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Holistic Approach to Assess the Potential of Using Traditional and Advance Insulation Materials for Energy Retrofit of Office Buildings

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***Abstract*—**Improving the energy performance of existing buildings can be challenging, particularly when facades cannot be modified, and the only available option is internal insulation. In such cases, the choice of the most suitable material becomes increasingly complex, as in addition to thermal transmittance and capital cost, the designer needs to account for the impact of the intervention on the internal spaces, and in particular the loss of usable space due to the additional layers of materials installed. This paper explores this issue by analyzing a case study of an average office building needing to go through a refurbishment in order to reach the limits imposed by current regulations to achieve energy efficiency in buildings. The building is simulated through dynamic performance simulation under three different climate conditions in order to evaluate its energy needs. The use of Vacuum Insulated Panels as an option for energy refurbishment is compared to traditional insulation materials (XPS, Mineral Wool). For each scenario, energy consumptions are calculated and, in combination with their expected capital costs, used to perform a financial feasibility analysis. A holistic approach is proposed, taking into account the impact of the intervention on internal space by quantifying the value of the lost usable space and used in the financial feasibility analysis. The proposed approach highlights how taking into account different drivers will lead to the choice of different insulation materials, showing how accounting for the economic value of space can make VIPs an attractive solution for energy retrofitting under various climate conditions.

***Keywords*—**Vacuum insulated panels, building performance simulation, payback period, building energy retrofit.

I. Introduction

BUILDINGS are the highest energy user and are responsible for one third of the global carbon emissions. Nevertheless, building energy demand is constantly on the rise, due to rapid growth in global building floor area and greater use of energy to provide better quality indoor environment and comfort. This has led to an increase in use of non-renewable energy resources worldwide and has raised concerns over depletion of these energy resources and their environmental impact. In an effort to reduce energy use toward Net Zero Targets, improving building thermal envelope insulation has been identified as a priority issue. This is achieved by lowering the overall heat loss coefficient (U-value) of building the building envelope through the use of better performing materials. Currently used conventional thermal insulation material require large thicknesses to achieve very low U-values to meet stringent building regulation requirements which may not be feasible for certain construction scenarios especially for refurbishment of old building stock. Advance thermal insulation materials such as Vacuum Insulation Panel (VIP) can help tackle this problem; VIPs can reach 8-times higher thermal resistance compared to conventional thermal insulation materials, resulting in a proportional reduction of thickness [1], [2]. However, use of such advanced materials is very limited in the construction sector, mainly due to their higher cost [3], [4], this is also hindered by the diffused use of assessment methods which focus only on energy costs, which tend to favor the cheaper alternatives.

Use of VIPs and their effect on the building energy consumption and economic feasibility have been investigated in previous studies. Mujeebo et al. [5] simulated the effect of VIPs on energy consumption in multi-story office building in the hot climate of Kingdom of Saudi Arabia. In this case study, integrating VIPs in walls and roofs led to decrease of only 0.8% annual energy consumption compared to that of base case scenario (uninsulated). Further, simple payback analysis revealed that VIPs are not a cost-effective insulation option for this case study building; however, as mentioned above, this assessment was done only focusing on energy savings, and not accounting for other impacts of using such advanced materials, such as the space saved in the application of the insulation layer.

Alam et al. [6] found that using fumed silica core VIPs in multi-story office case study building in the UK (London) led to reduction in space heating energy of 10.2% and made them an economically feasible insulation option in higher rental locations if economic value of the space saved is considered in the payback period calculations. However, this study focused on space heating energy, under the assumption this is the dominant form of energy in cold climates.

Lim et al. [7] assessed the use of VIP insulation in multi-story apartment building in South Korea using IES energy simulation software, and found that applying VIPs would reduce the annual energy consumption of the building compared to the base case (Expanded Polystyrene insulated building). However, no cost effectiveness analysis was carried out in this study.

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Fantucci et al. [8] assessed a reference building using VIP insulation accounting for the value of space saved, concluding that VIPs can be an economically favorable option when rental value of building is approximately higher than 220 €/m^2 per year.

Biswas et al. [9] performed the energy analysis of using modified low-cost VIP insulation in single story domestic building retrofit in cold climate of New York (USA) and predicted that heating energy consumption can be reduced by 12.5% compared to the baseline building. However, again, the payback period calculated in their study resulted longer than 100 years for retrofitting a building with no pre-existing insulation.

It is evident from previous studies that viability of using VIPs in buildings depends not only on Fanucci the climatic zone, location of building and location of insulation (external or internal), but also on a proper assessment of all impacts generated by the use of such material, including the difference in space requirements. In this context, this paper provides the comparative energy and economic analysis of using VIPs, mineral wool and extruded polystyrene (XPS) for retrofitting a case study building for three different climatic conditions/ locations while applying the proposed holistic approach.

II. Methodology

The presented research applies a case study approach, in which an ideal building is defined with the purpose of generalizing a subset of existing buildings and be investigated, assessing the environmental and financial feasibility of energy retrofits, including both traditional and innovative insulation materials.

Once the building has been defined, dynamic building performance simulation is applied in order to assess the energy needs of both pre and post refurbishment scenarios. In order to further assess the feasibility of such intervention under variable external conditions, three different locations are identified in the study to represent both different climate and financial conditions. For the purpose of this study, a simplified building performance simulation model approach [10] has been used, allowing for the definition of a building model based on a limited number of inputs. Building performance simulation is used to determine the annual heating and cooling needs for the case study building in each of the selected locations; both pre-refurbishment identifying the baseline results, and post refurbishment under each energy retrofit as-assumption made. Subsequently, the capital cost of each retrofit intervention is identified allowing, in combination to the results of the building performance simulation, to assess the financial feasibility of the retrofit in each of the identified locations. Three different approaches are identified based on which a financial feasibility is delivered:

- A “Heating Only” approach, in which only the positive impact of the insulation on heating needs is accounted for, under the assumption that any changes in cooling needs is either negligible or can be counteracted by ad-hoc measures such as changes in ventilation and lighting strategies not accounted for in the calculations. This is the easiest approach and the most likely to be seen used when simplified steady-state calculations are used in practice.
- A “Heating + Cooling” approach, in which the full potential of the building performance simulation is taken advantage of, and a worst-case scenario in which no countermeasure is taken to avoid the increase in cooling loads is considered, highlighting the impact on environmental and financial analysis when only heating needs are accounted for.
- An “Holistic” approach is finally defined attempting to not only account for the changes in energy needs for the building due to the retrofits, but also other changes that are typically neglected, such as the change in usable space within the building, trying to better quantify the real repercussion of using different materials, the approach is defined so that it can be further expanded to account for other repercussions in the future, such as the carbon footprint of each assessed solution.

In order to apply the holistic approach defined above, it is first of all necessary to calculate the variation of internal surface available pre and post refurbishment under the different assumptions. For the purpose of this study, the holistic approach is used as a comparative measure between different insulation materials, and therefore the space saved is calculated as detailed in (1), as the amount of space saved through the use of the better performing material.

$$Space\ Saving\ (m^2) = 2 \times \Delta d \times n \times \left[\left(w_i - \frac{\Delta d}{2}\right) + \left(l_i - \frac{\Delta d}{2}\right)\right] \quad (1)$$

where Δd = Thickness difference between insulation materials; n = Number of floors in the building; w_i = Internal floor width of the building; l_i = Internal floor length of the building.

For the purpose of this study, the financial assessment is then concluded by the calculation of simplified payback time as highlighted in (2):

$$Payback\ time\ (years) = \frac{Capital\ costs}{annual\ savings} \quad (2)$$

where $capital\ costs$ = Total initial expenditure expected in \$ for each retrofit solution; $annual\ savings$ = Sum of annual savings in \$ determined by the applied approach.

III. Description of Case Study Buildings

A case study building has been selected in the form of a notional medium-large building of average size and characteristics in order to generalize the results obtained from the assessment.

Details for the building can be seen in Table I, and represent a traditional medium-large multi-story office building, built between 1985 and 1990 for a total gross floor area of 16,000 m^2. The end use category, medium office, has been selected in order to represent the type of buildings in which the authors consider the proposed approach to be most relevant, where energy refurbishments are most likely to happen at building level and space considerations are of most interest due to the renting space value. Energy performance of the envelope has been determined based on the building regulations in place at the time of the theorized construction based on UK regulation, therefore referring to the "Building Regulations 1985" [11] and particularly to "Part L" of "schedule 1 – requirements", mandating the maximum U-Value of surfaces as detailed in Table I, assuming no energy refurbishment took place in the building concerning the opaque envelope. Since the study focuses on the insulation of opaque surfaces, in order to reduce the impact of other variables on results, it is assumed transparent surfaces have been refurbished already since the building construction and double-glazed windows with clear glazing and selective filters, with PVC frames are installed with U-Value of 1.656 W/m^{2}K and Solar Heat Gain Coefficient (SHGC) of 0.424.

TABLE I
CASE STUDY BUILDING DETAILS

Building characteristics			
Input definition	Baseline	Refurbished	Units
Length of North/South front	80	-	m
Length of Est/West front	25	-	m
Floor to floor height	3.5	-	m
Number of Floors	8	-	-
End use category	Medium Office		
Structural type	Masonry with concrete floor		
Roof transmittance	0.35	0.18	W/(m^2 · K)
External wall transmittance	0.60	0.28	W/(m^2 · K)
Ground floor transmittance	0.35	0.22	W/(m^2 · K)
Type of windows	Double glazed with PVC frame		
Total north facing windows	1120	-	m^2
Total south facing windows	1120	-	m^2
Total east facing windows	352	-	m^2
Total west facing windows	352	-	m^2

For the purpose of this study, it is assumed that the building envelope is refurbished in order to achieve minimum requirements established by current UK regulation, Approved Document L2B: conservation of fuel and power in existing buildings other than dwellings, 2010 edition [12]. Required U-Values to achieve after the refurbishment are highlighted in Table I. It is assumed that, only available option for the energy efficiency measure is to apply an internal layer of insulation, due to the nature of the building; three different insulation material options are assessed including XPS, mineral wool (MW) and vacuum insulated panels (VIPs).

Since the target is to achieve the same U-Values using different materials, the variable becomes the thickness of the required insulation layer. Table II shows material properties and insulation thickness values for the various options assessed.

TABLE II
THERMAL INSULATION MATERIALS AND THEIR PROPERTIES

	Thermal conductivity (W/mK)	Insulation Thickness (m)	Volume of material (m^3)
XPS	0.033	0.063	369
MW	0.035	0.067	392
VIP	0.007	0.013	78

In order to assess the impact of different weather conditions on the environmental and financial feasibility of the different solutions, three different locations have been selected to represent cold, warm and mild conditions in the continental/ temperate climate area, associated with large cities in which office buildings are likely to be located. The selection has been based on the analysis of the typical mean year weather data required to perform the subsequent analyses, and more specifically on the calculation of heating degree days (HDD) for the heating period and cooling degree hours (CDH) for the cooling period. A summary of the weather conditions of the three selected locations: Toronto (CAN), Madrid (ESP) and London (GBR) can be seen in Table III.

TABLE III
WEATHER SUMMARY OF SELECTED LOCATIONS

	Max. Temp. (ºC)	Min. Temp. (ºC)	Av. Temp. (ºC)	STDEV (ºC)	HDD (ºC)	CDH (ºC)
Toronto	32.5	-19.4	7.4	10.8	3892	640
Madrid	40.4	-4.6	14.3	8.6	1995	4110
London	31.3	-5.9	10.2	6.0	2923	85

IV. ENERGY CONSUMPTION ANALYSIS

Further to the definition of the case study, a simplified building simulation model has been implemented and dynamic building performance simulations have been carried out for both the baseline case study and each refurbishment option, in each of the identified locations; simulations are run with a sub-hourly time step based on typical mean year weather files available for an entire solar year, for the purpose of identifying heating and cooling energy needs for each combination of insulation scenario and location.

Since the thickness of insulation layer for each refurbished scenario has been determined with the aim of achieving the same target U-Values, as shown in Table I, and other thermal properties are expected to have limited impact on the thermal behavior of the building, for the purpose of this paper energy needs for the refurbished scenarios will be discussed as a single scenario, however, simulations have been performed for each scenario to validate this assumption, resulting in variations of less than 0.04% on the annual heating needs and less than 0.06% on the annual cooling needs, without any appreciable variation in the hourly energy needs pattern. This confirms how, from a thermal behavior standpoint, each of the identified energy retrofit solution behaves in a comparable way, allowing for a direct comparison in terms of cost and environmental impact.

TABLE IV
SUMMARY OF HEATING AND COOLING NEEDS

	London		Madrid		Toronto	
	Heat	Cool	Heat	Cool	Heat	Cool
Baseline (MWh)	512.7	126.8	209.1	593.4	1,116.9	341.4
Refurbished (MWh)	447.4	151.9	174.1	626.3	1,018.1	369.1
Savings (MWh)	65.3	-25.1	35.0	-32.9	98.8	-27.6
Savings (%)	14.6	-16.5	20.1	-5.3	9.7	-7.5

Summary results for the baseline and refurbished scenarios, including both heating and cooling needs for each location are shown in Table IV.

It is worth noting how, due to the nature of the case study as a medium office building, simply improving the U-Values of opaque surfaces without accounting for other measures can lead to sub-optimal results, depending on the weather conditions of the selected location. This is highlighted in how, for each analyzed location, cooling needs post refurbishment are increased due to the increased U-Values therefore contributing to a reduction in energy savings and an increase in risk of overheating during the summer. This is particularly relevant the more the climate is cooling dominated in the selected location, as shown in the Madrid scenario, where the increase in cooling needs of 32.9 MWh nearly equals the reduction in heating needs of 35 MWh during the winter periods. It is also worth noticing how the change in cooling needs for each location following the refurbishment is comparable, ranging from 32.9 MWh to 25.1 MWh, suggesting the increase is likely connected to the internal loads and could likely be counteracted with the implementation of appropriate solutions such as an effective ventilation strategy.

V. Space Saving Calculations

Since each refurbishment option, characterized by the use of different materials, aims at achieving the same U-value, thermal behavior of the building and energy needs are comparable and any difference is negligible between the various options, as detailed in the previous chapter; however, using different insulation materials can generate significant differences in terms of required space, due to the thickness of the insulation material. This difference has a direct impact on the usable space within the building, and therefore the intrinsic economic value of the building. In order to quantify this impact, (1) is applied to the different refurbishment scenarios to quantify the amount of space saved by using VIP insulation as opposed to XPS or MW, resulting in space savings of 83.1 m^2 and 89.7 m^2 respectively. Subsequently, the amount of space saved is given a value based on the average rental value of office spaces in the three different locations analyzed. Rental values for the purpose of this assessment for London, Toronto and Madrid are shown in Table V and converted in US Dollars for easier comparison [13]-[15].

TABLE V
Rental Value for Office Space in Different Locations

	Value per ft^2	Change Rate	Value in $\$/m^2$
London	£72.50	1.29	1006.70
Toronto	$59.13	0.75	477.36
Madrid	€ 38.46	1.17	484.36

Finally, the amount of space saved is given a financial value based on the assumed rental value of the property in different locations, a summary of the values is included in Table VI. Similarly, the problem can be approached by quantifying the amount of space lost for each refurbishment scenario compared to the baseline case. Both approaches lead to similar conclusions, therefore we will limit to detailing the first approach in this paper.

TABLE VI
Summary of Space Savings Calculations

		VIP vs. XPS	VIP vs. MW
Δd (m)		0.0495	0.0534
Space Saving (m^2)		83.12	89.67
Annual Rental income saved	London	$83,677.96	$90,267.42
	Madrid	$40,260.44	$43,430.86
	Toronto	$39,678.25	$42,802.83

VI. Payback Period Evaluation

Having calculated both the impact of the different refurbishment scenarios in terms of thermal behavior and space savings, for each of the assessed location, it is now possible to assess the financial feasibility of each intervention with a more holistic approach. In order to do so, we first need to calculate the capital costs required for the installation of each energy efficiency solution. Table VII provides an overview of the different costs; insulation cost per unit of volume for each scenario has been obtained based on commercial prices. The cost of each refurbishment scenario has been assumed constant throughout each location.

Additionally, other assumptions are made in order to allow a complete financial analysis; seasonal energy efficiency for the heating system is assumed at 80%, powered by a natural gas boiler, with gas costed at 0.04 £/kWh; meanwhile seasonal cooling energy efficiency is assumed at 2.8, powered by electric chiller with a unified cost of electricity of 0.19 £/kWh. All assumptions are maintained unchanged for each scenario and simulation in order to allow direct comparison based on weather conditions, although it is expected energy costs would vary based on location.

TABLE VII
Summary of Capital Costs per Refurbishment Scenario

	Net Insulation Volume	Insulation Cost (£/m^3)	Insulation Cost ($\$/m^3$)	Total cost ($)
Baseline	0	0	0	0
XPS	184.38	240	309.6	57084
MW	195.83	135.6	174.9	34255
VIP	39.04	2840	3663.6	143059

Table VIII includes a summary of the results for the financial analysis in the different scenarios and under different approaches, highlighting both how MW is the best performing material under a traditional approach, but under an holistic approach, if the space saved by the use of VIPs can be given a value, the use of VIPs quickly outperforms any of the traditional insulation materials considered, in each of the locations analyzed, with payback times always below 4 years and as low as 1.6 years in London due to the high rental value of the space saved.

TABLE VIII
PAYBACK TIME IN YEARS - SUMMARY TABLE

		XPS	MW	VIP	VIP (vs. XPS)	VIP (vs. MW)
London	Heating	13.6	8.2	34.0	-	-
	Heat+Cool	28.3	17.0	70.9	-	-
	Holistic	-	-	-	1.7	1.6
Madrid	Heating	25.3	8.9	63.4	-	-
	Heat+Cool	Inf.	Inf.	Inf.	-	-
	Holistic	-	-	-	3.7	3.4
Toronto	Heating	9.0	5.4	22.5	-	-
	Heat+Cool	14.5	8.7	36.2	-	-
	Holistic	-	-	-	3.3	3.1

VII. CONCLUSION

Correctly assessing the environmental and financial impact of energy efficiency measures is a fundamental requirement in order to correctly identify the optimal solution in different contexts. This becomes even more important when complex situations are approached in which more common solutions might lead to undesired or suboptimal results, such as the presented case of an energy retrofit of an existing office building in the urban context. This study presents an initial step toward defining a holistic approach that combines building performance simulation, taking into account specific climate conditions and the dynamic thermal behavior of the building, with other energy and economic implications of the use of different types of insulation materials, including advanced ones such as VIPs, and the amount of space required and the associated value. Case study results show how, while a traditional assessment would suggest MW to be the more attractive solution, as soon as a more holistic approach is taken, VIPs become a more attractive solution with payback time lower than 4 years under all analyzed climates, this is due to the traditional approach not accounting for all energy and economic implications. Following this initial study, the holistic approach will be expanded upon, to account for other variables and potential implications of the use of different material solutions.

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