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Diagnostics and intervention methods for façade retrofit of post-WWII non-domestic buildings in Europe for energy efficiency

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ABSTRACT: The growing demand of deep façade retrofits in refurbishment projects across Europe, is often accompanied by low-energy targets and architectural attributes. Factors like variability in context, material, environment and composite construction types and comfort requirements, often complicate the façade retrofits. It becomes difficult to generalise the method of retrofit for each building case. A proper understanding of the diagnostics and intervention principles improves the overall cognizance of retrofits with other systems and sub-systems. Passive retrofit strategies offer great potential to reduce the energy demand of non-domestic buildings. This paper presents a review of research and passive intervention methods that can act as guiding principles for modern façade retrofits for post-war non-domestic buildings and maintain the integrity of the building to provide higher human comfort levels and improved energy performance.

KEY WORDS: Retrofits, Energy efficiency, Passive design strategies

1 INTRODUCTION

The post-1945 economic boom almost doubled the building stocks in many European countries [1]. It was responsible for the growth of non-domestic buildings such as office, commercial, health and educational facilities. Approximately 37% of the non-domestic building stock (age between 31-50 yrs.) are likely to get retrofits in the next 20 years [2]. Buildings from this period are generally characterized with poor insulation, large single glazed façades, larger floor plates, high costs for energy, and carbon footprints. Non-domestic buildings in Europe account for 25% of the total stock and it is a well observed fact that they have greater energy consumption per unit of floor area compared to dwellings [3]. Occupants experience high thermal discomfort that further leads to a reduction in productivity levels in these buildings. It has been advised to prioritize the need for reducing energy demand through retrofitting [4]. Often in refurbishment projects, façade retrofits are undertaken to fix maintenance problems, translate into costly interventions especially for overcoming energy failure and architectural decay. This study highlights the importance of development of guidelines for retrofitting such buildings to meet the current energetic requirements. Planning the retrofits strategically with effective diagnosis of problems would result in huge reduction of capital costs, operational and embodied energy, improvement in indoor environment, air quality, thermal comfort and disruption caused in the building. These end benefits can potentially be reduced by deep retrofit of the existing façades.

1.1 Building stock

In the non-domestic sector of Europe, building refurbishments offer greater opportunities than building new energy efficient buildings to meet Europe's emission targets, as new buildings represent annually less than 1.5% of the total building stock [5]. The post-war non-domestic buildings are generally built during the years 1945 to 1975 when the building regulations were not stringent and had little focus on energy conservation [6]. New technologies resulted in acceptance of the glass and metal curtain walls and realisation of machine made envelopes [7]. The implementation of poor building technology employed in these buildings and high-energy consumption are well-defined traits to identify them [3]. They followed an international, modernist and minimal style architecture, which is uniform across many of the non-domestic buildings from that period [8]. A prominent category of buildings from this period, have, either partially or fully glazed façades. After the energy crises in 1970's thermal energy efficiency of buildings gained importance in the legislations across Europe [3]. Therefore, this study focuses on these buildings, which are potentially promising to investigate the façade retrofit opportunities and energy savings.

1.2 Methodology

The aim of this study is to identify different technical diagnosis and passive (without active mechanical systems) intervention methods used to improve the energy efficiency and quality of building under the following aspects:

- Post-war glazed façades
- Passive environmental strategies
- Low- emission refurbishment

Further, a comprehensive literature review demonstrates the diagnosis of defects with the limitations of passive interventions in façade retrofits for achieving energy efficiency. Active systems and methods are out of scope of this paper.

2 BUILDING PHYSICS

2.1 *Energy efficiency, thermal performance and moisture control*

Energy efficient retrofit has become a focal point of construction activity in Europe after EU mandates [9,10]. There is an evident influence of façade retrofits on the total energy loads and internal environment conditions with respect to thermal and moisture balance. The infill panels, the frame construction, spandrel and other perimeter areas affects the thermal performance of glazing systems [11]. Better High performance insulating surfaces hold a direct reduction in the surface temperatures and the risk of radiant temperature asymmetry is minimised. It also blocks the downdraft of cold air descending through the glazed surfaces and heating systems influence on comfort is reduced [12]. Generally, large glazed surfaces are associated with the objectives of building physics, materials, components and climatic response of the building [13]. This can guide us further into taking down the information and evaluate them based on retrofitting objectives. Moisture protection is the main objective of glazing systems but poor systems can allow water to penetrate through gravity, kinetic energy, air pressure difference, surface tension, and capillary action [14].

2.2 *Human comfort*

One of the most important component of human comfort in retrofits is the perceived room temperature [15]. With large glazed façades, there is a high possibility of uneven surface temperatures [16]. Figure 1 indicates the comfortable temperature range for surrounding surfaces. A study conducted by Lyons et. al [17] which evaluated generic glazing systems from clear single panes to high performance glass for comfort impacts, concluded that direct solar load has major influence on comfort and draft effects are higher with large glazed façades.

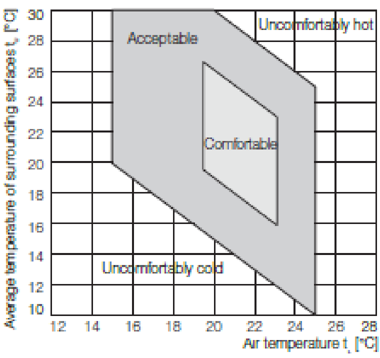


Figure 1: Comfort in relation to the interior air temperature and the temperature of the surroundings [12]

3 RETROFIT CONCEPTS

In an energy efficient refurbishment, the construction standards of the existing building are upgraded to comply with retrofit norms and regulations [18]. Possible construction upgrades for post-war non-domestic buildings include improving the thermal insulation, eliminating thermal bridges, renewal glazing or windows, and solar heat gain reduction by providing sunshades, or retrofitting of thermal mass in the form of latent storage media [12]. Providing weatherproof windows and extractor fans can control the natural ventilation. Other ventilation measures such as ducts and atria can optimise the cross-ventilation of the building. In non-residential buildings, an even distribution of daylight as far into the building as possible is essential. Daylight optimisation measures with larger windows can improve the daylighting in the spaces [19]. However, large areas of glazing increase the thermal loads in the summer and the sunshades required to combat this can lessen the amount of daylight entering the building.

One of the most cost effective ways to improve the façade are the passive design strategies, which can deeply reduce the thermal loads of the building. Section 6 will elaborate more on passive interventions and their effects. Passive interventions are based on design strategies like: passive heating, passive, cooling, passive ventilation and daylighting [20].

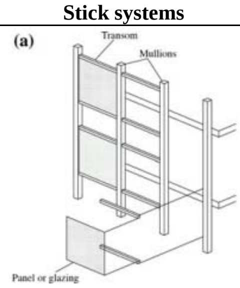
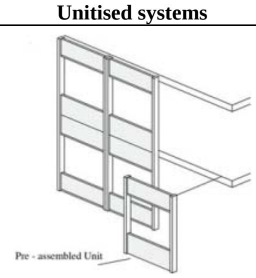
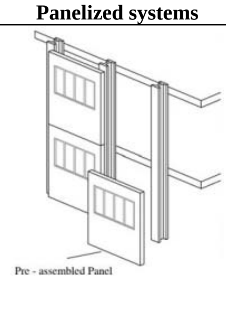
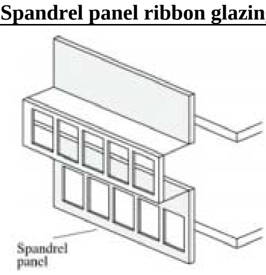
According to Rey [7], interventions on building façades are significant as they are linked to technical installations. There can be three types of strategies for retrofitting:

1. Stabilization strategy: Holds incremental interventions, that does not modify the appearance
2. Substitution strategy: Consists of complete replacement and transforms the appearance and substance
3. Double- skin façade strategy: Partially stabilises the façade and add a new glass skin, preserving the original state of the façade.

4 FAÇADE SYSTEMS

Flat sheets of polished cast mirror glass and drawn window glass were the most common types of glass used in buildings until the rise of double glazing (two panes of glass separated by strips of aluminium) in the post war period [21]. Some of the most common glazing systems observed in the post-war non-domestic buildings in Europe are shown in Table 1 [22].

Table 1: Common post-war glazing systems in Europe

Stick systems	Unitised systems
	
Panelized systems	**Spandrel panel ribbon glazing**
	

Stick systems consist of vertical members (mullions) and horizontal members (transoms) anchored to the structural frame. Glass or other panels are then fixed into the openings of the metal grid. Unitised systems are panels that are pre-assembled prior to installation in the field and then units are stacked to form mullions and transoms. Panelised systems utilise features of unitised and stick systems where prefabricated units are attached to already installed mullions. These systems later developed into more efficient curtain walling systems such as structural sealant glazing and point fixed structural glazing. They were constructed with timber sections, aluminium sections or rolled steel sections with a coating to prevent corrosion [23].

5 FAÇADE FAILURES

5.1 *Driver of façade retrofits*

To improve the serviceability and indoor environmental conditions majority of façade retrofits are planned for non-domestic buildings. The service life of a building is generally 60 years but building components have shorter duration. Table 2 gives an indication of the age of the components desired for retrofitting the façade [12].

Table 2: Life time expectancies of envelope components [12]

Component	Min. (yrs.)	Max. (yrs.)
Render, façades	30	60
Windows	25	40
Insulating glass units	20	35
Building envelope as a whole	20	60

Diagnosis would have been very simple if there was just one solution to the existing problems. Several defects or combinations of defects cause the façades to fail. The failures can be due to physical problems, material failure due to ageing, detailing failure, maintenance failure or outmoded and obsolete production of façade components [24]. These are the major drivers of façade retrofits and they are responsible for acceleration in deterioration [25]. Table 3 indicates the general problems with glazed façades, their probable cause and locations.

Marradi et al. [26] performed a process mapping with experts for glass façade renovations and found that the main issue while dealing with existing façades is the complexity in assessment of its current performance. The suggestion encompassed to evaluate the existing façade performance through sensor based monitoring or in-situ tests with regard to thermal and structural conditions.

5.2 *Diagnosis of façade failures*

5.2.1 Survey of existing structure

The cataloguing and description of damages including earlier repairs is a crucial step in retrofit planning. A differential analysis of the causes of damages is advised by Schittich [13] to address:

- Ageing, material fatigue and wear and tear
- Poor/non-existent maintenance and upkeep
- Inexpert repairs or renovations
- User behavior in terms of heating and cooling
- Status of building technology and standards of the time
- Planning and production errors

- Table 3: Problems in glazed façades

Problem	Causes	Location
Water penetration	Improper design Improper installation Glazing leaks Sealant failures Weather-stripping Thermal break shrinkage Improper repairs	Glazing pockets Internal gutter or flashings Glazing joints Property of sealant Operable windows Mullion system Drainage holes and joints
Air leakage and thermal discomfort	No air barrier and thermal breaks	Operable window vents, joints at mullions, defective sealant joints
Condensation	No insulation	Perimeter joints, mullions near spandrel
Acoustics	Loose infills, air leakage	Junctions and joints
Material failures	Electrolytic action	Frame joints with structure, coatings
Structure failure	Poor connections High wind loads	Frame

Visual inspection is necessary for primary qualitative data collection prior to detailed inspection about the building and it is effective if reflected in performance evaluation of the façade [12]. A number of surveys can integrate the concept of visual inspection, to check conformance to design documents, load and environmental conditions, external appearance, interior condition and supporting services [18].

5.2.2 Inspection and measurements

There are established standard practices for inspections and measurements which can positively be employed for identifying the performance issues [27]. ISO 12655:2013 governs the calculation of measured energy use in buildings. Air-tightness and air-infiltration testing is done through blower door test (ISO 9972:2015). Infiltration rates can be measured using tracer gas measurements (ISO 12569:2012). Thermal imaging aids in identification of thermal bridges, air and moisture penetration (ISO 6781:2015). For non-destructive tests, dielectric meters perform the surface scanning to quantify the presence of moisture. The Glaser or dew point method helps to study the occurrence of interstitial condensation for steady-state interior and exterior climate conditions, for assessment with respect damage to component (ISO 13788:2012). Figure 2 illustrates an example of the condensation point analysis in a wall assembly.

For in-situ, measurement of thermal resistance and thermal transmittance of opaque elements of the existing façade thermofluxometry is used (ISO 9869-1:2014). ISO 15099:2003 assists to assess the thermal performance of fenestrations and shading devices. Spectrometer can also be used to measure the glazing emissivity.

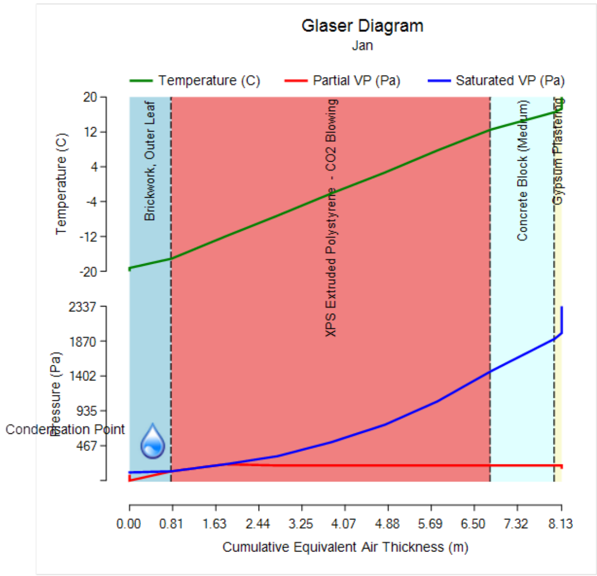


Figure 2 Example of condensation analysis in a wall assembly

5.2.3 Analysis and evaluation

A detailed analysis and evaluation of the collected information is very critical for broader decision-making before commencing retrofits based on uncertainties such as financial risks involved, time required, cost benefits and lifecycle scenarios [28]. The preparation of the diagnosis scenario can involve mapping the overall determination of façade condition and quantitative information about its energy performance. The methodologies must be developed according to a set of procedures with a logical sequence in order to adopt a proper solution, since many failures in interventions result from the inexistence or inadequacy of diagnosis [29]. Diagnosis or other expert systems can be utilised for logical diagnosis of defects using data banks, charts, fault tree tools or knowledge based systems [30]. Therefore, this study discusses the passive retrofit interventions for façades to ascertain their impact and benefits.

6 PASSIVE RETROFIT INTERVENTIONS

Considering the environmental approach, passive retrofitting strategies are ideal but the choice of passive system/s is difficult to adopt for existing buildings where the other systems and sub-systems are already in place. Therefore interventions can build upon four basic strategies build upon, 1) Heat loss in summer, 2) Overheating in summer, 3) Natural ventilation measures and 4) Daylight utilisation opportunities [31]. Passive retrofit strategies can have deep impact on thermal loads of post-war glazed façades with measures such as shading, fabric insulation, reduction in glazing area, and adaptive controls [5].

6.1 Passive design strategies

Passive design strategies can be an individual or a combination of passive design elements for the retrofit of façades. Table 4 lists common passive design elements mapped against the actions and strategies from the analysis of literature. They can be utilised for their benefits towards the reduction in energy loads and improvement in indoor comfort levels for post-war non-domestic buildings.

Table 4: Passive design strategies and respective elements

Design elements	**Application**	**Passive design strategies**			
		H	C	V	D
Building shape	Extensions, sunspaces, balconies	◆	◆		◆
Buffer spaces	Ventilated, double skin, atriums, glazed balconies	◆		◆	◆
High performance glazing	Clear/ low-e/double/ triple glazing, aerogel glazing, vacuum glazing, switchable reflective, SPD film, fritting	◆			◆
Operable windows	Size, placement, low conductance frames			◆	◆
Solar shading (operable/ fixed)	external sunshades, louvres, blinds, overhangs, vertical fins	◆	◆		
Thermal Mass	PCM, aerated concrete	◆	◆		
Light colours	Colour of exterior finishes		◆		
High performance insulation	PCM, vacuum insulation panels	◆			
Air and moisture tightness	Caulking/sealing	◆			
Natural lighting improvement	Reflective blinds, light shelves, clerestories				◆
WWR (wall window ratio)	Low(N/E), high (S/W)	◆	◆		◆
Waste heat recovery	Mixed mode heat-recovery ventilation	◆		◆	

Note: H: heating, C: cooling, V: ventilation, D: daylighting

Research and case studies in literature suggest that passive methods for façades cannot only save significant energy but also improve comfort levels in the existing office and commercial buildings [32]. A study by RIBA investigated use of passive design strategies in refurbishment of an office building built in 1970’s [5]. The reduction in primary energy consumption achieved was 64%. Hestnes et. al [33] studied retrofitting scenarios with passive design strategies on office buildings and was able to reduce the energy loads to <100kWh/m^2/year. Façade interventions are fundamental to deep retrofits and aim to achieve efficiency of more than 50% in energy reduction [34]. Cellai et. al [35] simulated the effects of shading device typologies for energy efficient refurbishment of existing buildings and presented a comparative analysis that determined the effects on thermal and visual comfort. The effect of double layer glass façades was also studied for office buildings by Brunoro and Rinaldi [36] through several case studies where the energy performance before intervention was 250-270 kWh/m^2 that got reduced to about 30-40% after retrofit.

6.2 Scale and cost of interventions

The original structure undergoing refurbishment holds several perplexities of preservation and conservation. They require critical understanding before approaching for any refurbishment measures.

Six intervention approaches are discussed by Samuel [37] as shown in Table 5 below.

Table 5: Types of intervention methodologies (adapted)[37]

Approach	**Activity**	**Cost**	**Action**
Abstention	Do nothing	Directly proportional to risk (loss of property)	-
Mitigation	Around the façade	Inexpensive	Band aid-repairs, selective reconstruction
Reconstitution	On the façade	Inexpensive	Over cladding
Substitution	Direct replacement	Expensive	Recladding
Circumvention	Different than original	Expensive	New and different façade
Acceleration	Controlled demolition	Very expensive	Removal

Doing nothing is less costly than doing something initially, but ultimately it costs in terms of the loss of the components or building [38]. Mitigation involves treatment to selective portions of façade demanding attention and left untouched due to limitation of budgets or avoidance of disturbance. Mitigation is an inexpensive approach [39]. Reconstitution in a similar way is inexpensive, as the existing façade remains as it is and an additional layer is provided to meet the required objectives of energy and façade preservation [37]. Substitution requires complete replacement of façade and its components, such as re-cladding [38]. On the other hand, most expensive options include circumvention and acceleration that have high carbon footprint and are less desirable for energy efficient retrofits but may be unavoidable in some situations [37]. A recent study on cost of refurbishments evaluated that major causes of disparity in EU are market practices, maturity and quality and experience [40] .

6.3 Life cycle impact of interventions

Façade retention for protected structures promotes sustainability and reduces the embodied and operational energy compared to new builds [41]. Boardman suggests that cheapest way to achieve zero carbon requirements is through refurbishment to higher standard [4]. Life cycle studies (LCA/LCCA) are among least included ones in planning stage of façade retrofits or in general, in the refurbishment projects [25]. On a general note, the overall impact of refurbishment will always be lesser than demolition or new builds due to the embodied energy contained in the materials [5].

Generally, building envelope repair and replacement costs contribute 20–30% of the overall building repair and maintenance life cycle costs [42]. An example of cold climate building upgrade using LCC is shown in Figure 3, where envelope only modifications contributed to up to 60% energy savings during the buildings' service life of 30 years [43]. This supports that passive interventions to façade retrofits can potentially reduce the energy consumption to a significant level.

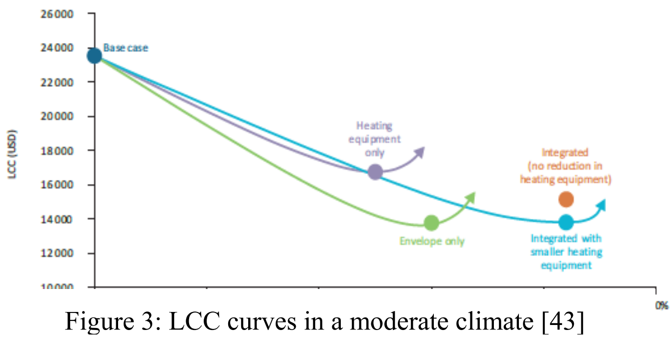


Figure 3: LCC curves in a moderate climate [43]

There exists a lack of regulations or protocols for evaluation of production energy requirements in retrofitting [44]. The use of regulated values for the production, maintenance and disposal of materials will lead to greater energy savings and measurable use of energy resources in retrofits [22]. Three façade variations in a hypothetical assessment in Figure 4 showed variations in embodied energy (surface area 50m^2)- a) fully glazed- 515 kWh/a- 185%, b) partially glazed- 423 kWh/a- 152% and c) totally closed- 278 kWh/a- 100%. The diagnosis and interventions if planned strategically can reduce the environmental impact in terms of cumulative embodied energy and operational energy during buildings life cycle.

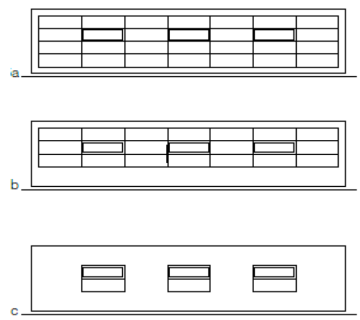


Figure 4: Glazing scenarios to evaluate embodied energy [31]

7 CONCLUSIONS

The complexities in retrofitting the post-war façades require greater collective understanding of the functional, economic and environmental requirements to meet the challenges of current regulations and EPBD targets. A logical sequence based on the knowledge systems that address various surveys, inspections and measurements according to standards and evaluation addressing risks and uncertainties, should lead to the selection of the appropriate diagnostic techniques. The passive intervention opportunities offer higher energy savings and increased thermal comfort. Handling the issues of embodied and operational energy during the life cycle of building should involve careful consideration about the scale and cost of interventions. Well-established guidelines and protocols are needed to identify the optimum intervention levels for the retrofit of post- war glazed façades.

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