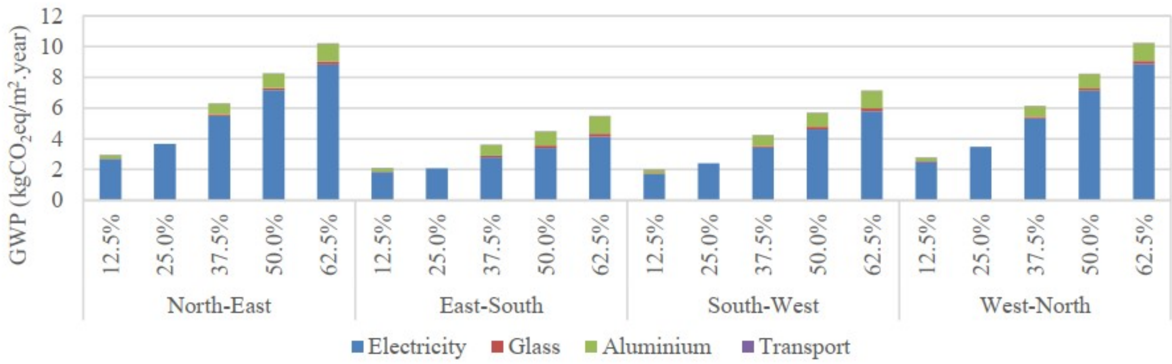

Figure 5. Global Warming Potential impact per $m^2 \cdot$ year – WWR scenarios.

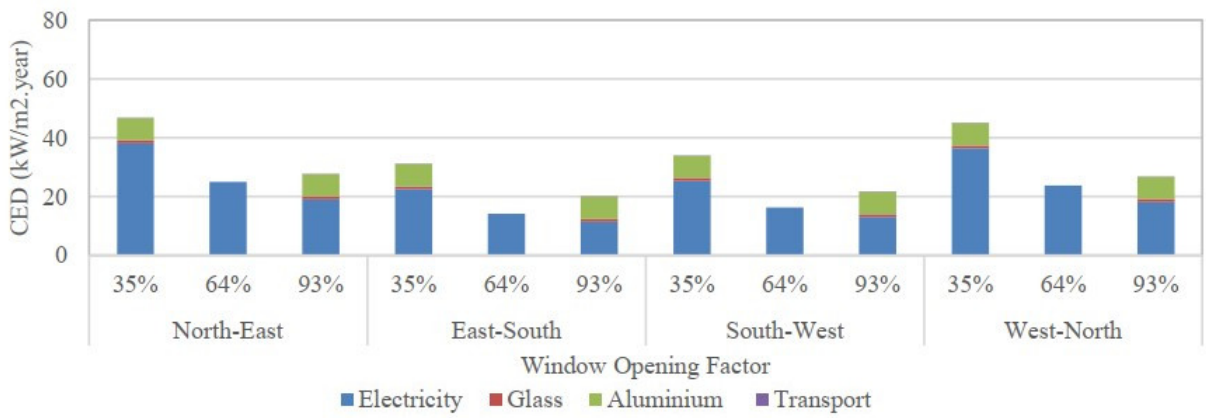

Figure 6. Embodied Energy per $m^2 \cdot$ year – window opening factor scenarios.

Figure 7. Global Warming Potential impact per $m^2 \cdot$ year – window opening factor scenarios.

area, which impairs natural ventilation. The reduced impact of the window opening factor variation over the results could be due to the fixed WWR of the reference model (25 %), which is relatively low.

The office rooms facing North-East and West-North had similar performance for both variable parameters. The cooling energy demand of these rooms, when WWR is 12.5 %, reduced approximately 40 %, if compared to the reference model (WWR = 25 %). If compared to the South-West and East-South rooms, the cooling energy demand was approximately 40 % higher. The reference model scenario (WWR = 25 %) presented cooling energy demand 40 % to 50 % higher for the North facing rooms, if compared to the East-South room, which showed the best energy performance for both variable parameters.

The electricity showed the highest annual embodied energy and carbon dioxide emissions in all cases (Figures 4 to 7). The embodied energy analysis showed the 12.5 % WWR scenario as the best case, even when considering the embodied impacts due to the replacement of the window frames, if the solar office room is facing North (Figure 4). When considering a better solar orientation (East-South or South-West), the WWR reduction was not an advantageous option, from the embodied impact perspective. The scenarios with WWR higher than the reference model (37.5 %, 50 % and 62.5 %) showed an increase in the cooling energy demand – and, consequently, in the embodied energy and GWP impacts – for all cases (Figures 4 and 5).

The 64 % (reference model) and the 93 % window opening factor scenarios showed similar CED and GWP results (Figures 6 and 7). In fact, the latter equalled or exceeded the reference model results, showing to be counterproductive, when its embodied impacts were taken into consideration.

4. Conclusions

This paper aimed at analysing the thermal and energy performance of retrofitting window frames of mixed-mode office buildings located in São Paulo, Brazil. Only single glazed aluminium window frames were herein investigated. Though this might limit the information value for temperate and cold climates, such configuration corresponds to typical mixed-mode buildings in Brazil and are also ubiquitous in many tropical regions. Results showed that reducing the WWR and increasing the window opening factor could indeed convey operational energy savings to the existing buildings. Such reduction, however, increases environmental impacts through the addition of materials that demand energy consumption for their production, transport, maintenance and end of life. In some scenarios tested, reducing WWR and increasing the window opening factor outweighed the CED and GWP of the reference model, showing to be counterproductive retrofit measures. The case study here presented demonstrates the importance of analysing the energy performance not only from an operational perspective but also from the embodied impacts perspective.

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